Book of Abstracts

NFSD
Nordic Fire & Safety Days

June 21-22, 2022
in Lund, Sweden



RISE Research Institutes of Sweden AB
RISE Report: 2022:72
ISBN: 978-91-89711-12-9
DOI: 10.23699/sgj7-kd69
Borås

Preface

It is our pleasure to hand over to you this book of abstracts for the Nordic Fire & Safety Days 2022 organized by RISE, Research Institutes of Sweden in collaboration with Lund University, the Technical University of Denmark, Norwegian University of Science and Technology, University of Stavanger, Western Norway University of Applied Sciences, Luleå University of Technology and Iceland University as well as VTT Technical Research Centre of Finland Ltd, the Danish Institute of Fire and Security Technology and Aalborg University in Copenhagen. The book of abstracts the Nordic Fire & Safety Days 2022 contains 63 Nordic and international contributions. As in the previous years, the work presented at the conference has strong scientific and societal relevance. The areas of fire and safety engineering presented have are of great interest in the Nordic countries. The NFSD follow up on challenges with respect to safety dealing with aspects of energy, biomaterials as wood, fire and actions of the rescue service as well as human behaviour and risk management. This year's keynotes and panel discussions deal with energy related topics, namely Safety of timber building s and safe green energy.

Anne Dederichs, RISE Research Institutes of Sweden (conference chair)

Table of Contents

Fire Safety Engineering

Human & Fire

Safe Energy

Structural Fire Safety

Transport & Structures

Wood

Nordic Collaboration in Developing Educational Activities in Emerging Fields of Engineering – Fire Safety and Risk Engineering

Anne Dederichs
RISE
Malmö, Sweden
Anne.Dederichs@ri.se

Margaret McNamee
Dept. of Fire Safety Eng
Lund University
Lund, Sweden
Margaret.McNamee@brand.lth.se

Bjarne Husted
Danish Institute of Fire and Security Technology (DBI)
Denmark
Bjarne.Husted@brand.lth.se

Tuula Hakkarinen
VTT Technical Research Centre of Finland
Finland
Tuula.Hakkarainen@vtt.fi

Simo Hostikka
Aalto University
Finland
Simo.Hostikka@aalto.fi

Ove Njå
Stavanger University (UIS)
Stavanger, Norway
Ove.njaa@uis.no

Anne Steen Hansen
Norwegian University of Science and Technology (NTNU)
Trondheim, Norway
anne.steen-hansen@ntnu.no

Björn Karlsson
Dept. of Civil and Env. Eng
University of Iceland
Reykjavik, Iceland
bjornk@hi.is

Lars Schiøtt Sørensen
Technical University of Denmark (DTU)
Denmark
Lsso@byg.dtu.dk

Michael Försth
Luleå Technical University
Luleå, Sweden
michael.forsth@ltu.se

Ragni Fjellgaard Mikalsen
RISE Fire Research (RISEfr) Norway
ragni.mikalsen@risefr.no

Marcus Abrahamsson
Dept. of Societal Risk
Lund University
Lund, Sweden
Marcus.Abrahamsson@risk.lth.se

Bjarne Hagen
Western Norway University of Applied Sciences (HVL)
University College of Haugesund, Norway
bch@hvl.no

Keywords:* *(5 key words)
Nordic Fire and Safety Days, NFSD, Nordic Fire and Safety Network Focus on Energy, NFSNergy, Nordic Education Collaboration, Fire Safety Engineering, Risk Engineering, Education, Core Curriculum.

Abstract

Fire safety regulations can have a major impact on many aspects of the overall design of a building, including layout, aesthetics, function, and cost. Rapid developments in modern building technology in the last decades often have resulted in unconventional structures, new building materials and design solutions. Past experiences or historical precedents, which form the basis of many current prescriptive building codes and regulations, rarely provide the guidance necessary to deal with fire hazards in new or unusual buildings. Therefore, there has been a worldwide movement to replace prescriptive building codes with ones based on performance. The increased complexity of the technological solutions, however, requires higher levels of academic training for professionals in fire safety engineering and a higher level of continuing education during their careers.

Four decades ago a specific engineering BSc study program in Fire Safety Engineering was formed at Lund University, and several Nordic universities have since included courses on such subjects in their own BSc og MSc programs. A core curriculum for such educational programmes was developed early on [1] and has been re-evaluated more recently [2], [3]. Three years ago a research agenda for the discipline was published by an international group of educators and scientists [4].

The field of fire safety engineering encompasses topics from a wide range of engineering disciplines, including mathematics, physics, chemistry and advanced engineering courses such as heat transfer, thermodynamics and fluid dynamics. It is not immediately obvious how to balance the need for knowledge from fundamental, applied and specific courses to be taught within the discipline of fire safety engineering.

A long standing cooperation across 13 Nordic universities and research institutions has made this distinction clearer The NFSD is a Nordic platform aiming at being a meeting point for professionals from industry, research institutes, universities and municipalities, including the fire service and other local government professionals. The origin of the network are the Nordic Fire and Safety Days, held biannually in the Øresund Region.

At the same time, the topic of Societal Risk has gained much prominence in contemporary society. Being a truly multi-disciplinary subject, encompassing a very wide range of scientific fields, there is an acute need for educators to collaborate in developing educational material and defining curriculums for educational programs at universities in this emerging field.

The Nordic cooperative network NFSD, which initially focused on fire safety, very early on widened the scope to include to concepts of safety and security, and therefore the engineering discipline of Risk Engineering.

Most recently the NFSD network secured Nordic funding for three years for a specific cooperation program in education, including PhD exchange programs and the development of a summer school for students of engineering, focusing on fire safety and energy.

The success of the NFSD has been used as a model for expanding the collaboration to a broader network as presented in the project The Nordic Fire and Safety Network Focus on Energy (NFSNergy), which was funded in 2020 by Nordic Energy Research.

Besides organizing the Nordic Fire and Safety Days, the network organizes the exchange of PhD students and researchers. The focus is safety of buildings and energy infrastructures. Furthermore, NFSN will run summer schools, webinars, and teaching for professionals, as well as supporting research collaborations. The project will bring together multidisciplinary teams working on important energy-related initiatives promoting:

- the fire safety of new bioenergy systems,
- energy storage systems in green buildings,
- improved digitalization through Building Information Models in construction and
- the fire safety of new energy carriers in green transport systems.

Current members of the NFSNergy consortium are the Technical University of Denmark in collaboration with RISE (Research Institutes of Sweden), Norwegian University of Science and Technology, Lund University, Aalto University, Luleå University of Technology, University of Stavanger, Western Norway University of Applied Sciences and the University of Iceland, as well as VTT Technical Research Centre of Finland Ltd and Danish Institute of Fire and Security Technology.

As an example of the various levels of educational cooperation, a number of the consortium members have been cooperating for over two decades within one of the key courses in Fire Safety Engineering, called „Enclosure Fire Dynamics“, the study of how a fire develops in a building. Here, engineering methods based on classical physics and chemistry are used to simulate the environment due to fire, allowing engineers and designers to test and compare various possible design solutions regarding building fire safety. This has required careful development of educational material in close cooperation between a number of Nordic universities. The fruitful cooperation has resulted in the production of comprehensive educational material such as textbooks, homework assignments, laboratory instructions and computer labs, to name a few examples of results. Most of the material is free of charge and available on the internet.

The authors of this paper recognize that engineering education is acquired through programs of varying lengths and stages in a variety of institutions and that educators in all parts of this spectrum can learn from practice elsewhere. The work reported here provides an example of how this has been achieved by a cross-Nordic collaboration on providing and developing educational material in two emerging engineering disciplines: Fire Safety Engineering and Risk Engineering.

References

[1] Magnusson, S.E, Drysdale, D., Fitzgerald, R.W., Mowrer, F., Quintiere, J.G., Williamson, R.B., and Zalosh, R.G., (1995), "A Proposal for a Model Curriculum in Fire Safety Engineering", Fire Safety Journal, Vol. 25. DOI: 10.1016/S0379-7112(95)00038-0.

[2] SFPE, (2010) "Recommendations for a Model Curriculum for a BS Degree in Fire Protection Engineering", Society of Fire Protection Engineers, 2010

[3] SFPE, (2013), "Recommended Curriculum Content for an MS/ME in Fire Protection Engineering", Society of Fire Protection Engineers

[4] Margaret McNamee, Brian Meacham, Patrick van Hees, Luke Bisby, W.K. Chow, Alexis Coppalle, Ritsu Dobashi, Bogdan Dlugogorski, Rita Fahy, Charles Fleischmann, Jason Floyd, Edwin R Galea, Michael Gollner, Tuula Hakkarainen, Anthony Hamins, Longhua Hu, Peter Johnson, Bjorn Karlsson, Bart Merci, Yoshifuni Ohmiya, Guillermo Rein, Arnaud Trouve, Yi Wang, Beth Weckman, "IAFSS agenda 2030 for a fire safe world", Fire Safety Journal, Vol 110, December 2019) https://doi.org/10.1016/j.firesaf.2019.102889

The coupling between fire dynamics and fire resistance

Are we on the right path?

Robert McNamee[1,2]

[1]Fire and Security, RISE, Lund, Sweden
robert.mcnamee@ri.se

[2]Division of Fire Safety Engineering, Lund University, Lund, Sweden.

***Keywords:* Fire resistance, Fire dynamics, Standard time temperarure curve**

Introduction

The coupling between fire dynamics and fire resistance is not so straight forward as one might think at a first glance. The fire exposure during standardized fire resistance testing follows the so-called standard fire time temperature curve, defined as a growing fire (until prescribed time limits) without any cooling phase. Although this is not representative of all possible real fires, the use of the standard fire exposure allows for fire resistance rating of building elements independent of their final use in a building [1][2].

The standard time temperature curve and Ingberg's equal area hypothesis

When the standard time temperature curve, henceforth called the standard fire curve in this summary, was defined more than 100 years ago, our knowledge regarding fire dynamic was limited. No controlled fire dynamics experiments had been performed when the curve was developed in the USA [3]. But soon after the standard fire curve was defined, Ingberg conducted a series of fire dynamics experiments [4][5]. During these experiments, in a specially designed building, furniture and paper were allowed to burn until burnout. Finding from the experiments included that both the temperature development and the duration varied in real fires which made it problematic to use only one standard fire curve. Ingberg's solution for this problem was to eliminate one of the parameters, the varying temperature development. This was done by introducing the equal area hypothesis shown in Figure 1. The basic idea in this hypothesis is that the damaging potential of a fire on a structure is equal to the area under a time/temperature curve below a lower boundary temperature. Ingberg used both 150 and 300°C for this lower boundary for the area calculation and a cooling phase was included in the standard fire area. By using this concept, a series of experiments with different fuel loads, representing different occupancies, was converted to different times of standard fire exposure, i.e. this was the basic coupling between fire dynamics and fire resistance.

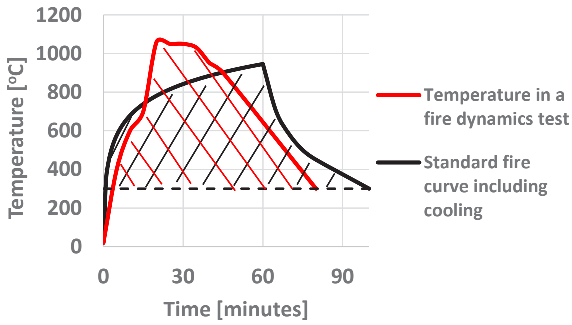


Figure 1. The principal idea with Ingbergs equal area hypothesis with 300°C as the lower boundary temperature [5] (fictive temperatures in the fire dynamics test).

About 20 years later in an experiment performed August 1, 1947, the equal area concept was checked at the SP Fire laboratory in Stockholm [6]. A bespoke test house was constructed with walls of light weight concrete with a reinforced concrete roof. The fuel load was chosen to represent two hours of standard fire according to the tables developed by Ingberg. After 40 minutes of slow burning the fire developed and a quite similar temperature development as the standard fire exposure was measured during 2 hours in the experiments. The conclusion from the experiment at that time was that Ingberg's coupling between fire dynamics (fuel load) and the standard fire curve concept was relevant. But it is important to remember that the material in the enclosure built specifically for the validation experiment was almost identical to Ingberg's test house where the correlation was developed. Interesting to note was that in both Ingberg's experiments and the tests at SP the opening area in the enclosures was actively changed during the experiments to make the fire as severe as possible. The changes in opening factor during the experiments was, however, not carefully recorded, neither by Ingberg nor in the experiments at SP.

Fire dynamics in fully developed room fires

The severe city fires in Japan during the second world war motivated Japanese research to develop their knowledge in the fire dynamics area [7]. This study led to the development of a famous fire dynamics correlation when Kawagoe stated that the intensity of fully developed fires (oxygen controlled) in an enclosure was proportional to the opening area times the square root of the opening height. In studies in the earlier 60's more advanced fire models were developed in parallel in Japan by Kawagoe and in Sweden by Kai Ödeen [8]. Ödeen's model was a balance equation over the fire room where the heat release was balanced against different losses. One important conclusion from Ödeen's study was that the temperature in the fire room was influenced by the thermal properties of the enclosure. This was a factor that was clearly missing in Ingberg's correlation.

The importance of self-extinction

The basic coupling between fire dynamics and fire resistance is in many cases that a structure should be able to survive a burnout, i.e. when all burnable content in the room is consumed the fire decays and the structure is still standing and carrying its load. In the case of fire exposed load bearing members made of combustible materials it is crucial to ensure that this decay is possible, i.e. when the burnable content in the room is consumed the structure itself should self-extinguish, otherwise the structure will not survive a burnout. This can be ensured by limiting the radiation exchange between burning surfaces of the load bearing structure.

The importance of the cooling phase

In traditional fire resistance testing the cooling phase is not included in the test procedure [9]. In real fires without fire fighter intervention, failure can also happen in the cooling phase. When using the duration of heating phase (DHP) concept failure during cooling is also evaluated [10]. When using the DHP concept, the shortest fire leading to collapse following a standard fire curve is investigated, including a cooling phase from the Eurocode [11]. When using this concept for a set of glulam columns, it was shown that the DHP was only 20-50% of their standard fire resistance [10].

Discussion

Traditional fire resistance rating is conducted following one prescribed heating exposure until failure, not including any cooling phase. If there is no fire fighter intervention during a fire in an enclosure, there will always be a cooling phase.

If the final use of an element or a structure is known, it is possible to do a detailed investigation of the fire resistance based on the expected fire dynamics and loads. This can be done experimentally or, if the structure is simple, by calculations. It is not realistic that this can be done for all possible situations, so a fire resistance rating before knowing the final use of the element is necessary. This is done in the standardized fire resistance rating system when elements are exposed to the standard fire curve where the fire resistance time rating is how long the structure can survive this exposure. As elements and structures can also collapse in the cooling phase and that this collapse in the cooling phase is not proportional to the traditional fire resistance rating when comparing different structures, a complementary robustness measure may be introduced. This complementary measure is the burnout resistance defined by the duration of heating phase. If developing this concept, a fire resistance rating may in the future be expressed as "R 60 B40" where the traditional fire resistance is 60 minutes (load bearing capacity) and the longest[1] standard fire including cooling that the structure can survive is 40 minutes. The different ways of evaluating fire resistance discussed is show in in figure 2. This methodology bolsters the benefit of traditional fire resistance testing by temper its use with a thorough understanding of burnout resistance of the tested building elements.

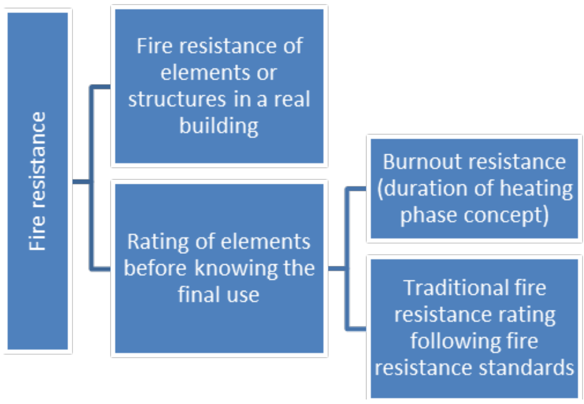


Figure 2. Different ways of evaluating fire resistance.

References

[1] McNamee R. "99 years of standard fire – succes or failure?" Nordic Fire and Safety Days, August 17-18, Copenhagen, Demnark

[2] McNamee R. & Ödeeen K. "Standardbrandkurvan – En pigg 103-åring?" (In Swedish) Bygg och Teknik, No5, 2021

[3] V. Babrauskas, Fire endurance in buildings" PhD thesis at the University of Berkeley, USA, 1976

[4] Babrauskas V. och Williamson R. B. "The historical basis of fire resistance testing- Part II" Fire Technology 14, sid 304–316, 1978

[5] Ingberg S.H."Fire loads", Quarterly Journal of the National Fire Protection Association, 1928

[6] Bergström M., Johannesson P. och Larsson G. "Brandteknisk forskning, nagra undersokningsresultat" Meddelande 122, Statens Provningsanstalt, 195

[7] Robertson A. F. & Gross A. F. "Fire load, fire severity and fire Endurance" Fire Test Performance, ASTM STP 464, 1970

[8] Ödeen K., "Theoretical Study of Fire Characteristics in Enclosed Spaces", Division of Building Construction, Royal Institute of Technology, 1963

[9] EN 1363 "Fire resistance tests – Part 1: General requirements" Brussels, February 2020

[10] Gernay T. "Fire resistance and burnout rsistance of timber columns" Fire Safety Journal, No 122, 2021

[11] EN 1991-1-2, Eurocode 1 – Actions on Structures. Part 1–2: General Actions – Actions on Structures Exposed to Fire, CEN, Brussels, 2002

[1] The DHP concept in ref [10] is expressed as the shortest standard fire including cooling leading to collapse.

Fire safety of timber buildings – past, today and future

Esko Mikkola
KK-Palokonsultti Oy
Espoo, Finland
esko.mikkola@kk-palokonsultti.com

Keywords: *Timber buildings, fire exposure, visible wood, fire load, sprinklers*

Abstract

Timber structures have been increasing their role in sustainable and economic development and have attracted worldwide attention especially in recent years. However, the combustibility of structural timber and wooden linings is one of the main reasons that still many building regulations and standards restrict the use of wood-based materials and structures.

Concern about the fire safety is understandable because exposed wood surfaces can contribute to the early stages of a fire and can add to the fire load in later stages of fire. Research projects conducted during the past three decades have provided basic data and information on the safe use of wood in buildings.

Technical basis for fire safety of timber buildings

Traditionally wood-based building products have been used in 1 – 2 storey buildings where potential fire risks are low / reasonable. In the Nordic countries a major research effort was started in 1990's to show acceptable ways of use of wood-based products in higher buildings. This resulted to the first version of a guidance book *Brandsäkra trähus* [1] in 1999 which dealt primarily with timber frame building systems. Later two new editions have been published including also Baltic countries in the third edition.

As an outcome of a European research project *FireInTimber* a guidance book *Fire Safety in Timber Buildings - Technical Guideline for Europe* [2] was published in 2010. This book includes a wide range of technical information including basis for many amendments of the ongoing revision of Eurocode 5, fire part.

An informal international group known as the *FSUW (Fire Safe Use of Wood)* group (established in 2003 with European partners) prepared the background for the *FireInTimber* project. Later this group (after extending to a global network) was also the initiator of a soon to be published guidance book *Fire Safe Use of Wood - Global Design Guide* [3].

Contribution of structural timber to fire development and fire exposure has been one important area of research. In Figure 1 examples of room fire test results of mass timber structures are shown for different levels of visible wood surfaces. According to the test results maximum temperatures can be 1000 – 1200°C when large areas of unprotected wood surfaces are exposed to fire and there is enough oxygen available [4].

Increased fire exposures lead to higher charring rates. This means that when sprinklers are not available, higher nominal fire resistance time requirements are needed to be used when structural design is based on standard temperature-time fire exposure curve.

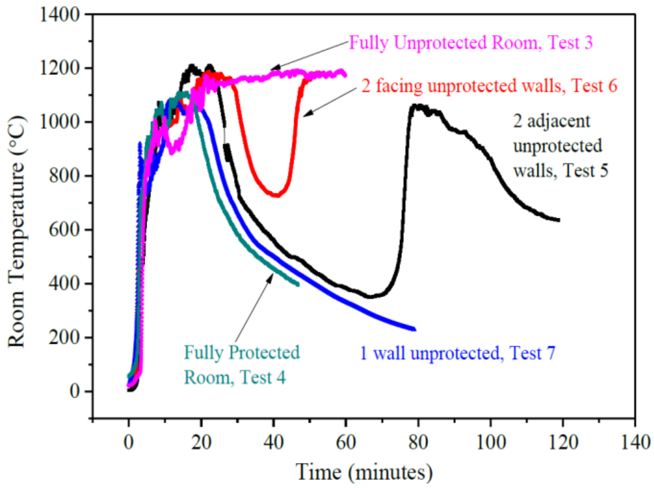


Figure 1. Room fire tests with mass timber structures (CLT) [4].

In a Canadian study [5] it was concluded that active safety systems of smoke alarms and sprinklers, played a much greater role in reducing the severity of a fire than the type of construction material. It is also shown in many studies that sprinklers are very effective in ensuring safety of life.

The current improved knowledge on fire design of timber buildings, combined with passive and active fire prevention measures, allow safe use of wooden linings and structural timber in a wide field of application.

Future challenges

Increasing use of wood-based products and structures is still possible when using the latest scientific knowledge and principles of performance-based design to further develop design codes and standards.

Research and guidance documents in the following areas would be helpful for design engineers and code writers:

- Contribution of exposed wood to the fire load in different conditions and layouts
- Self-extinguishment of charred wood – conditions for safe solutions
- Performance of wood in facades / new European fire test
- Performance of hybrid structures made of timber, concrete and steel
- Methods to combine passive and active fire protection for overall fire safety
- Procedures for building execution and control.

Acknowledgements

The author wishes to thank Birgit Östman and a number of colleagues (some of them mentioned in references) in many countries who have been working for fire safety of timber buildings.

References

[1] B. Östman, J. König, E. Mikkola, V. Stenstad, B. Karlsson B, L. Walleij. Brandsäkra trähus: Kunskapsöversikt och vägledning för lättbyggsystem i Norden. Trätek. Stockholm, 1999.

[2] B. Östman, E Mikkola, R Stein, A Frangi, J. König, D. Dhima, T. Hakkarainen, J. Bregulla. Fire Safety in Timber Buildings – Technical Guideline for Europe, SP Report 2010:19, SP Trätek, Stockholm, Sweden.

[3] Fire Safe Use of Wood in Buildings - Global Design Guide - in preparation. A. Buchanan, B. Östman, editors. CRC Press, 2022.

[4] X. Li, C. McGregor, A. Medina, X. Sun, D. Barber, G. Hadjisophocleous. Real-scale fire tests on timber constructions. WCTE 2016, World Conference on Timber Engineering. August 22-25, 2016. Vienna, Austria.

[5] A. Zheng, L. Garis, I. Pike. Fire Severity Outcome Comparison of Apartment Buildings Constructed from Combustible and Non-Combustible Construction Materials. Fire Technology 2022. https://doi.org/10.1007/s10694-022-01223-4.

Risk associated to H_2 vehicles in tunnels and other confined spaces

Paola Russo
Dept. of Chemical Engineering Materials Environment
Sapienza University of Rome,
Rome, Italy
paola.russo@uniroma1.it

Maria Clelia Cortellini
Dept. of Chemical Engineering Materials Environment
Sapienza University of Rome,
Rome, Italy

Frank Markert
Dept. of Civil and Mechanical Engineering
DTU,
Kgs. Lyngby, Denmark

Keywords: H_2 vehicle, tunnel, underground parking, risk analysis

Abstract
A risk analysis is performed to estimate what scenarios are most likely to occur in the event of a hydrogen vehicle accident in a tunnel or other confined spaces (i.e. underground parking). It provides a quantitative calculation for the likelihood of each scenario occurring, and of the possible consequences.

Introduction
Hydrogen energy is increasingly being introduced to fuel hydrogen vehicles. This includes the increasing production and transport of large quantities of hydrogen by tankers and other means. Both the vehicles and tankers will use the common infrastructures established for traffic. Therefore, it is necessary to ensure that the traffic infrastructures are able to withstand the specific risks that may arise from these new technologies. Hereunder the safe transport through tunnels is a very important issue.

In order to have an appropriate assessment tool for hydrogen vehicles transport through tunnels a new QRA methodology is being established. A prior literature review revealed a few risk assessment models and tools, but either they do not include hydrogen as a dangerous substance (i.e., the QRA from PIARC [1]), or the "low frequency – high consequence" events are not analysed (i.e., QRA developed in [2]).

In Europe, the PIARC [1] approach is widespread and chosen as a starting point for the new methodology. It already includes average data as traffic statistics, accident frequency, tunnel geometries including some prevention and protection measures. This approach is enhanced by enabling better implementation of hazards identification and respective sources for hydrogen vehicles. It facilitates a detailed analysis of the accident scenarios that are unique for hydrogen vehicles.

The new methodology here reported provides a quantitative calculation for the likelihood of each scenario occurring, and of the possible consequences together with the suggestion of engineering tools available for the analysis. Furthermore, its application to hydrogen powered vehicle accident in a confined space like a road tunnel and an underground parking is discussed.

Risk analysis of a H_2 vehicle in a tunnel
Event Tree Analysis (ETA) is the proposed technique to estimate the event frequencies. It depicts the chronological sequence of events that could occur following the initiating accident, including escalations and mitigation measures, e.g. first responders' intervention at the site of the incident. The difficulties in ETA for emerging technologies is a lack of statistics, failure rates and probabilities that make QRA uncertainty very high.

A detailed analysis of the incident scenarios that are unique for hydrogen vehicles such as consequences of the initiating events is included in the QRA methodology. The collision types that may result in a release of hydrogen gas in a tunnel and the location of such an accident are also considered. As an example, the worst-case incident scenario in a road tunnel is assumed to be a collision of a vehicle at high speed into the last vehicle in a queue. Then both hydrogen release from the hydrogen fuel system and TPRD are considered.

Regarding the latter, the proposed methodology enables the assessment and evaluation of scenarios involving external fires or vehicles that burst into a fire because of an incident or other ignition event. The heat impact on the hydrogen storage system is of great importance as it implies the storage tank rupture and gas cloud explosion scenarios. Therefore, both engulfing fire and localised fire scenarios are considered by application of different TPRD failure probability in a fire taken from publicly available sources. The reliability of the TPRD is not reported sufficiently. There are very limited literature data available, e.g. in the FireCOMP risk assessment study [3] and the SANDIA publication [2].

The results of the analysis show that the most likely consequence includes scenarios with no release or hydrogen release without ignition. When the hydrogen does ignite, it is most likely a jet fire from the hydrogen system or the TPRD.

The consequence analysis, therefore, includes the hazard from unignited release, hydrogen jet deflagration and fire, deflagrations/DDT/detonations of flammable cloud under a ceiling if it is created, blast wave and fireball after hydrogen storage tank rupture in a fire, etc.

For jet fire, the flame length, which depends on the storage pressure and release orifice diameter, is calculated using the dimensionless correlation for hydrogen jet flames [4]. In the case of TPDR releases impinging jet will be shorter due to loss of momentum and follow-up effect of buoyance than free jet and therefore the correlation can be considered as a conservative estimate.

For the blast wave in tunnels, the engineering tool for the calculation of the hazard distances [5] is employed for the consequence analysis. For fireball after high-pressure hydrogen tank rupture in a fire the engineering correlations for assessment of hazard distance (defined by the fireball size) are available both for stand-alone and under-vehicle tanks rupture in the open atmosphere, but not in confined spaces [6].

Prediction of the consequences of hydrogen detonation is important for hydrogen safety assessment in confined spaces. Li et al. [7] calculated the hydrogen dispersion in a tunnel to evaluate the risk of flame acceleration and the DDT. The detonation in the tunnel is calculated by assuming a strong ignition at the top of the tunnel at an unfavourable time and location. The pressure loads are calculated to evaluate the consequence of the hazard.

The QRA output is individual risk in terms of human fatality per vehicle per year for a selected scenario. Probit functions are used to provide harm probabilities for the range of incidents included in the risk assessments.

The application of the analysis to case studies has shown that road tunnel risks with the largest consequences are the scenarios leading to gas cloud explosions and tank rupture.

Risk analysis of a H_2 vehicle in an underground parking

The case from the road tunnel scenario is applied with some adaptions to a scenario where hydrogen cars are parked in an underground car park.

While accident scenarios involve severe collisions in road tunnels, the situation in underground parking is different due to the very low speeds of the vehicles in such an infrastructure. Also, only cars and small vans are expected to use ordinary underground parking. Nevertheless, vehicles still may self-ignite due to technical defects, be ignited by an arsonist, etc. Fires in car parks are not very frequent and the vast majority is extinguished within a short time. The mitigation systems that are required for underground parking are very different from country to country depending on the size of the parking. The vehicles are having a certain distance to the neighboring vehicles and only the burning vehicles heat radiation is impinging the potential hydrogen vehicles body, while the pressure vessel is shielded due to the vehicle body. It may be realistic to assume that only in case the fire spreads to the hydrogen vehicle after a certain duration, the hydrogen tank could be exposed to a strong enough thermal impact. Here the reduction of distance between vehicles may be an important factor and may increase the likelihood of fire spread from car to car.

The scenarios with the potential catastrophic rupture and deflagration need more detailed consideration as these may develop in very short time leaving only very little time for safe egress time of people in the car park. It should also be assessed in more detail whether the consequences of such explosions and the resulting blast waves may impact on the carparks structural integrity and possibly could affect the floor separations etc..

Acknowledgments

This research is funded through the HyTunnel-CS project "Pre-normative research for safety of hydrogen driven vehicles and transport through tunnels and similar confined spaces". This project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking (now Clean Hydrogen Partnership) under Grant Agreement No 826193. This Joint Undertaking receives support from the European Union's Horizon 2020 Research and Innovation program, Hydrogen Europe and Hydrogen Europe Research.

References

[1] PIARC. World Road Association, Technical Committee C.4 Road Tunnel Operations, "Current practice for risk evaluation for road tunnels", 2012R23EN, 1-91, 2012.
[2] B.D. Ehrhart, D.M. Brooks, A.B. Muna, and C. B. LaFleur, "Risk Assessment of Hydrogen Fuel Cell Electric Vehicles in Tunnels", Fire Technol , 56, pp. 891–912, 2020.
[3] J. Saw, Y. Flauw, E. M. Demeestere, V. Naudet, P. Blanc-Vannet, K. Hollifield, et al.. "The EU FireComp Project and risk assessment of hydrogen composite storage applications using bow-tie analysis", In Proceedings of Hazards 26, Edinburgh UK, 2016
[4] V. Molkov, J.-B. Saffers, "Hydrogen jet flames", Int. J. Hydrog. Energy, 38(19), pp. 8141–8158, 2013.
[5] V. Molkov, W. Dery, "The blast wave decay correlation for hydrogen tank rupture in a tunnel fire", Int. J. Hydrog. Energy 45, pp. 31289–31302, 2020.
[6] D. Makarov, V. Shentsov, M. Kuznetsov, V. Molkov, "Hydrogen Tank Rupture in Fire in the Open Atmosphere: Hazard Distance Defined by Fireball", Hydrogen, 2, pp. 134–146, 2021.
[7] Y. Li, J. Xiao, H. Zhang, W. Breitung, J. Travis, M. Kuznetsov, T. Jordan, "Numerical analysis of hydrogen release, dispersion and combustion in a tunnel with fuel cell vehicles using all-speed CFD code GASFLOW-MPI", Int. J. Hydrog. Energy, 46, pp. 12474-12486, 2021.

Battery Safety

From Battery Cells to System Applications

Ola Willstrand
Fire & Safety
RISE Research Institutes of Sweden
Borås, Sweden
Ola.Willstrand@ri.se

Keywords:* *Li-ion batteries, thermal runaway, fires, safety

Abstract

Li-ion batteries have unmatched properties in comparison to other batteries on the market, especially when it comes to energy density. However, due to the high cell potential, these batteries need to have an organic electrolyte instead of a water-based electrolyte as in precursor technologies. Together with the active electrode elements this makes thermal runaway a possible outcome, often resulting in violent ejection of toxic and flammable gases, and jet flames. In combination with high risk of escalating events and that Li-ion battery fires are hard to extinguish this have put battery safety high on today's agenda. Even more so as time passes, due to the trend with higher capacities and increasing electric vehicles ranges, etc., which today typically imply less stable battery materials [1, 2]. However, for electric vehicles, available statistics show that battery fires are rare and the probability of a fire in an electric vehicle is generally lower than for conventional vehicles [3, 4].

Except finding new more safe materials or battery concepts (e.g. solid state electrolytes), safety measures can be implemented on cell level up to system level. Measures often implemented include e.g. short circuit protection, overcharge protection, cooling systems and mechanical protection to prevent a thermal runaway event, as well as different measures to prevent thermal propagation and suppress fire. The quality of all the components and especially the battery management system (BMS) is very important for high safety, which is the likely reason why cheaper consumer products have been more frequent in fire incident statistics [3].

Battery cells

Thermal stability is often seen as a measure of safety level. There are three important temperature values that are good indicators for a cell; onset temperature of exothermic degrading reactions, onset temperature of thermal runaway, and maximum temperature during thermal runaway [5]. However, a more thermally stable Li-ion cell can still encounter a violent thermal runaway and it may be more important e.g. to avoid an internal short circuit. Depending on state of charge the heat produced from a short circuit could increase the cell temperature several hundred degrees and then the matter of thermal stability may be less important. Another interesting aspect is that more thermally stable cells could also typically be less prone to self-ignition during thermal runaway. This could be seen as a benefit, but it will depend on the application since production of flammable gases without self-ignition could result in increased risk of gas explosion. The point is that not only one attribute is important but several.

To assess the outcome of a thermal runaway one should look at gas production and gas composition, heat production, onset temperatures, maximum temperatures, and rate of temperature rise. More in depth studies could also include venting and flaming behavior as well as particle analysis. There are several factors affecting the outcome except material composition (cell type), such as state of charge, potential triggers, cell size and format, potential aging effects, and boundary conditions such as pressure, atmosphere, and temperature. For a holistic assessment of battery cell safety, one should look at several factors affecting the outcome as well as several evaluating criteria.

Battery modules and packs

Going from cell to module and pack means that some more factors will affect the outcome, such as separation distances and materials (both between cells and between modules), serial/parallel cell configurations and connections, efficiency of cooling system, venting strategy, and mechanical integrity.

Thermal runaway can provoke exothermic reactions in the neighboring cells and propagation will continue as long as the heat produced in a cell is enough to start thermal runaway in the next cell. Total heat generation from a Li-ion battery going into thermal runaway in inert atmosphere or without combustion of vented gases is in general only a tenth of the heat generation possible during combustion. Surrounding oxygen is therefore important factor for heat propagation. The project LionFireII [6] have assessed thermal propagation between modules and the potential impact of different suppression systems, including inert gas system.

However, it has been suggested that the state of charge has a greater impact on the thermal propagation probability than e.g. inert/non inert atmosphere or separation distance [7]. A high charge state corresponds to higher gas rate build up and higher temperatures, but always operating at a low state of charge is usually not a feasible alternative.

Except mitigating a thermal runaway event, it is of course better to prevent it from happen at all. Integrated safety devices and the BMS (Battery Management System) should protect the battery against many potential failure modes such as overcharge, over-discharge, ambient extreme temperatures (by regulating cooling) and external short circuits. However, protection against internal short circuits, mechanical damage, or external fire (or other external high heating source) cannot, in general, be guaranteed

Battery system applications

Safety aspects in battery system applications relate to potential health effects, environmental effects, or property damage. Toxic gases from electric vehicle fire and contaminated extinguishing water are studied in the projects ETOX [4] and ETOX2 (ongoing). The health and safety perspective of electric vehicles onboard ships have also been studied in BREND2 [8]. A general conclusion is that the fear of electric vehicles has been slightly exaggerated, and with knowledge and sometimes new procedures the safety can be kept similar as for conventional vehicle fires.

In the project Electric Light [9] a battery fire safety concept was developed for fully electrically powered ships. In such an application it is important that thermal runaway integrity and propagation protection is connected to e.g. the ventilation concept for the battery room. In the concept a "casualty unit" of the battery is defined, which is the design level based on other safety systems, battery configuration and probability of an event. Further, the concept considers location of the energy storage, compartmentalization, structural integrity of the room, detection and suppression, risk analysis, and testing requirements.

Conclusions and outlook

Based on statistics, safety aspects should not be a showstopper for Li-ion batteries, but it is important to continuously study and improve safety. Much research has been done on battery cell level, but there is still much to do from a safety perspective, e.g. regarding aging, second life, modelling, and new material trends. Also new solutions that are claimed to be safer, e.g. solid state Li-ion batteries or Na-ion batteries, need to be further investigated.

Testing on battery packs and systems is expensive and therefore less research has been performed. Large-scale testing is however needed, but more research also into modelling of battery failures would accelerate learning and enable much more variations in investigated scenarios.

References

[1] G. H. Waller, J. K. Ko, T. H. Hays, and D. A. Fuentevilla, "Emerging Enrgy Storage Technologies," Technical Report, 2020.

[2] X. Feng, M. Ouyang, X. Liu, L. Lu, Y. Xia, and X. He, "Thermal runaway mechanism of lithium ion battery for electric vehicles: A review," Energy Storage Materials, vol. 10, pp. 246–267, 2018.

[3] U. Bergholm, "Sammanställning av bränder i elfordon och eltransportmedel år 2018-2020", MSB, 2021.

[4] O. Willstrand, R. Bisschop, P. Blomqvist, A. Temple, and J. Anderson, "Toxic Gases from Fire in Electric Vehicles," RISE Report 2020:90, 2021.

[5] X. Feng, S. Zheng, D. Ren, X. He, L. Wang, H. Cui, X. Liu, C. Jin, F. Zhang, C. Xu, H. Hsu, S. Gao, T. Chen, Y. Li, T. Wang, H. Wang, M. Li, and M. Quyang, "Investigating the thermal runaway mechanisms of lithium-ion batteries based on thermal analysis database," Applied Energy, vol. 246, pp. 53-64, 2019.

[6] R. Bisschop, P. Andersson, C. Forsberg, J. Hynynen, "Lion Fire II - Extinguishment and Mitigation of Fires in Lithium-ion Batteries at Sea," RISE Report 2021:111, 2021.

[7] C. Lee, A. O. Said and S. I. Stoliarov, "Impact of State of Charge and Cell Arrangement on Thermal Runaway Propagation in Lithium Ion Battery Cell Arrays," Transportation Research Record, 2673(8), pp. 408–417, 2019.

[8] J. Gehandler, A. Olofsson, J. Hynynen, A. Temple, A. Lönnermark, J. Andersson, J. Burgén, C. Huang, "BREND 2.0 – Fighting fires in new energy carriers on deck," RISE Report 2022:47, 2022.

[9] RISE Research Institutes of Sweden and Chalmers University of Technology, "Electric Light – Lightweight and electrically propelled Ro-Pax ship," Lighthouse - Swedish Maritime Competence Centre, 2021.

Prevention of work related accidents among firefighters

A mapping of serious and common work related accidents

Hanne Riis Ketler
Danish Emergency Management Agency, (DEMA)
Denmark
brs-ktp-via@brs.dk

Keywords: (5 key words)
Firefighting, occupational injuries, call-outs, education, exercise

Abstract

Introduction
The project 'Analysis to practice: Prevention of occupational injuries among firefighters' has the objective to map injuries among firefighters during call-outs, education, and exercise (Phase 1) and to identify risk factors and possible preventive measures (Phase 2).

Phase 1- Methods and materials
The report 1[1] 'Work accidents in the fire brigades' is the result of the first phase of the project and presents the mapping of occupational injuries and risk factors in the fire brigades in the period 2008 to 2018. The study includes firefighters (full- and part-time employees, volunteers, conscripts and rescue specialists) in the fire brigades, Falck (private emergency services company) and the Danish Emergency Management Agency (DEMA).

Firefighters have a significantly increased risk of occupational accidents compared to other parts of the workforce. The main purpose of the project is to map occupational accidents involving firefighters during operations in Denmark and to use the knowledge obtained to identify risk factors for occupational injuries.

The focus of this analysis is on operative tasks related to firefighting, rescue operations as response to CBRNE incidents, weather related incidents, emergency call-outs etc. as well as operational education and exercises. Occupational disorders are not included.

Phase 1- Results
The report presents results on occupational injuries based on data from the Danish Working Environment Authority [2], the Labour Market Insurance and data regarding call-outs and information on personnel from the Statistics Bank[3] hosted by the Danish Emergency Management Agency.

The analysis shows that notification practice and data quality has improved during the study period. Both the municipal fire brigades, Falck and DEMA report a high number of occupational injuries with expected absence of less than 1 day and near-misses as seen in figure 1.

In the period between 2015-2018 these injuries accounted for almost two thirds of all notifications – even though there is no formal requirement for notification of these injuries.

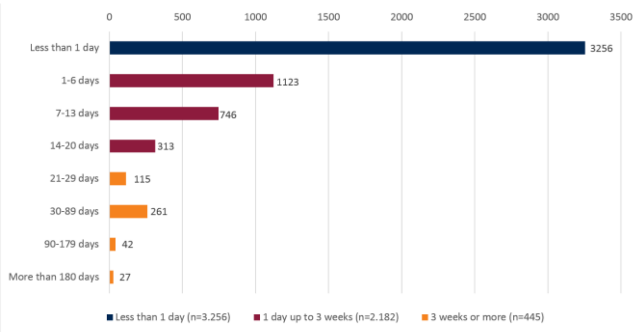


Figure 1. Expected absence 2008-2018

Some personnel categories are at increased risk of injury. The younger age groups including conscripts have an increased risk together with women and the employees, who handle the acute phase of the incident [4]. Conscripts mainly experience injuries during education and exercises.

Older age groups experience a higher proportion of serious injuries with expected absence of 3 weeks or more. Due to data protection rules and in accordance with the character of a national overview the descriptions of accidents are at an overall level.

The most frequent tasks for the fire brigades are firefighting and rescue tasks and the most frequent injuries fall into these categories as well - firefighting (n=2.363 accidents), rescue tasks (n=2.006 accidents).

The most common work related injuries are sprains, strains and other injuries to joints and muscles. Bone fractures (open or closed) have a particularly high proportion of serious injuries, as almost half of them result in an expected absence of 3 weeks or more as seen in figure 2.

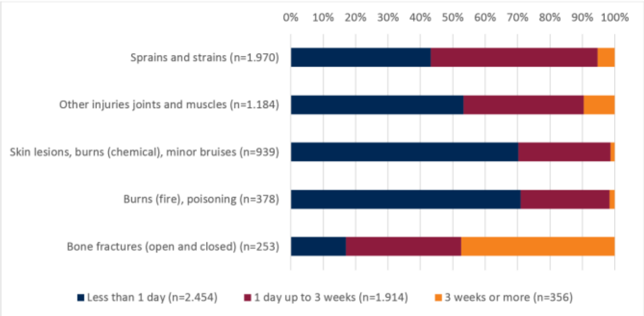


Figure 2. Top 5 Expected absence due to type of injury 2008-2018

In total, the incidence of occupational injuries with absence of at least 1 day was 145 per 10.000 persons. This is just below the mean incidence of 150 per 10.000 for all employees in Denmark in 2018. For comparison the industry group 'Police, emergency services and prisons' had in 2017 an incidence of occupational accidents with at least 1 day of 247 per 10.000 [5].

However, when taking into account that many persons in the fire brigades are part-time employees or volunteers, the incidence of occupational injuries with at least 1 day of absence can be calculated to 29 per million working hours, which is relative high compared to other groups in the work force [6].

In the study period, there is a decrease over time of occupational injuries, when related to the number of call-outs to real alarms. The observation is seen as an expression of a lower number of injuries per call-out.

Phase 2 – Methods and materials

The results from the report 1 are included in the 2nd phase of the project with the purpose of identifying possible preventive measures that can substantiate a reduction of occupational injuries in the fire brigades.

Phase 2 - Results

The work environment groups of the fire brigades, Falck, DEMA and relevant unions have contributed to the 2nd phase of the project with local knowledge about work related injuries. They often see accidents, which occur as results of twists, falls or crash on terrain, materials or in relation to a building structure with the type of damage seen in the survey - ankle sprains, strains and other injuries to joints and muscles.

Based on the identified risk factors a crew consisting of experienced firefighters has tested a number of selected types of incidents - typical for fire and rescue missions - under tactical conditions. The test exercises were evaluated with a focus on the working environment based on the given framework for firefighting and rescue work, such as darkness, smoke, poor working postures, etc.

Discussion and conclusions

In the 2nd phase of the project a set of preventive measures are targeted operative, training/exercise-related and organizational levels. The measures range from topics on safe driving/emergency driving, use of equipment and PPE, risk factors in firefighting, search and rescue, ergonomics and working conditions to the role of the firefighting crew leader.

As shown in the project the fire brigades, Falck and DEMA have a needed focus on safety and a healthy working environment – both during education, exercises and call-outs, due to the given framework on working conditions during operations. The project shows that there is a potential for a common focus on the topic of safe working environment for firefighters [7].

Acknowledgements

The project 'Prevention of occupational injuries among firefighters' is funded by the de Danish Working Environment Research Foundation. The launch of the project is in collaboration with a group of stakeholders; primarily the Danish Emergency Management Agency (DEMA), the municipal fire brigades and Falck as the main employers.

The framing project is inspired by national and international studies [references 8-12].

References

[1] Beredskabsstyrelsen/DEMA ' Delrapport 1 – Arbejdsulykker i redningsberedskabet, December 2021, https://www.brs.dk/globalassets/brs---beredskabsstyrelsen/dokumenter/forskning-statistik-og-analyse/

[2] Danish Working Environment Authority: Arbejdstilsynet. Årsopgørelse 2018. Anmeldte arbejdsulykker 2013-2018.

[3] Beredskabsstyrelsen/DEMA Statistics Bank: https://www.brs.dk/da/redningsberedskab-myndighed/viden2-data-og-dokumentation/redningsberedskabets-statistikbank/

[4] Beredskabsstyrelsen/DEMA ' Delrapport 1, figure 2.23

[5] Danish Working Environment Authority: https://at.dk/brancher/politi-beredskab-og-faengsler/branchegruppen/

[6] Dansk arbejdsgiverforening. Fald i Ulykkesfrekvens og ulykkesfravær. 2018: https://www.da.dk/statistik/ulykkesstatistik/ulykkesstatistik-2017 tilgået 2021-02-10

[7] Beredskabsstyrelsen/DEMA 'Delrapport 2 – Mulige forebyggende tiltag', April 2022, https://www.brs.dk/globalassets/brs---beredskabsstyrelsen/dokumenter/forskning-statistik-og-analyse/

[8] Hodous TK, Pizatella TJ, Braddee R, Castillo DN. Fire fighter fatalities 1998-2001: Overview with an emphaisis on structure related traumatic fatalities. Injury Prevention 2004;10:222-226

[9] 16 Bui DP, Porter KP, Griffin S, French DD, Jung AM, Crothers S, Burgess JL. Risk management of emergency service vehicle crashes in the United States fire service: process, outputs, and recommendations. BMC Public Health 2017;17:885

[10] Kræftens Bekæmpelse, Bispebjerg Hospital, Arbejdsmiljøforskningsfonden - EpiBrand: Registerbaseret kohorteundersøgelse af danske brandfolks mulige helbredsrisici ved arbejdet. Nationalt Forskningscenter for Arbejdsmiljø, oktober 2017

[11] Li C-Y, Sung F-C. A review of the healthy worker effect in occupational epidemiology. Occupational medicine 1999; 49(4):225-229

[12] National Institute for Occupational Safety and Health. ALERT: preventing injuries and deaths of fire fighters due to structural collapse. 1999; no. 99-146.

Manual Firefighting Tactical Measures for the AutoStore System

Ingunn Haraldseid
AutoStore AS
Nedre Vats, Norway

Keywords: ***AutoStore, Top-Loading Automatic Storage and Retrical system, Manual Firefighting, Final Extinguishment***

AutoStore

The AutoStore system was created based on the idea of technical director Ingvar Hognaland, who recognized that there is to much air in traditional warehouses. Air is expensive and wasteful, the idea resulted in the game changing Cube Storage Automation System: AutoStore [1].

The five modules that make the AutoStore system: robot, grid, bin, ports and controller. The dense storage system, where goods are stored in open-top containers stacked directly on top of each other is relatively new to the market. Warehouses today are getting more and more complex, with a variety of storage solutions and automatic storage solutions. This represents a new challenge for firefighters for how to access the seat of a fire. AutoStore has taken a scientific approach in evaluation and finding solutions for a suggested manual firefighting tactical measure.

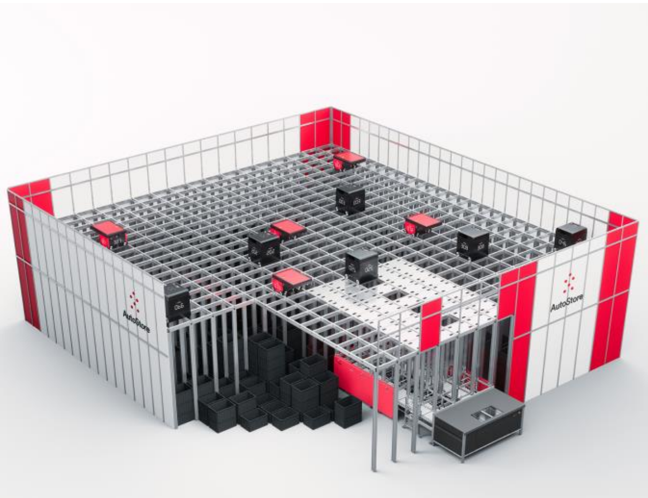


Figure 1: AutoStore system

Fire Testing History

AutoStore AS has conducted more than 100 individual small-, intermediate-, and large-scale fire tests since 2009. AutoStore has chosen a scientific approach to answer fire protection questions, through research of fire development and means to suppress a fire through different approaches. The fire protection methods tested are foam, hypoxic air and ceiling-level sprinklers. Based on the results, valid fire protection measures for an AutoStore system have been developed. AutoStore fire tests show that ceiling-level sprinklers will suppress and control a fire inside the system.

Tactical firefighting measures

A sprinkler system suppresses and control a fire, in any facility, final extinguishment is usually accomplished by manual firefighting efforts. In October 2020, AutoStore started a collaboration with Underwriters Laboratories Inc. (UL) and their Fire Fighter Subject Matter Expert's (SME's) to develop a safe and efficient method for accessing the seat of the fire from floor level [2].

In May 2021, a full height grid was assembled in UL's test facility, in this test the method developed in March through cold tests where to be tested in a fire test. A total of 19 firefighters from across the US was invited to participate in the live fire test. A ceiling-level sprinkler system was installed, and the ceiling height was 7.6 m. One sprinkler activated, and the sprinkler was allowed to operate for 1 hour before the control was handed over to firefighters.

The firefighters started by removing MDF panels, before tunneling through 7 rows, 3 bins wide area of the grid, before concluding on final extinguishment. The method was found to be safe, with no grid collapse or falling bins. It also brought awareness for the firefighters how to fight such a fire in a systematic order to prevent falling hazards and avoid content spill.

References

[1] AutoStore AS, «AutoStore System,» [Internett]. Available: https://www.autostoresystem.com/company.

[2] Underwriters Laboratories Inc., «Large Scale Sprinkler Tests with the AutoStore system incorporating polypropylene plastic bins with cartoned unexpanded group A plastic commodity including fire fighter response test, Project 4789911434, NC13069,» 2020.

The risk-based approach – a critique from within

Towards a concept of qualitity in the fire service profession

Mikkel Bøhm
Beredskab Øst
Denmark
boe@beros.dk

Nikolaj L. Marquart
Beredskab Øst
Denmark
mq@beros.dk

Daniel Bojsen
Beredskab Øst
Denmark
danb@beros.dk

Keywords:* *(5 key words)
Fire service, risk-based approach, municipalities, risk analysis, accepted risk

Introduction

In Denmark planning and organizing the fire service is an obligation on municipal level, characterized by a high degree of autonomy. The standards of service from the fire service are due to the legislation based on a risk-based approach, where the concept of adequacy towards risks is displayed through risk identification, risk- and capacity analysis, which must be reviewed at least once in an election period. The Danish Emergency Management Agency (DEMA) is the Danish governmental agency related to the fire service profession under the Ministry of Defence. One of the primary tasks from DEMA is to supervise the municipal rescue preparedness, and DEMA provides a statement upon the conducted risk-based analysis. The statements are then part of the local political processes. Thereby the municipalities decide the level of accepted risk and the quality standard of fire service offered in each municipality. This study illustrates a need towards articulating the concept of quality in the current risk-based approach.

Methods

The critique is based on three different studies. The first study is a statistical review of data from a particular case – a fire department in Denmark. The study demonstrates the relation between units dispatched and units applied on scene. The second study is an analysis upon the statements from DEMA on the risk-based analysis from the municipalities. The purpose is here to identify a pattern in the statements regarding the scenario, capacity and risk-analysis, with a specific focus on how the notion of quality is understood. The third study is qualitative workshops conducted with representatives from different municipal fire services in Denmark. The purpose is to investigate how the fire services from a tactical point of view handles similar cases. Thereby it becomes possible to demonstrate how different levels of service handle similar cases.

The foundation of the statistical review usually sets of in the existing turnout codes. The turnout codes have evolved over time and are fundamentally flawed when it comes to determining the adequate turnout size. Often the fire service dispatches too many units but sometimes, unfortunately, too few. Alarming the fire services, in case of an emergency, in Denmark is done by three means. 1) calls to the main public service answering point [PSAP] (the 112 number) 2) automated fire alarms (smoke detectors, sprinklers etc.) that transfer the alarm directly to the fire services dispatch central and in a few cases, 3) direct call to the fire service. In Denmark, the fire services receive around 40.000 alarms a year. Almost half of the alarms are from automated systems and the other half from the PSAP. Only 424 alarms are by direct call to the fire service. This study has analysed data from the Danish national database for turn out data, ODIN, upon a specific case. Specifically, we are looking at turnouts in the period from 2016.01.01 00:00 to 2021.12.31 00:00 – in total 15.339 turnouts. 14.965 have been within the authority of the fire service, 2820 have been fire turnout and 2148 have been turnouts to building fires. The remaining turnouts have been for rescue, EMS, and automatic fire alarms. In the following initial examination fire turnout reports, reports regarding automated fire alarms have been neglected despite being the origin of some fires. This was done because the sheer number of false alarms would distort the result. Optimizing turnout for automated fire alarms is worthy a study of its own.

In the second study 21 statements from DEMA are analysed. The statements are coded towards the following codes: Risk identification, risk analysis, legislation, level of service, ODIN-data, command-structure, water supply, evaluation, preparedness. The categories are then analysed with a particular focus upon identifying common denominators. In this context it is important to bear in mind, that there is a relationship between autonomy in the municipalities and the governmental responsibility from DEMA. This relationship will eventually and naturally provide some specific limitations in the critique upon the specific levels of service in the municipalities. The statements from DEMA provide directions towards how the municipalities should interpret and operationalise what an adequate, feasible and responsible emergency response is. would be.

The third study focus on the actual sharp end practice and investigate the level of service in 5 different municipalities within 5 cases, which represent everyday types of domestic fires in different types of building constructions. The study was arranged as a workshop with officers from the fire service. In the workshop the officer's responded to a fire simulation made upon a building which they placed in their local area. They then responded to the simulated fire with their actual types and number of units. Their tactical decisions, and request for further resources were then documented in a Gantt chart. The purpose was not to discuss the local political agreements, but to analyse the actual tactical handling.

Results

The quantitative analysis shows that for a regular building fire (I.e. apartment fire, villa fire etc.), the particular fire service usually dispatches 5 fire units. Usually, a combination of 2 engines, 1 ladder, 1 tanker and an incident commander. In the ODIN data fire units can be logged either as cancelled, engaged, on scene (not engaged) or standby at station. Examining the building fire turnouts where 5 fire units in total were dispatched (324) shows that 1/3 (112) started as a minor incident that needed assistance and "grew" into a 5 unit's incident. In more than 1/5 (82) of the 5 unit's turnouts none of them are used. When a fire unit is logged as on scene (not engaged) this shows that is has not been necessary to use any equipment from the unit. When a 5 unit's turnout is logged as having no units engaged, then it can be interpreted to illustrate that that the process of choosing the right turnout code has failed to an appropriate turnout size.

The analysis of the patterns in the statements from DEMA demonstrate an unclear conceptualisation of quality in the emergency service profession. The focus in the statements regarding the risk-analysis is commonly upon changes in resources allocated regarding personnel, engines, ladders etc. There is a consistent focus upon the minimum requirements due to the legislation, and statements regarding the notion that the technical leader should arrive as soon as possible and at least at the same time as assisting units is consistent. However, the statements do not encapsulate or comment upon the notion of accepted risk in the scenario- and risk analysis, and discussions regarding how adequate, feasible and responsible the response is remains unquestioned. There is furthermore a lack in the statements regarding the relationship between the parts of the plan and the actual sharp-end practice. There are no requirements in the statements towards feedback loops between learning points from real incidents back to the educational plan, or requirements towards assessing the degree of success from the plan to actual practice to ensure, that everyday incidents are handled due to specific levels of standard. The statements thereby end up decoupling the plan from the actual practice, and thereby blurring the quality criteria regarding the accepted risks, and the residual risks.

The analysis of the Gantt chart assessing the actual planned practice shows that even though alarm codes and scenarios are similar, different vehicle compositions, crews and equipment are sent, and thus manifests divergent differences both internally and externally in the emergency services' tactical handling towards fire in building constructions. When deployed to a fire, the emergency services lack professional standards which contribute to misunderstandings as practices are interpreted differently, e.g. the term 'stop line' (an unrecorded method) is understood differently internally in the emergency services and therefore, there are large differences in what equipment, vehicles and personnel are seen as required. There is a lack of feedback loops on training and sharpening practice, which otherwise provides increased knowledge for the next incident. The evaluation practice during and after a complex type of incident is deficient or lacking. In the evaluations, there is a lack in articulating quality aspects and goals to define whether the effort has been a success regarding e.g. minimization of damages, sufficient value rescue, or whether the incident could have been done differently, so that existing knowledge can contribute to the handling of the next case.

Discussion and conclusion

The purpose of this work in progress is to initiate a discussion upon the current use of scenario, capacity and risk-analysis which detach the analysis from the actual practice conducted. We propose a progression where focus is not only upon statistical data, but a statistical analysis which encompass a discussion regarding how close the fire services are to hit the bull's eye in the sense, that the resources dispatched correlates with the units needed. The study indicates that the alarm codes could be subject to changes. A model where units is successively dispatched as the call-taker at the PASP is therefore a subject for further research. Such an approach would demonstrate the degree of accepted risk and would allow the fire service profession to compare levels of service, and thereby demonstrate the willingness to pay for higher degree of service, and thereby reducing risk. The qualitative studies demonstrates that the statements upon the conducted risk-based analysis focus on changes in the numbers of units responding to specific alarm codes. The statements furthermore focus on types of incident analysed upon, hereby especially complex and complicated types of incidents. The pattern shows indeed a reluctance towards articulating quality aspects upon the analysis conducted from a methodological perspective and do not demand relations between the statistical data and evaluations towards the actual practice conducted.

Thereby the level of accepted risk becomes unclear which affect the possibility to assess the overall quality delivered by the fire service.

References

[1] Beredskabsloven, Bekendtgørelse nr 314 af 03/04/2017.

[2] Grimwood, P., & Sanderson, I. A. "A performance based approach to defining and calculating adequate firefighting water using", pp. 155-167, October 2015.

[3] Haurum, G., "Slukningsteknik", Virum: Brandskole, vol 2., 1995.

[4] Karlsson, B., & Quintiere, J. G. "Enclosure Fire Dynamics", Boca Raton: CRC Press", 1999.

[5] Spearpoint, M, "Fire Engineering Design Guide", Christchurch, New Zealand,: New Zealand Centre For Advanced Engineering, 2008.

[6] Särdqvist, S., Jonsson, A., & P. Grimwood., "Three Different Fire Suppression Approaches Used by Fire and Rescue Services", Fire Technology, December 2018.

[7] Trafik-, Bygge-, og Boligstyrrelsen, "Bygningsreglements vejledning til kap 5 – Brand", retrieved from https://bygningsreglementet.dk/: https://bygningsreglementet.dk", april 2020.

FIRE SAFETY OF PLASTIC CIRCULATION AND RECYCLED PLASTICS

Nikhil Verma
VTT Technical Research Centre of Finland Ltd, Espoo, Finland
nikhil.verma@vtt.fi

Terhi Kling
VTT Technical Research Centre of Finland Ltd, Espoo, Finland
terhi.kling@vtt.fi

Tuula Hakkarainen
VTT Technical Research Centre of Finland Ltd, Espoo, Finland
tuula.hakkarainen@vtt.fi

Keywords:
Circular economy, plastic recycling, plastic storage, plastic fires, plastic waste fire safety

Abstract
Plastic recycling involves fire safety risks in both storage and processing. Fire safety of recycled plastics and waste centres has been studied to some extent, and significant fire risks related to recycling and waste stations have been identified. As the circular economy of plastics has changed and developed significantly in recent years, it is crucial to identify and manage the new fire risks that arise from it. VTT's research project has conducted a literature review on the fire safety risks of plastic waste management involved in the recycling process. This research supports the development of the circular economy of plastics and thus promotes the sustainable development of the use of plastics.

Issues, concerns and the path ahead
Waste fires are, in general, difficult to contain, as they are very large fires with very high heat content. The difficulty for water to penetrate to reach the fire seat makes them even more challenging to extinguish. Large resources are needed for prolonged firefighting in waste fires. Additional challenges are caused by reduced visibility and fire products toxic in nature. Re-ignition has been reported, which has reinitiated firefighting. At times, people from the surrounding area have been evacuated for safety. Moreover, firefighting water run-off has the potential to contaminate water bodies. Given the number of challenges involved in dealing with such fires, improper planning and approach to fight such fires would be futile and exhausting. [1-6]

Plastic waste fires altogether throw a different set of challenges (Figure 1). Different types of plastics thermally decompose differently as they have different chemical compositions [7]. For example, Polyethylene (PE) Terephthalate on thermal decomposition will lead to the evolution of light volatile products, which makes them easily ignitable. Their volatile matter feeds the flame and shows limited tendency to form char. Whereas, High and Low Density Polyethylene (HDPE and LDPE) on thermal decomposition in air produce partially oxygenated products such as aldehydes, ketones and major combustion products such as carbon monoxide, carbon dioxide, water etc. Polystyrene being amorphous in nature, degrades thermally in a single step which leads to a rapid initial decrease in molecular weight. Oxygen plays a very important role in the degradation of Polystyrene, which involves thermo-oxidative products including benzaldehyde, benzoic acid, phenol, and benzyl alcohol. With such variation in thermal decomposition, it is clear that each type of plastic will contribute in its way to fire and its products. Different types of additives like plasticizers, stabilizers and colorants, which are added to plastics during manufacturing, can further alter their behaviour in fire (examples of various types of additives can be found from Table 1 of [8]). Moreover, recycled plastics are often seen as blends of plastics as it is often impossible to completely separate one plastic type from another type (seen as impurity) during the recycling process apart from other non-plastic impurities. For example, Dutch recycled-PE from separate collection consisted of approximately 91% PE, 8% PP (Poly Propylene), 0.4% black plastics, 0.3% PVC (Poly Vinyl Chloride), 0.2% PS (Polystyrene), 0.2 % PET (Polyethylene Terephthalate) and 0.1% paper [9]. The presence of two main polymers (for example, PE in PP or PP in PE as an impurity) can form an immiscible blend. Typically, the blend morphology (in the theoretical framework) is determined by the concentration of polymer present, miscibility and compatibility of the two polymers and processing variables such as temperature and shear forces which, in turn, determine the dispersion of the second immiscible polymer in the matrix of the main polymer. This blend morphology will, in turn, determine the material properties, of which some will strongly relate to the molecular architecture of the recycled plastics. Properties related to melting and viscosity which can play a role in spreading fire on melting, may be affected. Other mechanical properties like tensile strength, impact resistance etc., can also get affected by such blend existence in composition [9-10]. Thus, it can be concluded that impurities can also alter the way plastic will burn and thus its fire-related properties based on its percentage and chemical composition. Risks of plastic waste fires are further raised by the fact that they burn at temperatures higher than other waste fires [11]. Higher temperature fires can cause the breakdown of volatile compounds, which emit dense black smoke [12-13].

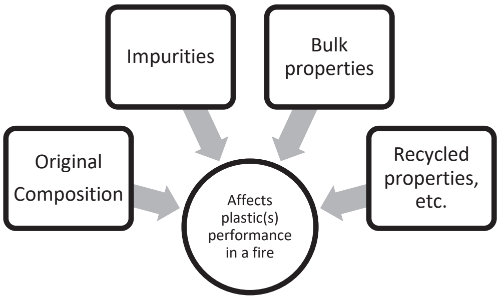


Figure 1. Some factors affecting the performance of plastic(s) in a fire

Given the high heat content of plastic waste fire, limiting the stockpile of plastic wastes to certain volumes and keeping the minimum separation between stockpiles could limit the fire spread. However, such fire can also spread by either radiative heat flux or the flow of molten plastics. Moreover, the effectiveness of sprinklers over stockpiles is questionable as water reaching the fire seat is not certain. Although, sprinklers could keep the adjacent stockpiles cool to stave off any possibility of ignition. The possibility of the production of dense and toxic smoke raises challenges for both indoor and outdoor storage. Indoor storage should be equipped with proper smoke and heat control systems to support safe evacuation and firefighting. Furthermore, based on wind conditions, fire in outdoor storage can cause difficulty for firefighting and may trigger the evacuation of people from the nearby area.

The dearth of data and the challenges involved in evaluating fire properties of plastics to find the holistic behavior of plastic bulk in question (during a fire) further raise concerns about addressing the issue. Evaluation of fire properties of plastics is not a straightforward process. Collected plastics can comprise just one type or multiple types of plastics, which in turn can either be made of virgin or recycled plastic. The chemical composition of a bulk consisting of one type of plastic is expected to be more or less homogeneous and can be tested to evaluate its (average) fire performance. However, when a bulk consists of multiple types of plastics, its (average) fire performance apart from chemical composition will also be dictated by the mass percentage of individual plastics. Consumer usage patterns of different types of plastics can differ from one municipality to another based on their socioeconomic status and, thus, the mass percentage of individual plastics collected for recycling. Data of different types of plastics collected by different plastic recycling companies would be a good starting point to the average mass percentage of individual plastics present in the collection. If such data are not available, then adequate samples representative of an adequate number of collections can be directly tested for their fire performance, and evaluated fire properties can be used for further fire safety studies. At least to account for fire-related properties, ignitability, flame spread rate, heat release rate, ease of extinction, smoke production, and effluent toxicity have to be evaluated for a plastic-type or bulk collection [7]. From the viewpoint of fire research, at least the following determinations should be made on the materials:

- Estimation of the heat of combustion per kg of plastic waste (MJ/kg)
- Estimation of burning rate (kg/s)
- Tendency of ignition and flame spread (plastics can melt, and a pool of molten plastics can easily spread fire)
- Fire products: CO, soot, other toxic yields.
- Other thermal properties: conductivity, specific heat, density etc.
- Most importantly, heat release rate with respect to time.

Small-scale and bench-scale tests can be done to estimate fire properties. With such estimations, new methods can be devised or fire simulations can be used to study the effects of different configurations of plastic storage on fire in a built-in environment or outdoor space with wind conditions. This can enable us to tackle the risks of plastic fires in a more informed way.

References

[1] Mikalsen R. F., Lönnermark A., Glansberg K., McNamee M., Storesund K., Fires in waste facilities: Challenges and solutions from a Scandinavian perspective, Fire Safety Journal Volume 120, 2021.

[2] Stenis J., Hogland W., Fire in waste-fuel stores: risk management and estimation of real cost, Springer, Mater Cycles Waste Manag 13, 2011, pp. 247—258.

[3] https://yle.fi/uutiset/osasto/news/tampere_evacuates_350_residents_over_hazardous_waste_fire/11345970 [Referred 12.01.2021]

[4] https://www.bbc.com/news/uk-england-stoke-staffordshire-38878262 [Referred 12.01.2021]

[5] https://www.thehindu.com/news/cities/Kochi/plastic-waste-catches-fire-at-brahmapuram/article4419738.ece [Referred 12.01.2021]

[6] https://news.sky.com/story/fire-at-recycling-plant-in-blackburn-engulfs-100-tons-of-plastic-10999166 [Referred 12.01.2021]

[7] Witkowski A., Stec A., Hull T. A., SFPE Handbook of Fire Protection Engineering, Thermal Decomposition of Polymeric Materials, 5th Ed., Springer, 2016, pp. 167—254.

[8] Hahladakis J. N., Velis C. A., Weberb R., Iacovidoua E., Purnella P., An overview of chemical additives present in plastics: Migration, release, fate and environmental impact during their use, disposal and recycling, Elsevier, Journal of Hazardous Materials 344 , 2018, pp. 179—199.

[9] Chacon F. A., Brouwer M. T., Thoden van Velzen E. U., Smeding I.W., A first assessment of the impact of impurities in PP and PE recycled plastics, Wageningen University & Research: Wageningen Food & Biobased Research, Public Report 2030, 2020.

[10] Thoden van Velzen E. U., Chu S., C F. A., Brouwer M. T., Molenveld K., The impact of impurities on the mechanical properties of recycled polyethylene, Wiley, Packaging Technology and Science, 2020, DOI: 10.1002/pts.2551.

[11] Waste Industry Safety And Heath Forum (WISH) Report: Reducing Fire Risk at Waste Management Sites, 2017.

[12] Fire safety in waste facilities, Fire and Rescue NSW, Community Safety Directorate, Fire Safety Branch, D17/81582, 2020.

[13] Landfill fires, their magnitude, characteristics, and Mitigation, Federal Emergency Management Agency, United States, Fire Administration National Fire Data Center, TriData Corporation, FA–225, 2002.

Towards a fire-safe sustainable built environment – what should we measure to assess it?

Ulises Rojas-Alva
Department for Fire-safe Sustainable Built Environment (FRISSBE) at ZAG (Slovenian National Building and Civil Engineering Institute); Dimičeva ulica 12, 1000 Ljubljana, Slovenia; ulises.rojas-alva@zag.si

Andrea Lucherini
Department for Fire-safe Sustainable Built Environment (FRISSBE) at ZAG (Slovenian National Building and Civil Engineering Institute); Dimičeva ulica 12, 1000 Ljubljana, Slovenia; andrea.lucherini@zag.si

Grunde Jomaas
Department for Fire-safe Sustainable Built Environment (FRISSBE) at ZAG (Slovenian National Building and Civil Engineering Institute); Dimičeva ulica 12, 1000 Ljubljana, Slovenia; grunde.jomaas@zag.si

Friderik Knez
Department for Building Physics at ZAG (Slovenian National Building and Civil Engineering Institute); Dimičeva ulica 12, 1000 Ljubljana, Slovenia, friderik.knez@zag.si

Keywords: fire safety, LCA, Green Deal, sustainable built environment, resilience

Abstract
Fire safety is not yet an explicit aspect of the assessment of sustainability in the built environment. The main reason for this is that there is a lack of consensus in thinking and approaches in the fire safety and sustainability communities. To alleviate this, a map of the current practices is required to harmonise stakeholders' goals and leverage more oriented-based solutions towards an improved level of safety in the built environment. There is currently an excellent window of opportunity to achieve this, due to ambitious policies (UN goals and EU goals), to target such a complex multi-disciplinary problem.

Introduction
Climate change and environmental deterioration pose a real threat to humanity [1]. The energy use in the built environment (heating, cooling, and servicing) accounts for 60% of the worldwide global energy consumption and 40% of the carbon emissions [2,3]. In the EU, the built environment's energy consumption accounts for 40% of the overall consumption and is responsible for 36% of greenhouse gas emissions [4]. In attempts to address this, supranational, national, and local governments have established sustainability goals for the near (2030) and somewhat more distant future (2050). Sustainability can be evaluated based on balancing economic growth, social development, environmental protection and conservation [5]. For example, the UN established 17 Sustainable Development Goals (SDGs) [6]. Similarly, the EU has ambitious goals to achieve carbon-neutrality by 2050 [7], mainly through implementing the European Green Deal, which focuses on energy consumption, research and innovation actions [1], and the Renovation Wave Strategy to improve the energy performance within the built environment [4]. Currently, 75% of the European building stock is inefficient, and 80% will remain in use by 2050 [7].

Higher fire risks
Fires accidents have a direct detrimental impact on society. In Europe alone, 5,000 fire incidents occur every year, causing 4,000 fatalities and 70,000 hospitalisations. These fire events cost €126 Billion per year, which is equivalent to 1% of the EU's GDP [7]. Moreover, fire directly impacts the environment due to global and regional pollution (air, soil, and water). Fires in warehouses in England and Wales add 135,000 tonnes of CO_2 to the atmosphere every year. Outside the standard built environment, other fire scenarios can emerge, such as wildfires, peat fires, and fires in informal settlements, and they increase the emissions of greenhouse gases significantly [8].
At the same time, the industry related to sustainable built environments is rapidly growing [10]. The programmatic needs for reducing pollution and buildings' carbon footprint push for new construction materials and complex systems [9]. In these settings, safety is often considered a burden until an accident occurs, and it is lagging behind the general development related to sustainability [5]. Still, there is a public acknowledgement of the impact on fire safety and unintended consequences (increased fire risk) [2,10,11]. The increased risk is due to an array of causes. Examples are flammability of thermal insulating materials (e.g. plastic-based), systems that may enhance fire and smoke spread (e.g. double-skin facades), PV systems and combustible insulation, thermal runaway of lithium-ion batteries, Electric Vehicles, green façades and roofs, unprotected structural elements and spalling of lightweight concrete [9,11].

The current state-of-the-art in the quantification of sustainability
There are many well-established assessments methods related to sustainability in the built environment, where BREEAM and LEED address building projects, while BEES focuses on building products. Other common tools are LCA and DGNB. One key measure in these methods is carbon emissions, and there are currently explicit goals for CO_2 emissions per m^2 of buildings (LCA, BREEAM, DGNB). However, the consequences of fire events are not addressed in those methods. One reason for this could be that fire safety

engineering in building codes primarily focuses on protecting human life. As a result, property protection and operability are left to be addressed elsewhere, for example, under resilience, which again can be quite loosely defined. As a result, most sustainable solutions have not yet been tested regarding fire incidents [12].

Attempts have been made to address fire through risks assessment. To achieve sustainability goals, fire risks can be accounted for through performance-based design in fire engineering. In the literature, examples of guidelines (ISO 26367), holistic approaches and frameworks (BRANZ and others) can be found [10,13]. However, those approaches do not address all the fire risks arising from sustainable solutions, but they have suggested paths for improved resilience.

The sustainability measures

The question that arises is then on the quantification of fire in the sustainable built environment. How can fire safety be explicitly included when assessing sustainability in the built environment? Is a mass timber building more sustainable than a concrete or steel one in case a fire leaves them out of commission? Which option would be more efficient in case of a fire scenario? Traditionally, the fire performance is not part of an LCA [14]. However, fire can be incorporated, as reported by Andersson et al. [15]. Their model (Fire-LCA) used case studies focused primarily on emissions but did not provide more relevant information. The Fire-LCA does not quantify the fire impact on society emerging from various fire scenarios (toxicity, monetary costs, emissions and life cost).

Currently, there is inadequate communication between sustainability and fire safety fields [10,16]. Still, closely interlinked fire safety and sustainable design can reinforce each other, and it can be beneficial for society and the environment [10,16]. Also, there is an abundance of vocabulary referring to sustainable fire safety [11] that is not helping in terms of making a consensus. Therefore, there is a need to understand and map the current practices (methods, standards, systems) in the field. This will eventually allow us to understand and unify the lexicon and metrics and align stakeholders' goals. Consequently, such analysis will serve as a basis to develop a more oriented-based solution to quantify fire safety in the sustainable built environment.

References

[1] A European Green Deal | European Commission, (n.d.). https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en (accessed March 31, 2022).
[2] Global Plan for a Decade of Action for Fire Safety, 2021. https://ifss-coalition.org/ (accessed March 24, 2022).
[3] Zero carbon cities: Insulating populations for a sustainable future, (n.d.). https://www.rockwool.com/group/advice-and-inspiration/blog/zero-carbon-cities-insulating-populations-for-a-sustainable-future/ (accessed March 31, 2022).
[4] Renovation Wave Strategy, (n.d.). https://ec.europa.eu/commission/presscorner/detail/en/IP_20_1835 (accessed March 31, 2022).
[5] W. Nawaz, P. Linke, M. Koç, Safety and sustainability nexus: A review and appraisal, Journal of Cleaner Production. 216 (2019) 74–87. https://doi.org/10.1016/J.JCLEPRO.2019.01.167.
[6] D.A. Martin, Linking fire and the United Nations Sustainable Development Goals, Science of The Total Environment. 662 (2019) 547–558. https://doi.org/10.1016/J.SCITOTENV.2018.12.393.
[7] What makes a building sustainable – A sustainable building starts with a fire safe building, (n.d.). https://www.rockwool.com/group/advice-and-inspiration/blog/what-makes-a-building-sustainable/ (accessed March 31, 2022).
[8] M.A. Moritz, S.L. Stephens, Fire and sustainability: considerations for California's altered future climate, Climatic Change 2007 87:1. 87 (2007) 265–271. https://doi.org/10.1007/S10584-007-9361-1.
[9] U. Krause, W. Grosshandler, L. Gritzo, The International FORUM of Fire Research Directors: A position paper on sustainability and fire safety, Fire Safety Journal. 49 (2012) 79–81. https://doi.org/10.1016/J.FIRESAF.2012.01.003.
[10] BC. Roberts, M.E. Webber, O.A. Ezekoye, Why and How the Sustainable Building Community Should Embrace Fire Safety, Current Sustainable/Renewable Energy Reports. 3 (2016) 121–137. https://doi.org/10.1007/S40518-016-0060-2/TABLES/4.
[11] B. Meacham, M. Mcnamee, Fire Safety Challenges of "Green" Buildings and Attributes , Quincy, MA, 2020. www.nfpa.org/foundation (accessed March 30, 2022).
[12] F. Asdrubali, F. D'Alessandro, S. Schiavoni, A review of unconventional sustainable building insulation materials, Sustainable Materials and Technologies. 4 (2015) 1–17. https://doi.org/10.1016/J.SUSMAT.2015.05.002.
[13] P.O. Akadiri, E.A. Chinyio, P.O. Olomolaiye, Design of A Sustainable Building: A Conceptual Framework for Implementing Sustainability in the Building Sector, Buildings 2012, Vol. 2, Pages 126-152. 2 (2012) 126–152. https://doi.org/10.3390/BUILDINGS2020126.
[14] S. Schiavoni, F. D'Alessandro, F. Bianchi, F. Asdrubali, Insulation materials for the building sector: A review and comparative analysis, Renewable and Sustainable Energy Reviews. 62 (2016) 988–1011. https://doi.org/10.1016/J.RSER.2016.05.045.
[15] P. Andersson, M. Simonson, H. Stripple, Life-Cycle Assessment Including Fires (Fire-LCA), Springer Series in Materials Science. 97 (2007) 191–213. https://doi.org/10.1007/978-3-540-71920-5_11.

Full scale tests IG-541 (Inergen) for at-risk groups

Eirik R. Nordstrand
Western Norway University of Applied Science (HVL), Haugesund, Norway

Sebastian Dimmen
Western Norway University of Applied Science (HVL), Haugesund, Norway

Hågen Solbakken
Western Norway University of Applied Science (HVL), Haugesund, Norway

Arjen Kraaijeveld
Western Norway University of Applied Science (HVL), Haugesund, Norway

Keywords: Fire suppression, IG-541, At-risk group, detection, experiment.

Abstract

Karmøy municipality in Norway will build three houses dedicated residents belonging to the at-risk group of people struggling with drug abuse and mental disorders as part of a pilot project. Based on the history and statistics of people with these issues, fires are most likely to occur at some point.

Therefore, focus is on implementing innovative solutions with regards to fire safety. A research project founded by the Norwegian Research Council is started to assure that the houses will be equipped with innovative solutions. Focus is on long term cost and effectivity. Participants in the research project are Karmøy municipality, the Norwegian research institute Norce and Western Norway University of Applied Science (HVL).

At the same time, Western Norway University of Applied science is carrying out a research project called Builder. The goal of work package (WP-5) is to find new technological solutions which can increase the fire safety for people in at-risk groups. Based on both these projects, one of the tasks is to investigate what kind of fire suppression systems are suitable for people groups with a high risk in terms of fire safety. Early intervention will reduce the fire damage, the use of a personal safe gas-based system will avoid secondary damage after a fire.

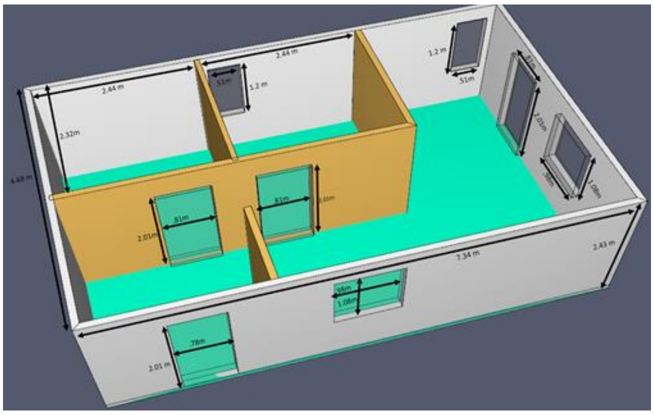


Figure 1. The test room is prepared following a similar layout of the dwellings to be constructed in Karmøy ROP project. The whole apartment has a floor area of 35 m2.

Problem statement

The Norwegian building regulations requires fixed fire extinguishing systems in care homes (hazard class 6). People who are drug addicts or struggle with mental illness are part of a group of people who are involved in a relatively high percentage of fire incidents. There are many challenges regarding the fire prevention in dwellings where these persons live. Some of the known problems are frequent fire outbreaks which often leads to secondary damage, unwanted activation of the fire suppressing system due to intensive smoking, disassembly of installations, downtime of the system and relocation of the resident while the apartments are rehabilitated after damage. The main task is consequently to research if a gas-based fire extinguishing system using IG-541 (brand name Inergen) as an agent could be a suitable alternative for these kinds of buildings.

The focus of the paper will mainly be to investigate the functionality of the system, but will as well briefly look into reliability, environmental factors, and personal safety when using the described fire extinguishing agent.

Method

The method consists of both experimental work and a study of literature. A full-scale dummy apartment is built at ‘the hall of flame’, the full-scale laboratory facility at HVL. Several full-scale fire tests will be carried out in the apartement as a part of a bachelor thesis. The whole loop of the extinguishing system, with multi criteria detection, alerting, discharge of the extinguishing gas, and extinguishing will be tested. A pre-study will reveal which scenarios are most likely to occur and should be tested. Adjustable parameters such as openings of doors and windows, ventilation velocity and the use of extended discharge will be varied.

Furthermore, an analysis of the long-term costs when installing an IG-541 fire suppressive system will be carried out. The paper will also include a short literature study of the environmental effects of the system, and a brief look into the reliability and the person safety regarding the system.

Earlier work

Earlier work has shown that IG-541 might be a suitable solution to protect at-risk groups [1]. Early intervention will lead to early extinguishment of a fire, low levels of CO and reduced damage. Safety is considered to be well taken care of in CO2-compensated hypoxic atmospheres, for exposures up to 30 minutes [2] [3].

Open doors and windows might cause a large uncertainty, this can probably be solved by extended discharge and/or apply a combination of IG-541 and pressurized air [4].

Result & Observation

To be added after conducting a full-Scale Experiment by the mid of March.

The expected outcome of the study

The main goal of the study is to gain experience based upon realistic fire scenarios to evaluate whether the proposed fire detection and suppression system might be able to protect the residents and avoid damage to the dwelling. The outcome will be reported to Karmøy municipality.

References

[1] A. Kraaijeveld, «Fire Protection of at Risk Groups by IG-541 and Water Based Sprinklers: Full Scale Tests,» Western Norway University of Applied Science, 2019.

[2] E. J. Skraastad, «PERSONAL SAFETY IN ATMOSPHERES WITH A REDUCED OXYGEN LEVEL COMPENSATED FOR WITH INCREASED CARBON DIOXIDE,» Trondheim, 2019.

[3] T. Jansen, «ANVENDELSE AF INERGEN I BRANDBEKÆMPELSESØJEMED – EN VURDERING AF PERSON OG PATIENTSIKKERHED. SÆRLIGT FOKUS PÅ EFFEKTEN AF AKUT HYPOXI HOS RASKE OG SYGE INDIVIDER,» University of Copenhagen, København, u.å..

[4] C. L. Larsen, «The effect of inert gas in fire Suppression systems, Protection of a stairwell,» DTU, Slagelse, 2021.

Data Assimilation in the smoke spread simulator ARTSS

A gradient-based optimisation approach

My Linh Würzburger
Civil Safety Research, Forschungszentrum Jülich (FZJ)
Jülich, Germany
m.wuerzburger@fz-juelich.de

Lukas Arnold
Civil Safety Research, Forschungszentrum Jülich (FZJ)/University of Wuppertal (BUW)
Jülich/Wuppertal, Germany

Wolfram Jahn
Pontificia Universidad Católica de Chile
Santiago, Chile

Keywords: CFD, data assimilation, GPU, smoke, gradient-based optimisation

Abstract

This paper describes the concept and application of a gradient based method to estimate input parameters for the smoke simulator ARTSS. The aim here is to align the simulation with given experimental or synthetic data (in the first step) with the future goal to use this approach to couple the simulations to real-time sensor data. Here, we focus on the determination of initial conditions of the heat source. For simplicity, the analysis is limited to the maximal heat release rate (HRR) and the (one dimensional) position of the fire source, where the sensor data used for the assimilation is based on simulation data produced by another simulation tool. To determine the gradient, a finite difference method in the parameter space is used.

ARTSS

ARTSS (Accelerated Real-Time Smoke Simulator) [1] is a CFD (computational fluid dynamics) based smoke simulator, which specialises in fast calculations. The purpose is to create a real-time and eventually even prognosis simulation of smoke propagation in complex buildings. The approaches to achieve this goal are adapting the modelling and the numerical algorithms, as well as implementing the use of highly parallel systems, like graphics processing units (GPU). With the focus on runtime, there are corresponding sacrifices in accuracy. Thus, in this application scenario the faster algorithms are preferred to the more accurate ones for the calculation. Additionally, in favour of acceleration, models for thermal radiation, pyrolysis, combustion etc. are neglected. To compensate for these accuracy losses, an assimilation of the data is used.

Data Assimilation

Data assimilation is a method that is widely used in weather forecasting. It is used to estimate the initial conditions with the help of external data at all grid points and based on the estimate a forecast is made. We are applying this concept to the context of fire simulation. The idea is to change the course of a running simulation with the help of e.g. sensor data and to adjust it when necessary to ensure that the simulation still represents reality.

Practically in ARTSS, the changes are done at runtime by communicating with an external program, in our case a Python script. The external program can read in the simulation data and decide whether it aligns enough with the given sensor data. If the simulation does not fit the criteria, the Python script can request a rollback. Which means that the simulation will go back to the specified time step (see Figure 1). Here the parameters can be changed as well as direct changes in the simulation data performed. In our case we can change the HRR as well as the position of the temperature source. The simulation will run from the rollback point on with the changed parameters and/or the changed simulation data. Direct changes of the field data in the course of the simulation can be conducted as well.

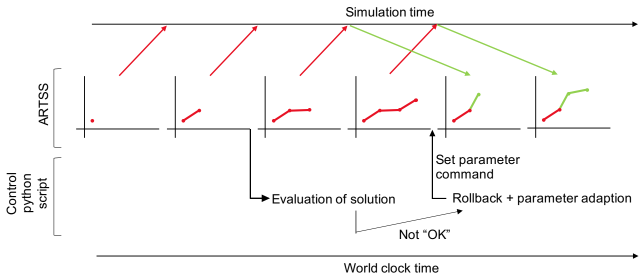


Figure 1. ***An external Python script reads out the simulation data, e.g. at time step 3. It checks whether the simulation data is accurate enough with regard to the sensor data. If it is not, it can send a message to ARTSS to request a rollback to the time step with changed parameters.***

Gradient-based Optimisation

The general idea is to investigate a certain time window and compare it to the sensor data. Explicitly for our case study, four different cases of rollbacks will be investigated, which follow a finite difference scheme. One case is to rise the HRR and move the fire source in one direction, accordingly the other cases are combinations of lowering the HRR and moving the fire source in the other direction. Based on these four cases the new parameters will be determined by calculating the gradient and changing the fire parameters into its negative direction. The result will be sent to ARTSS. This process will be repeated for the subsequent time windows. Adjusting the parameters over the whole simulation may not result in finding the correct starting parameters but at least the result will be similar to the simulation with the correct starting parameters.

For the evaluation of the data assimilation method, simulation data based on FDS (Fire Dynamic Simulator) [2] calculations will be used. The same simulation scenario as in FDS is started in ARTSS, but with changed parameters of the fire source. Over the period of the simulation, data from the FDS simulation is then transmitted to ARTSS to mimic sensor data. At the end, the effect of the change of the fire source on the final result is analysed by comparing the simulation result of ARTSS directly with the one of FDS. Accordingly, FDS represents experimental data or data from a real fire.

Use Case

The final goal is to use ARTSS as an aid in the event of a fire and to give first responders such as the fire brigade or adaptive technical building installation additional information about the course of the fire. Data assimilation can compensate for unknown or incorrect data. Unknown or inaccurate data may include (combustible) furniture or the heat release rate of the fire source. Incorrect data includes, for example, the position of the fire source.

An intermediate target that we demonstrate here is the active correction while ARTSS is running. This means that our tool allows fast rollbacks of simulations, so that they do not have to be restarted with the new parameter settings, this implies, that the simulation parameter are not fixed in time but rather variable per construction. Using a simple communication layer allows for an efficient online monitoring and steering of the simulations. In addition, the solvers can also be exchanged during runtime, which makes it possible to take a simple model for the fire spread and then switch to a model for the full fire phase.

Examined Scenarios

We have chosen three scenarios of varying complexity. The simplest is a tunnel or an elongated cuboid with open ends, see Figure 2. The second scenario is two rooms connected by a corridor (see Figure 3) and the most complex setup is an open plan office (see Figure 4).

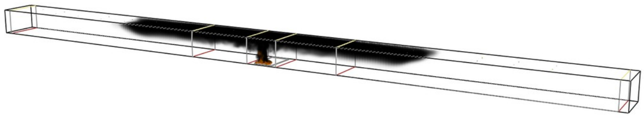


Figure 2. *Experimental setting in FDS. A tunnel with open ends on the left and right side. The fire starts spreading in the middle section of the tunnel.*

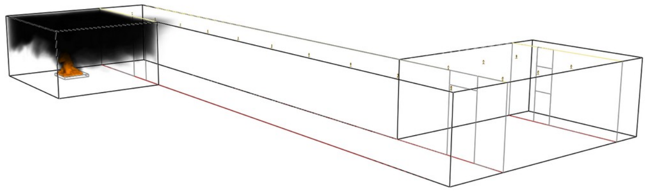


Figure 3. *Experimental setting in FDS. Two rooms connected by a long floor. The fire starts spreading in one room.*

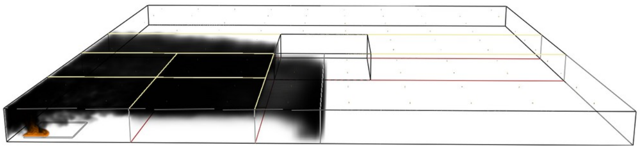


Figure 4. *Experimental setting in FDS. An open plane office. The fire starts in the corner.*

Outlook

The next step will be to compare the gradient-based optimisation with other optimisation algorithms. Furthermore, there is data that can be changed at runtime, such as doors or windows, which can be opened or closed. Whether these can be recognised and corrected accordingly also remains to be investigated.

References

[1] Anne Kuesters, Real-Time Simulation and Prognosis of Smoke Propagation in Compartments Using a GPU, 2018, Dissertation at the University of Wuppertal, ISBN: 9783958063792

[2] Kevin McGrattan, Randall McDermott, Marcos Vanella, Simo Hostikka, Jason Floyd (2022), Fire Dynamics Simulator: User's Manual, NIST Special Publication 1019 Sixth Edition, National Institute of Standards and Technology, (http://dx.doi.org/10.6028/NIST.SP.1019).

Fast cone calorimeter model for optimization of pyrolysis parameters

Timo Korhonen
VTT Technical Research Centre of Finland
Espoo, Finland
timo.korhonen@vtt.fi

Antti Korkealaakso
VTT Technical Research Centre of Finland
Espoo, Finland

Nikhil Verma
VTT Technical Research Centre of Finland
Espoo, Finland

Terhi Kling
VTT Technical Research Centre of Finland
Espoo, Finland

Tuula Hakkarainen
VTT Technical Research Centre of Finland
Espoo, Finland

Alexandra Viitanen
VTT Technical Research Centre of Finland
Espoo, Finland

Keywords: cone calorimeter, pyrolysis, flame heat flux, FDS, FDS, optimization

Abstract

Climate change has prompted construction and the construction products industry to use materials that leave fewer carbon footprints. Carbon footprints can be reduced, among other things, by using more wood and various bio-based polymers. However, such materials are often required to pass fire-related performance tests, which increases the time and the cost involved in the process. Attempts to reduce such time and cost have led to the development of fire-related computational tools that can virtually test the performance of such materials during a fire. Cone calorimeter is one such testing tool, and computational tools based on Computational Fluid Dynamics (CFD) are available to simulate it. This paper presents a new simulation model to aid the simulations of such cone calorimeter tests in CFD based software named Fire Dynamics Simulator (FDS). High accuracy required in such simulations demands very fine mesh, which leads to time-consuming "conventional simulation" that includes gas-phase calculation. The presented solid-phase-only model includes the spatially varying effect of flames in solid-phase-only calculation by using pre-calculated heat flux from different flame sizes for the different locations on the sample's surface. The exclusion of flame and inclusion of pre-calculated heat flux in the simulation results in much faster and encouraging results, although there are acceptable differences from the results of the conventional simulation. Nonetheless, the approach and results look promising to study the pyrolysis process of material undergoing degradation during cone calorimeter test.

Modelling Approach

The purpose of this work is not to model the cone calorimeter experiment exactly but to produce a fast and approximate computational model that produces acceptable results. In a typical application, problems in the modelling of the cone calorimeter experiment are emerging when a sample ignites and there will be a flame over the sample after it ignites. This flame will heat the sample surface in addition to the external radiative flux from the cone-shaped radiative panel that produces almost spatially constant radiative flux at the sample surface without the flame. In this work, the effect of the external radiative flux from the heated cone is simplified. It is assumed that all the nominal radiation emitted from the heated cone will reach the sample surface without any attenuation due to the flame or pyrolysis gases.

In this work, a fast and robust method to approximate the heat flux from the emerging flame back to the sample surface is addressed. The model is based on the fluid dynamics based fire simulation programme Fire Dynamics Simulator (FDS). The fast cone model is used together with FDS to optimize the material and pyrolysis parameters that are used to model the material in FDS. The main application of the fast and robust cone calorimeter FDS model is to use it to produce a FDS material model that can be used in larger-scale FDS simulations. The dimensions of these applications (affordable computational mesh sizes are of order from tens of centimetres to meters) are such that the LES is the only practicable mode of calculation. Thus, the cone calorimeter is modelled with the same basic assumptions as the larger-scale application will be using. Using LES mode of FDS enables the use of the same combustion reaction model.

The fast and robust FDS model for the cone calorimeter (in air) consist the following steps:

1) The radiative and convective heat transfer from the emerging flame are estimated using separate gas burner calculations, where a fine computational mesh (1 mm grid resolution in this work) is used to calculate a gas burner that has the dimensions of the cone sample (100 mm × 100 mm). The fuel gas is introduced evenly on the surface and many different heat release rates are simulated that span the typical range of heat releases of samples in the cone calorimeter (50 kW/m^2 to 1000 kW/m^2 in this work). The calculated radiative and convective fluxes due to the flame are recorded in the calculations and they are tabulated as a function of the position for later use.
2) A fast FDS calculation without any gas phase calculation is done, where the radiative heat flux from the cone heater is applied as a boundary condition to the 100 mm × 100 mm surface representing the sample. Basically, just the one-dimensional solid state heat conduction model of FDS is done in the fast model. At the ignition of the sample, the external flux given as a boundary condition is modified by adding the contribution of the flame that was tabulated in the step 1 above. This can be done automatically in the FDS simulation using a device measuring the heat release rate (the fuel gas mass flow multiplied by the heat of combustion, no gas phase reaction in the simple solid only model) over the whole sample surface. This device is then used together with a ramp, where the tabulated fluxes as a function of heat release rate are given, to add the flame flux to the external flux boundary condition that is applied to the surface.

Step 1 is only done once and it does not matter that it is computationally a large task. Step 2 is fast, just some minutes even when a relatively fine grid resolution (2 mm) is used. The run time of the fast solid only model can even be made faster using the symmetry. In the quarter of the sample, there are many grid cells that are equivalent and there is no need to calculate them all. The gas burner data is tabulated using the L0 norm (max(x,y)), so there are, for example, just 10 different surface cells that need to be calculated when a grid resolution of 5 mm is used whereas we have used 100 surface cells to represent the quarter of the sample. Actually, the fast cone model is not sensitive to the computational (surface) grid cell resolution. The test calculations showed that using grid resolutions starting from 1 mm up to 50 mm (same as just one grid cell over the whole sample due to the symmetry) give almost same results. The 50 mm case had some variations compared to 10 mm or finer meshes.

Conclusions

Results from fast solid only FDS model are very promising when compared to full FDS simulations with different grid resolutions for acceptable accuracy and significantly lesser simulation time. The run time of the fast solid only FDS models were under ten minutes compared to full FDS model which ran for multiple weeks. The way of modelling the radiative heat flux and convective heat flux by using results from gas burner simulations to mimic the effect of them from the flame back to the surface has proved to work well.

Acknowledgement

Funding for this work was received from VTT Technical Research Centre of Finland Ltd and is gratefully acknowledged. The authors wish to thank Mr Marko Mäkipää, Research Team Leader, for his constant support to make this research project possible.

(Mis)use of Visibility in Fire Safety Engineering

Ahmed Ahmed Ali Awadallah
The Danish Institute of Fire and Security, (DBI)
Hvidovre, Denmark
aaa@dbigroup.dk

Konrad Wilkens Flecknoe-Brown
The Danish Institute of Fire and Security, (DBI)
Hvidovre, Denmark
kwi@dbigroup.dk

***Keywords:* fire, FDS, smoke management, visibility, evacuation**

Introduction

Performance-based design (PBD) is an approach widely used by fire engineers to justify deviations from prescriptive guidelines. Central to PBD is the use of simulation tools such as the Fire Dynamics Simulator (FDS) to quantify the risks induced by such deviations. However, users must be familiar with the underlying models, limitations and default values used. Hence these tools are only as good as their user.

This study focuses on visibility and the available methods in FDS for measuring and calculating it. Additionally, an investigation on the color of light used and type of exit sign was carried out. It is important to ensure that enough time is available before untenable conditions set-in during a fire emergency in order for occupants to escape, that is; available safe egress time is greater than the required safe egress time (ASET>RSET). In simple terms, visibility refers to the maximum distance at which an observer can see an object [1]. It is heavily dependent on many factors including smoke concentration, illumination, type of exit sign, wavelength of light, color of exit sign, background contrast level and the observer's light perception[2], [3]. However, visibility is usually simplified as a light attenuation problem [4].

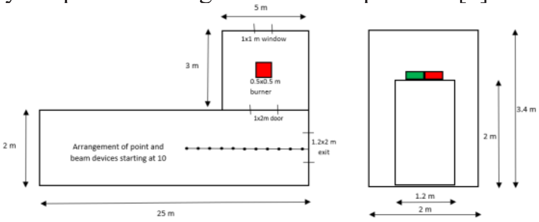


***Figure 1.* Layout of model - plan (left), exit door (right)**

Method for Determining Visibility

There are several ways in which visibility can be determined in FDS. A common practice is to place visibility 'slices' at desired heights on the z-plane. These slices are then analyzed in SmokeView to determine the time at which a particular visibility is lost. Additionally, point devices may be placed at certain points of interest in large domains or along exit paths to record the transient loss in visibility.

This common practice by engineers is inadequate for proper determination of visibility. Firstly, interpretation of z-plane slice results is subjective, and the loss of visibility reported by one engineer will differ from another for the same simulation. Furthermore, the type, arrangement, number, and calculation approach of devices used influences the results.

Analytical calculation methods used in models were originally developed for a homogenous smoke layer and show be used carefully. This is because such an assumption is only valid in well-mixed conditions where visibility no longer becomes a concern. Nonuniform smoke conditions are more prevalent in practice such as in situations where the fire is still in its growth stage or where smoke is spilling into a corridor or balcony from a compartment fire. Under these scenarios the smoke properties along the entire line of sight from observer to sign differ and must be considered.

In this study, the setbacks of the above practices are outlined. Three types of point devices for determining visibility were investigated – visibility (VIS), extinction coefficient (EXT), and smoke density (SMD) point devices. 25 devices of each type were arranged on the midpoint of the corridor, from 10m to the exit sign (Figure 1), along the line of sight from observer to the sign. A numerical averaging approach was then employed to determine visibility. Additionally, two in-built FDS devices that work on the principle of light attenuation called beam obscuration (BO) and transmission (BT) devices were also placed at 10m from observer to exit to mimic a ray tracing technique similar to the methods proposed by [4] and [6].

Description of Model

A corridor, 25m long and 2m wide is attached to a 5x3m room of fire origin both with a 3.4m ceiling height was built in FDS as shown in Figure 1. The room is open to ambient with a 1x1m window and to the corridor with a 1x2m door. The exit door of interest is 1.2x2m and was also open to ambient. The fuel used was toluene with steady HRR of 404.7 kW and a soot yield of 0.18 kg/kg from [7]

Several simulations (table 1) of an identical scenario were carried out while varying the mass extinction coefficient (K_m) and visibility factor (**C**). **C** indicates exit sign type; 3 for a reflecting (FDS default [9]) and 8 for illuminated signs. By default in FDS, K_m is 8700 m^2/kg (D) [8]. Two additional K_m values calculated using the Widmann correlation [10] for green (532nm) and blue (405nm) light were also investigated.

Table 1. List of simulations carried out in this study

Simulation	**1**	**2**	**3**	**4**	**5**	**6**
K_m**(m²/kg)**	D	D	9088	9088	11966	11966
C (-)	3	8	3	8	3	8

Results

Simulation results revealed that the type of devices used has a major influence on the resulting calculation of visibility. Figure 2 shows results from single point SMD and VIS devices at 10m and beam obscuration and transmission devices at 10m. The 10m criteria was selected based on [5]. It can be observed that both SMD and VIS devices suddenly lost their visibility at approximately 25 and 26s respectively. The visibility calculated from BO and BT appears to fluctuate before stabilizing and losing its visibility at 18s.

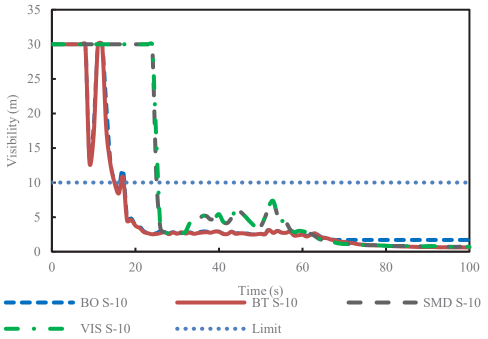


Figure 2. Visibility at 10m for different devices

Figure 3 shows the calculated visibility using the nonuniform approach using 25 SMD and VIS point devices each arranged along the line of sight from observer to exit as compared to the BT device. Good agreement is achieved for the visibility calculated using the average of SMD devices and BT, with visibility lost at 15s and 18s respectively at 10m. The average of the VIS devices however over predicts the time visibility is lost at 23s and shows a different trend in the time dependent calculations.

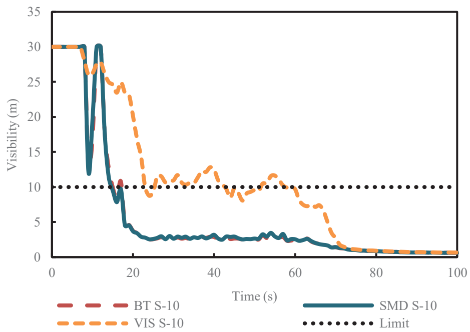


Figure 3. visibility at 10m using numerical averaging method

Table 2. Summary of results - effect of K_m and C on visibility at 10m

Simulation	1	2	3	4	5	6
Time Visibility is Lost at 10m (s)	18	21	18	20	14	18

Table 2 indicates that no major visible difference can be observed between the visibility recorded for the default and green K_m irrespective of **C**. This makes sense since both K_m values are close. Visibility using the higher K_m is lost earlier and hence its influence needs to be considered further. This is because modern exit lighting use cool white LEDs rather than green/red LEDs. This means exit signs have a K_m value closer to blue due to the strong influence of blue in these light sources [11] and will therefore lead to earlier loss of visibility than anticipated.

Conclusion

This study has revealed that current practices may lead to inaccurate visibility calculations. Interpretation of visibility slice planes is subjective, and hence is not a reliable measure of visibility. Using single point devices at a location leads to overprediction of visibility. The averaging approach for point devices however gives more accurate results, similar to BT devices, but only for SMD or EXT devices and not VIS devices. Engineers are hence encouraged to use BT devices due to postprocessing advantages. The type of sign and color of light should be simulated properly. White light is often used in signs hence an appropriate K_m closer to that of blue light should be considered instead of the default values given in FDS.

References

[1] ISO 13943, *Fire Safety – Vocabulary*. International Organization for Standardization, Editor, 2000.
[2] Y. He, "Evaluating visibility using FDS modelling result," in *FSE09: Fire Safety Engineering International Conference: Charting the Course*, Melbourne, Vic.: Engineers Australia Society of Fire Safety, Jan. 2009, pp. 77–88.
[3] G. W. Mulholland, "Smoke Production and Properties," in *The SFPE Handbook of Fire Protection Engineering*, 2nd ed., 1995, p. 2.
[4] K. Kang and H. Macdonald, "Modeling Smoke Visibility In CFD," *Fire Saf. Sci.*, vol. 8, pp. 1265–1276, 2005, doi: 10.3801/IAFSS.FSS.8-1265.
[5] D. Rasbash, "Smoke and Toxic Gas," *Fire*, vol. 59, no. 735, pp. 175–179, 1966.
[6] B. P. Husted, J. Carlsson, and U. Göransson, "Visibility through inhomogeneous smoke using CFD," p. 7, 2004.
[7] T. Rinne, J. Hietaniemi, and S. Hostikka, "Experimental Validation of the FDS Simulations of Smoke and Toxic Gas Concentrations," VTT, Finland.
[8] G. W. Mulholland and C. Croarkin, "Specific extinction coefficient of flame generated smoke," *Fire Mater.*, vol. 24, no. 5, pp. 227–230, Sep. 2000.
[9] T. Jin, "Visibility through Fire Smoke. J. Fire," *J. Fire Flammabl*, vol. 9, pp. 135–157, 1978.
[10] J. F. Widmann, "Evaluation of the planck mean absorption coefficients for radiation transport through smoke," *Combustion Science and Technology*, vol. 175, no. 12, pp. 2299–2308, Dec. 2003, doi: 10.1080/714923279.
[11] K. Jeykishan Kumar, G. Bharath Kumar, and R. Sudhir Kumar, "Photometric assessment of warm and cool white LED bulbs," *J Opt*, vol. 49, no. 4, pp. 476–484, Dec. 2020, doi: 10.1007/s12596-020-00640-4.

Modelling of Slow Chemistry and Weak Turbulent Flames

Bima A. Putra
NTNU – Norwegian University of Science and Technology
Department of Energy and Process Engineering
Trondheim, Norway
bima.a.putra@ntnu.no

Ivar S. Ertesvåg
NTNU – Norwegian University of Science and Technology
Department of Energy and Process Engineering
Trondheim, Norway
ivar.s.ertesvag@ntnu.no

Christoph Meraner
RISE Fire Research
Trondheim, Norway
christoph.meraner@risefr.no

Keywords: Computational Fluid Dynamics CFD, RANS, combustion modelling, Eddy Dissipation concept, fine structures

Abstract

A non-ideal reactor model is proposed to improve the Eddy Dissipation Concept (EDC) combustion model when capturing the effect of slow chemistry (Low *Da*) and week turbulence (Low *Re*). The reactor model is tested in a Moderate or Intense Low oxygen Diluted (MILD) jet-in-hot-coflow flame, and shown to give desirable effects, i.e., the reduction of scalars (temperature and species mass fractions), in certain cases. The outcome of this work is intended to motivate the development of fire modelling at oxygen-limited conditions

Introduction

Detailed flame temperature and species data for underventilated fires is lacking in the literature. Well documented flames in MILD conditions share some of the characteristics of underventilated fires, e.g., slow chemistry, and are therefore, of interest for validating numerical models. In the present work, the Adelaide jet-in-hot-coflow flame [1] is simulated in a Reynolds Average Navier-Stokes (RANS) framework with the focus on the modelling of turbulence-chemistry interactions.

The standard EDC combustion model [2] with unity reaction fraction (χ=1) has failed to predict MILD flames accurately. Therefore, researchers have proposed modifications to improve the EDC model by employing , e.g., locally modified EDC constants [3] or the variable reaction fraction [4]. However, other studies, Ertesvåg [5] and Lewandowski et al. [6], showed that the proposed modifications still have challenges such as the increasing viscous effect with increasing local *Re* for the former model and the ineffectiveness at moderately low *Re* for the latter model.

A non-ideal fine structure reactor is proposed as an extension to the standard EDC formulation for low Re application. This model determines that the mixing in fine structures is no longer perfect at a low Reynolds number. This condition can be described by a continuously stirred reactor with a non-reacting volume (dead volume). Consequently, the corresponding reactor residence time (τ^*_{LowRe}) must be shorter than the quantity from the original model (τ^*). The expression for τ^*_{LowRe} is modeled as

$$\tau^*_{LowRe} = C_f \tau^*, \qquad (1)$$

where C_f is a modification factor ranging between 0 and 1. In this work, C_f will be defined as a constant with the purpose to observe its effect on the scalars of interest.

It is important to note that the dead volume is regarded as a part of the surrounding region (excluded from the fine structure region). Therefore, a new expression for the ratio between the mass of fine structures and the total mass can be formulated as

$$\gamma^*_{LowRe} = \frac{C_f \rho^o}{C_f \rho^o + \rho^*(1 - C_f)} \gamma^*. \qquad (2)$$

Here, ρ^o and ρ^* is the density at, respectively, the inlet and outlet/inside of the reactor.

The reacting volume is treated as a Perfectly Stirred Reactor (PSR). Therefore, the species mass fraction inside the reactor (Y^*_k) can be obtained from the steady state solution of the following ODE equation,

$$\frac{dY^*_k}{dt} = \frac{R^*_k}{\rho^*} + \frac{1}{\tau^*_{LowRe}} (Y^o_k - Y^*_k). \qquad (3)$$

The kinetics of each individual reaction is considered in the calculation of reaction rate (R^*_k) using an Arrhenius model. The integration time for solving Eq.3 is usually set to a hundred times larger than τ^*_{LowRe}.

Finally, the mean reaction rate ($\overline{R_k}$) is computed as

$$\overline{R_k} = \frac{\bar{\rho}\gamma^*_{LowRe}}{\tau^*_{LowRe}} (Y^*_k - Y^o_k). \qquad (4)$$

Numerical setup

Simulations were performed using OpenFOAM v.7 in combination with the modified steady solver edcSimpleSMOKE [7]. OpenSMOKE library [8] was used to solve the chemistry. The Standard *k-ε* model was applied with the modification of turbulence model constant $C_{\varepsilon 1} = 1.6$ for a round jet. The maximum ratio between the mass of fine structure region and the total mass is set to close to one, i.e. $\gamma_{\lambda,max}$ =0.95, to avoid zero division error. The Damköhler number is calculated from the ratio between the Kolmogorov time scale and the chemical time scale obtained from the

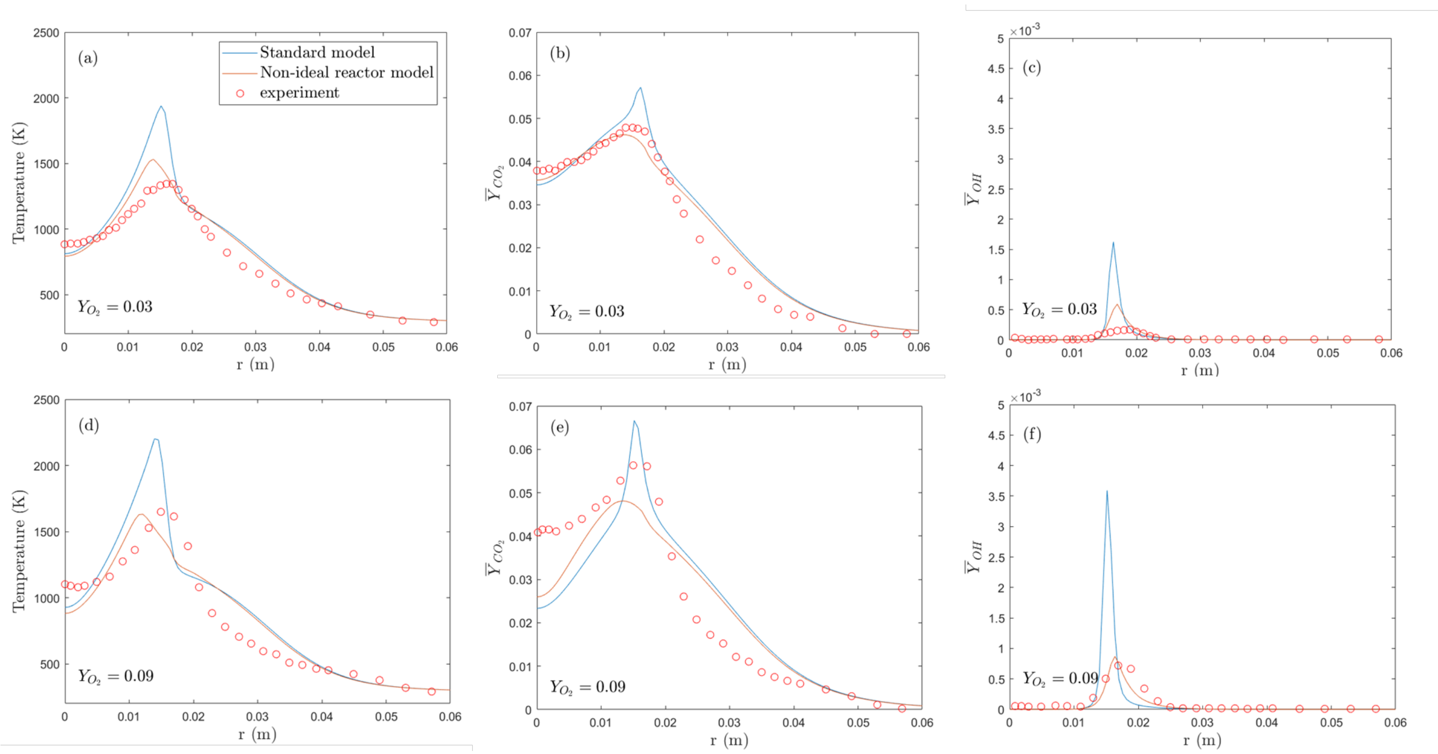


Figure 1. The radial profile of mean temperature, mass fraction of CO2 and OH at the axial location 120 mm downstream of the nozzle for the Adelaide flames. The oxygen mass fraction of the coflow is 3% (a,b,c) and 9% (d,e,f). The jet Reynolds number is equal to 10000 for both cases. The non-ideal reactor model is made by applying $C_f = 0.01$.

methane global reaction mechanism [9]. A minimum Damköhler number is applied, i.e. Da_{min} =0.03, to ensure (re)ignition [3][9]. Other simulation parameters refers to [6].

Results and discussion

The figure shows simulation results after applying the non-ideal reactor model with $C_f = 0.01$. It is visible that the modification has reduced the peaks of the three scalars for the case of 3% and 9% O_2 mass fraction. This confirms that the combustion model is now able to capture the effect of slow chemistry at weak turbulence. However, overpredictions of temperature and OH mass fraction is still present for the case of 3% O_2. Reducing C_f further could improve the result but could also lead to full extinction at some points.

It is important to note that the determination of Da_{min} plays an important role in the model as the flame could be fully extinguished when setting this parameter too low. A variable $Da_{min}$was proposed in [9] to improve the results while ensuring (re)ignition.

The radial locations of the temperature peaks are slightly deviated from the experimental data probably because the correction of $C_{\varepsilon 1} = 1.6$ is not optimum in predicting the jet spreading rate, cf. [6]. Therefore, optimization on the turbulence model could be a solution to this error.

There is a notable difference between the simulation and the experimental data of the temperature and CO_2 mass fraction at the position close to middle axis (r=0 mm). The inaccuracy of turbulence boundary condition of the fuel jet could be a factor as the experiment did not measure the quantity.

Conclusion

A non-ideal reactor model for the EDC fine structures has been proposed to predict the slow chemistry and weak turbulent flame, i.e., the Adelaide flame. The results show that the setting of $C_f = 0.01$ has decreased the flame temperature and the mass fraction of CO_2 and OH.

Further studies are in progress regarding the determination of C_f as a function of turbulence Reynolds number. More importantly, the generality of the model will be validated against, e.g., standard flames.

References

[1] B. B. Dally, A. N. Karpetis, and R. S. Barlow, "Structure of turbulent non-premixed jet flames in a diluted hot coflow," Proc. Combust. Inst., vol. 29, pp. 1147–1154, 2002.
[2] B. F. Magnussen, "The Eddy Dissipation Concept: A Bridge Between Science and Technology," ECCOMAS Themat. Conf. Comput. Combust., pp. 1–25, 2005.
[3] A. Parente, M. R. Malik, F. Contino, A. Cuoci, and B. B. Dally, "Extension of the Eddy Dissipation Concept for turbulence/chemistry interactions to MILD combustion," Fuel, vol. 163, pp. 98–111, 2016.
[4] M. T. Lewandowski and I. S. Ertesvåg, "Analysis of the Eddy Dissipation Concept formulation for MILD combustion modelling," Fuel, vol. 224, pp. 687–700, 2018.
[5] I. S. Ertesvåg, "Scrutinizing proposed extensions to the Eddy Dissipation Concept (EDC) at low turbulence Reynolds numbers and low Damköhler numbers," Fuel, vol. 309, p. 122032, 2022.
[6] M. T. Lewandowski, Z. Li, A. Parente, and J. Pozorski, "Generalised Eddy Dissipation Concept for MILD combustion regime at low local Reynolds and Damköhler numbers. Part 2: Validation of the model," Fuel, vol. 278, p. 117773, 2020.
[7] Z. Li, M. R. Malik, A. Cuoci, and A. Parente, "Edcsmoke: A new combustion solver for stiff chemistry based on OpenFOAM®," AIP Conf. Proc., vol. 1863, pp. 17–21, 2017.
[8] A. Cuoci, A. Frassoldati, T. Faravelli, and E. Ranzi, "OpenSMOKE++: An object-oriented framework for the numerical modeling of reactive systems with detailed kinetic mechanisms," Comput. Phys. Commun., vol. 192, pp. 237–264, 2015.
[9] M. T. Lewandowski, A. Parente, and J. Pozorski, "Generalised Eddy Dissipation Concept for MILD combustion regime at low local Reynolds and Damköhler numbers. Part 1: Model framework development," Fuel, p. 117743, 2020.

Demonstration test of passive fire safety measures for upholstered furniture

Application of fire-retardant treatment

Razieh Amiri
Civil and Environmental Engineering,
NTNU
Trondheim, Norway
razieh.amiri@ntnu.no

Anne Steen-Hansen
Civil and Environmental Engineering,
NTNU
Trondheim, Norway
anne.steen-hansen@ntnu.no

Anna-Carin Larsson
Civil, Environmental and Natural Resources Engineering, LTU
Luleå, Sweden
acla@ltu.se

Anuttam Patra
Civil, Environmental and Natural Resources Engineering, LTU
Luleå, Sweden
anupat@ltu.se

Cristina Sanfeliu Melia
RISE
Fire Research AS
Trondheim, Norway
cristina.melia@risefr.no

Keywords: ***Fire safety, dwellings, upholstered furniture, fire-retardant, passive measures***

Background

Although the number of fire fatalities in dwellings have generally been reduced during the last few decades [1], home fires can still lead to loss of life and severe injuries for the residents as well as damage to their assets, and the majority of these fatalities are mostly concerned with the vulnerable groups [2-3]. Therefore, home fires are still considered as a public socio-economic problem in several countries [4-6].

Furthermore, statistics shows that the most common room of fire origin for fire victims is the living room [2,7], where the fatalities have close connections with fires originated from upholstered furniture [8-11]. On this basis, it can be crucial to investigate different measures to improve fire safety of upholstered furniture. One of the practical approaches can be to study the preventive barriers including the passive fire safety measures. These measures can even be more vital in some situations. For instance, considering vulnerable groups, it cannot be practical to rely only on the active evacuation and barriers to reduce the consequences, but also to focus on preventive fire safety measures that can decrease and control the fire causes and hazards [12], as shown in Figure 1.

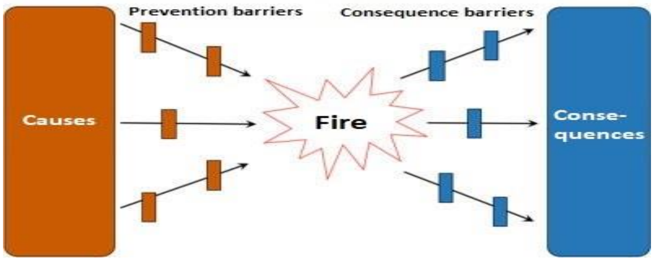


Figure 1. Bow-tie model showing the preventive & consequence barriers, locating respectively before and after the top event of fire [12]

Fire retardants (FRs) can be considered as one of the passive preventive fire safety measures for upholstered furniture. FRs are chemical substances that can improve the fire performance of the fabrics and upholstery foam, and potentially control or prevent the fire by performing as a heat barrier (a), modifying the chemistry (b), and/or extinguishing the flame (c), as shown in Figure 2.

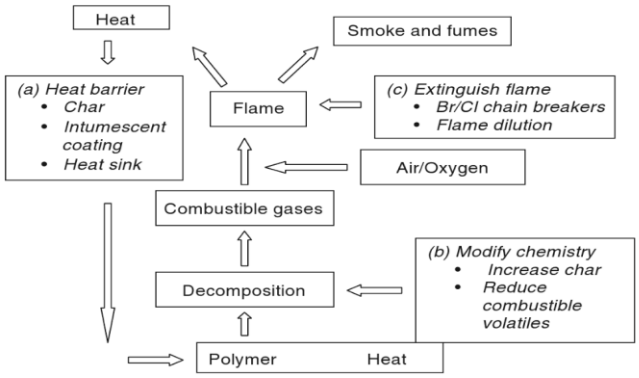


Figure 2. Schematic diagram of polymer combustion cycle with potential flame retardation modes indicated as (a), (b) and (c) [13]

Even though the FRs can improve the fire performance of the materials, the use of current products can have adverse results of short-term and chronic toxicity on the fire victims, as well as environmental damage [14]. In addition, during their synthesis, flammable and otherwise hazardous solvents are used, and toxic by-products may be generated. Many of these FRs, mainly the halogenated FRs, have been banned or restricted [15]. Thus, further research on non-toxic and environmentally friendly FRs can significantly extend the use of such measures in society. Such products, which are simple to use and maintain, easily accessible and have low-cost, can contribute to a higher level of fire safety in dwellings.

Small scale screening tests

In autumn 2021, a small-scale screening test series was performed on three types of cotton-based upholstered cover fabric materials treated with two different types of FRs.

The fabric materials consisted of different cotton and polyester proportions, named as A. 35% cotton and 65% polyester, B. 80% cotton and 20% polyester, and C. 100% cotton. The FR identifications and specifications are explained below. Fire retardant no.1 (F1) is claimed to be an environmentally friendly product. An aqueous solution containing 10% phytic acid, NaOH and arginine in 1:3:1

molar ratio was prepared. The samples were completely dipped and soaked in the solution for 20 seconds, followed by drying in air. This was followed by spraying aqueous aluminium chloride solution to those, and drying again. Fire retardant no. 2 (F2) is a commercially available product found on the Norwegian market. F2 is a chemical impregnation solution, and was prepared and applied on the samples by the lead author, based on the producer's instruction for cotton-based materials. The samples were dipped in the mixture consisting of 40% FR solution and 60% water. After the samples soaked up the mixture completely, they were removed from the mixture, and dried in air. After the treatments, we observed that the treated fabrics got stiffer compared to the untreated fabric materials. This attribute can affect the flexibility and comfort of the fabric in the production and use stage, and further investigations are needed in order to resolve this issue. F1 and similar FRs have already been successfully tested earlier on 100% cotton materials [16-18]. Therefore, it was decided to continue these experiments on the cotton-based materials. The objective of the screening tests was to determine the efficiency of the two chosen measures, F1 and F2, based on NS-EN 1021-1:2014 (smouldering cigarette test), NS-EN 1021-2:2014 (small flame ignition test), and ISO 5660-1:2015 (cone calorimeter) [19-21].

The results showed that the untreated materials did not pass any of the small flame ignition tests and smouldering cigarette test. The performance observed for both F1 and F2 were promising, meaning that they both had better performance compared to the untreated material. The results were very similar in different tests and materials, so it is difficult to choose one of these FRs specifically, over the other. However, the cone calorimeter test results showed a good improvement in time to ignition (tign), mass loss (ML), and heat release rate (HRR) using F1 compared to F2.

Large scale fire test

According to the results from the screening tests, a large scale fire test aims to experimentally demonstrate the different performances of the two types of FRs, F1 and F2. The main objective is to demonstrate the effect of the chosen measures, F1 and F2, in a large scale test of upholstered furniture.

On this basis, three identical single upholstered armchairs were purchased from a local shop. The cover fabric consists of material B, i.e., 80% cotton and 20% polyester. Material B was chosen based on a brief analysis on the shop's website. In this analysis, 205 cotton-based textiles (for textile upholstered furniture) were screened. It was found that the cover fabric material of almost half of the products consists of 75-80% cotton and 20-25% polyester. Note that only the cover fabric materials were treated with each type of FR. No fire retardant is used for other parts of the furniture e.g., filling material, wooden frame, etc. Treatment methods can be spraying, dipping, and using brush. However, only one layer of dipping treatment was applied to each armchair cover in this experiment. Besides the two treated armchairs, a test was also executed for a chair with the same untreated cover material and was considered as a reference test.

Each armchair was then tested sequentially in a large scale furniture calorimeter according to the method described in NT FIRE 032 [22]. The test results included t_{ign}, HRR, total heat release (THR), smoke production rate (SPR), and ML. Further details and results will be presented at the Nordic Fire & Safety Days 2022.

Acknowledgment

Hereby, the collaborations with RISE Fire Research AS, the Fire Research and Innovation Centre FRIC, and Brandforsk are greatly appreciated.

References

[1] A. Steen-Hansen, K. Storesund, and C. Sesseng, "Learning from fire investigations and research - A Norwegian perspective on moving from a reactive to a proactive fire safety management". Fire Safety Journal, 2021.

[2] P. Cassidy, N. McConnell, and K. Boyce, "The older adult: Associated fire risks and current challenges for the development of future fire safety intervention strategies." Fire and Materials, 2019.

[3] K. Storesund, C. Sesseng, A. Steen-Hansen, et al. "Rett tiltak på rett sted - Forebyggende og målrettede tekniske og organisatoriske tiltak mot døds-branner i risikogrupper." SP Fire Research AS, Norway, 2015.

[4] M. Ahrens, and R. Maheshwar, "Home Structure Fires - Supporting Tables." National Fire Protection Association, 2020.

[5] Ministry of Justice and Public Security. "Trygg hjemme-Brannsikkerhet for utsatte grupper. ", Oslo, Norway, 2012.

[6] J. A. Haagsma, N. Graetz, I. Bolliger, M. Naghavi, H. Higashi, E. C.Mullany, and U. Alsharif, "The global burden of injury: incidence, mortality, disability-adjusted life years and time trends from the Global Burden of Disease study 2013." Injury prevention, 22(1), 3-18, 2016.

[7] C. Sesseng, K. Storesund, and A. Steen-Hansen, "Analyse av dødsbranner i Norge i perioden 2005-2014." RISE Fire Research, Trondheim, Norway, 2017.

[8] K. Storesund, S. H. Steinbakk, and A. Steen-Hansen, "Brannsikkerhet og helse- og miljøeffekter i forbindelse med stoppete møbler, madrasser og innredningstekstiler." SINTEF NBL AS, Norway, 2012.

[9] M. Ahrens, "Soft furnishing fires: They're still a problem." Fire and Materials, 2020.

[10] E. Guillaume, R. D. Feijter, and L. Van Gelderen, "An overview and experimental analysis of furniture fire safety regulations in Europe." John Wiley & Sons Ltd., 2019.

[11] A. Hofmann, A. Klippel, T. Gnutzmann, S. Kaudelka, and F. Rabe, "Influence of modern plastic furniture on the fire development in fires in homes: large-scale fire tests in living rooms." 2020.

[12] G. Gjøsund, P. Almklov, K. Halvorsen, and K. Storesund, "Vulnerability and prevention of fatal fires.", London, 2016.

[13] D. Price, and A.R. Horrocks, "Combustion processes of textile fibres." Handbook of Fire Resistant Textiles, 2013.

[14] M.M. Hirschler, "Safety, health and environmental aspects of flame retardants.", Handbook of Fire Resistant Textiles, 2013.

[15] L. Costes, F. Laoutid, S. Brohez, and P. Dubois, "Bio-based flame retardants: When nature meets fire protection." Materials Science and Engineering R, 117, 1-25, 2017.

[16] A-C. Larsson and A. Patra, "Studies on environmentally friendly flame retardants for cellulosebased materials." Brandforsk, Sweden, 2020.

[17] A-C. Larsson, and A. Patra, "Environmentally friendly flame retardants for cellulosebased materials – Continuation." Brandforsk, Sweden, 2021.

[18] A. Patra, S. Kjellin, and A-C. Larsson, "Phytic acid-based flame-retardants for cotton." Green Materials, 8, 123-130, 2020.

[19] "EN 1021-1:2014, Furniture - Assessment of the ignitability of upholstered furniture - Part 1: Ignition source smouldering cigarette." CEN-CENELEC, Brussels, 2014.

[20] "EN 1021-2:2014, Furniture - Assessment of the ignitability of upholstered furniture - Part 2: Ignition source match flame equivalent." CEN-CENELEC, Brussels, 2014.

[21] "ISO 5660-1:2015, Reaction-to-fire tests - Heat release, smoke production and mass loss rate - Part 1: Heat release rate (cone calorimeter method) and smoke production rate (dynamic measurement)." ISO copyright office, Switzerland, 2015.

[22] "NT FIRE 032 - Upholstered furniture: Burning behaviour – Full scale test." NORDTEST, Finland, 1991.

Preliminary results from emission factor study

Methodology and findings

Joakim Åström
Lund University, Sweden
Joakim.astrom@brand.lth.se

Margaret McNamee
Lund University, Sweden

Benjamin Truchot
INERIS, France

Guy Marlair
INERIS, France

Keywords:* *Emission Factors, Cone calorimeter, FPA, Large scale, Comparison

Introduction

In order to fully understand the environmental impacts of fire incidents, be it forest fires or construction fires, there is a need for quantification of the emission factors. A recent overview of the environmental impact of fires concluded that much of the data concerning emission factors is limited or potentially out-dated [1].

A recent study conducted by Lund University and INERIS in France aims to create a new database containing emission factors (EF) of different species for a variety of materials. In this abstract the focus is on the methodology and results of EF for CO and CO_2 developed using bench-scale testing using the Cone Calorimeter (CC) [2] at Lund University, mainly compared to large-scale data collected at INERIS.

Experiments

A total of seven materials, wood and plastics, were tested using the cone calorimeter and FPA [3]. The aim of the tests was to measure CO and CO_2 production to quantify the emission factors for different phases of the combustion process and compare the two different scales.

The wood materials consisted of solid Pine, Plywood (PW), Oriented Strand Board (OSB) and Particle Board (PB). Three plastic materials where tested: High Density Polyethylene (PEHD), and two types of Poly Vinyl Chloride (PVC). The difference between the PVC materials is that the PVC2 has higher heat-, chemical- and impact resistance.

Methodology

The Emission Factor (EF) was calculated as Yield of the product normalized over the mass of burned material. Using the mass production of species and mass loss of the sample the EF can be calculated as follow.

Eq. 1 $$EF = \frac{\sum(\dot{m}_x * \Delta t)}{m_1 - m_2} * 1000$$

Where EF is the emission factor [g/kg], $\dot{m}_x$ is mass produced of the emission gas [g/s], Δt is the timestep between measurements [s], m_1 is sample mass at the phase start [g], m_2 is sample mass at the phase end [g].

The CC samples were prepared to fit in the standardized sample holder described in ISO 5660-1. Since the PVC expanded while heated the additional metal grid was used to keep the surface at the initial distance from the heater. Gas analyser measurements and load cell data was gathered for 1800 s at heat fluxes of 35-50 kW/m^2. The heat fluxes variation was due to the creation of a fuel rich mixture around the igniter at 50 kW/m^2 for the PVC1.

The large-scale tests were conducted in an 80 m^3 room at INERIS. The ventilation of the room was controlled through a duct which allows for smoke and gas analysis. The prepared samples had an exposed fire surface of approximately 0.5 m^2 and were placed on a load cell in the centre of the room. More details concerning both sets of tests are available in the research report [4].

Results

After collecting the measurement data, three phases of the combustion were defined, flaming, steady and smouldering. The phases in relation to HRR and production of CO for the CC-data are presented in figure 1.

The period named steady is determined as a phase of steady combustion and steady emissions of the species of interest. The flaming period is taken from the ignition of the sample until flameout. There are two ways to define the end of flaming for the wood samples, first is the operator determined time of entire surface flaming and the other is looking at the highest rate of change in the CO/CO_2 factor. Finally, the smouldering phase is taken from the end of flaming until the end of the test.

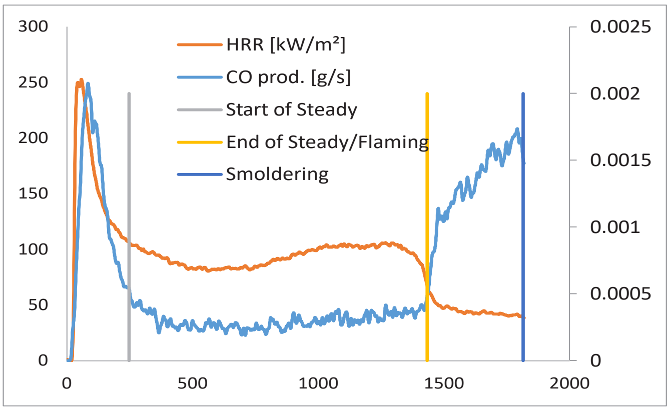


Figure 1. Combustion phases in relation to HRR and CO prod.

Based on the defined phases emission factors for CC and large-scale was calculated using equation 1. The calculated emission factors for the seven materials based on the CC results are presented in table 1. EFs calculated from large-scale test of solid pine are presented in table 2.

Conclusions

The EFs calculated indicate that smouldering materials have the highest release of CO during the smouldering combustion phase, as expected. Further, the EFs for the four wood materials are similar, even when comparing solid wood and engineered wood.

Lastly, the result for the solid pine in the CC compared to the large-scale indicates that comparable EFs are determined using the different scales. While preliminary, these results indicate that the development of EFs using bench-scale methods can be extrapolated to large-scale events, at least for major emissions.

Table 1. EF for CO and CO2 for the tested materials. EF are presented in [g/kg]. Note that PVC1 was tested with a HF of 35 kW/m2.

CO	Steady	Flaming	Smoulder	Total
Pine	5	5	155	26
PB	4	5	104	9
PW	5	7	165	19
OSB	4	6	178	16
PVC1	-	65	-	74
PVC2	-	83	-	74
PE HD	-	-	-	25
CO_2	Steady	Flaming	Smoulder	Total
Pine	1311	1306	2616	1480
PB	1168	1218	2649	1227
PW	1307	1264	3114	1415
OSB	1307	1264	3114	1415
PVC1	-	549	-	701
PVC2	-	687	-	746
PE HD	-	-	-	2147

Table 2. EF of CO and CO2 for large-scale test of pine.

Large	EF CO	EF CO2
Steady	2	1338
Flaming	9	1527
Smouldering	177	3187
Total	26	1697

References

[1] McNamee, M., et al., Research Roadmap: Environmental Impact of Fires in the Built Environment. Final Report, in FPRF Research Report, F.P.R. Foundation, Editor. 2020, Fire Protection Research Foundation: online. p. 80.

[2] SIS. (2019). SS-ISO 5660-1:2019 - Reaction-to-fire tests – Heat release, smoke production and mass loss rate – Part 1. Stockholm: Swedish Standards Institute.

[3] Brohez S., et al, Fire calorimetry relying on the use of the fire propagation apparatus. Part I: early learning from use in Europe, Fire Mater.2006;30:131–149

[4] McNamee, M., et al., Environmental Impact of Fires in the Built Environment: Emission Factors, Final Report, 2022, Lund University, Lund.

FDS -simulation of flame-induced surface heat fluxes on cylindrical polymer objects during cone calorimetry tests

Morteza Gholami Haghighi Fard
Civil Engineering Department
Aalto University
Espoo, Finland
morteza.gholamihaghighifard@aalto.fi

Simo Hostikka
Civil Engineering Department
Aalto University
Espoo, Finland
simo.hostikka@aalto.fi

Keywords:
Cone Calorimeter, FDS, Cylindrical Fuel, PMMA, HT3D

Abstract

Cylindrical polymers are increasingly used in building components and cabling systems. PMMA cylinders are widely used as common construction material for the sake of their aesthetics and ability to substitute inorganic glass [1]. Industrial cables are comprised of polymeric sheath, filler, and insulation layers in the cylindrical form [2]. Also, wildland combustibles such as pine needles, twigs, and shrubs are known to mainly possess cylindrical shapes of wood polymers [3]. Cone calorimetry is a well-known standard technique in fire safety engineering for the assessment of the flammability of the materials. Despite the fact that the exposed heat flux of the cone calorimeter is explicitly defined for flat, rectangular samples, its application has recently expanded to cylindrical polymeric samples as well. However, the non-characterized physics of the heat exposure on the curved cylindrical samples has led numerical simulators to strong simplifications while trying to calibrate pyrolysis models for these calorimetry experiments. The modeling simplifications include mapping of the volume of the cylindrical samples into a rectangular surrogate, and implementation of one-dimensional heat transfer and pyrolysis methods, which all lead to great model uncertainties [4].

The current study aims at characterizing the combustion physics of cylindrical fuels in cone calorimetry by performing experiments and 2D numerical simulation on black PMMA rods with 20 mm diameter. The tests are carried out in two conditions, namely non-flaming (gasification) and flaming. Also, two different fuel layouts, placing a single rod on the sample holder or tight alignment of five rods, are examined. For modeling, the 2D heat transfer and pyrolysis algorithms of the Fire Dynamics Simulator (FDS) code [5] are implemented to solve solid material degradation. The geometry of the cylindrical PMMA rods is replicated by putting together multitude of small, $1 \times 1\,\mathrm{mm}^2$ PMMA obstructions. This novel framework allowed capturing time-resolved cross-sectional shrinkage of cylinders upon a good agreement with experiments. Moreover, the method enabled the ability to extract more comprehensive thermodynamic information in the vicinity of rods such as radiative and convective fluxes, and wall/gas-phase temperature distributions.

Comparison of gasification and flaming modeling results provided significant information about the distribution of flame-induced heating on the surface of the cylindrical samples. For example, two results for the single rod test case, one for gasification and another for flaming condition, are presented in Figure 1 and Figure 2, respectively. The model shows a 15 $\mathrm{kW/m^2}$ increase of the incident heat flux on top of the rod, and an elevated convective heating, with a distribution on the sides of the rod peaking to about 30 $\mathrm{kW/m^2}$, because of the flame. This work included non-charring objects, however, the current numerical framework has the potential of further expansion to more complex objects such as wood rods, where charring physics must be considered as well.

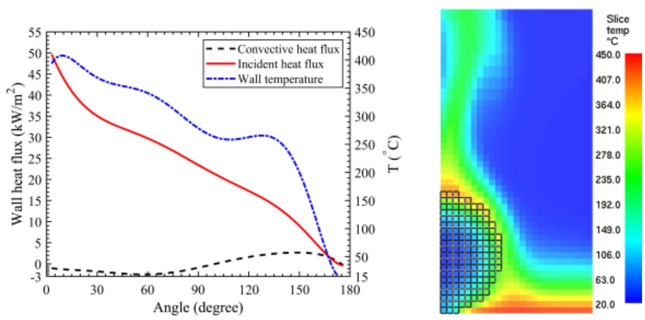


Figure 1. ***Simulated heat fluxes and temperature of the sample surface (left) and continuum temperature (right) for single rod gasification test.***

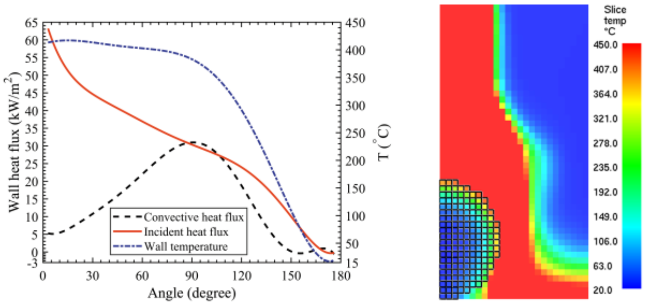


***Figure 2.** Simulated heat fluxes and temperature of the sample surface (left) and continuum temperature (right) for single rod flaming test.*

References

[1] S. Tao, J. Fang, Y. Meng, H. R. Shah, and L. Yang, “Ignition risk analysis of common building material cylindrical PMMA exposed to an external irradiation with in-depth absorption,” *Constr. Build. Mater.*, vol. 251, p. 118955, 2020.

[2] A. Matala and S. Hostikka, “Pyrolysis modelling of PVC cable materials,” *Fire Saf. Sci.*, vol. 10, pp. 917–930, 2011.

[3] S. McAllister and M. Finney, “Autoignition of wood under combined convective and radiative heating,” *Proc. Combust. Inst.*, vol. 36, no. 2, pp. 3073–3080, 2017.

[4] A. Matala, *Methods and applications of pyrolysis modelling for polymeric materials*. VTT Technical Research Centre of Finland, 2013.

[5] M. Bruns, R. McDermott, S. Benkorichi, and S. Hostikka, “Development of 3D Pyrolysis in FDS,” 2018.

Enabling a mass loss measurement in a tube furnace

Karen De Lannoye
Forschungszentrum Jülich GmbH (FZJ)
Jülich, Germany
k.de.lannoye@fz-juelich.de

Alexander Belt
Forschungszentrum Jülich GmbH (FZJ)
Jülich, Germany
a.belt@fz-juelich.de

Ernst-Arndt Reinecke
Forschungszentrum Jülich GmbH (FZJ)
Jülich, Germany

Lukas Arnold
Forschungszentrum Jülich GmbH (FZJ), University of Wuppertal (BUW)
Jülich/Wuppertal, Germany

Keywords: tube furnace, balance, mass loss, TGA

Abstract

In this contribution a new bench scale experiment is proposed. The new design consists of a tube furnace with additional installed measurement systems, among others a lever mechanism allowing for online mass loss measurement. A detailed description of the set-up is presented.

Additionally, the results of commissioning experiments will be shown. A simple material with only a single pyrolysis reaction peak is used for these experiments. The results are compared to results from a thermogravimetric analysis.

Introduction

Thermogravimetric analysis (TGA) and cone calorimetry are two small scale experiments often used in fire safety science. The TGA has well known boundary conditions, like for example the flow conditions of the purge gas and a controlled heat flux to the sample. However, the TGA only allows for very small sample sizes (mg range). The cone calorimeter, on the other hand, allows for larger samples sizes. However, its boundary conditions are less well defined, e.g. the flow velocities around the sample and the unknown heat flux from the flame. The proposed tube furnace set-up aims to combine the best of both devices. The tube furnace allows for samples of around 100 g while having the well-known boundary conditions like in the TGA. Additionally, the new device could contribute to an extensive database on pyrolysis to improve model development, with e.g. the fire dynamics simulator (FDS).

In order for the tube furnace to be as valuable as the cone calorimeter and the TGA, an online mass loss measurement has to be installed. This is why a balance for the tube furnace was developed. Due to the challenging realization, i.e. the sample is located in a closed small tube, there have been no similar experiments build so far.

Description of the set-up

The design of the tube furnace is based on ISO 19700 [1]. It consists of a quartz glass pipe lying in a furnace (figure 1). The furnace has 11 heating elements over a range of 51 cm. The quartz glass tube has an inner diameter of 90 mm and a wall thickness of 2.4 mm. Experiments can be carried out under both air and nitrogen atmosphere as well as any atmosphere of choice. The design allows to conduct both experiments at a constant temperature, at a constant heating rate as well as with a constant heating power. Thermocouples are installed at 11 locations at the outside of the tube furnace. Small quartz glass tubes are fixed to the glass tube to assure the position of the thermocouples, see picture 1a. Several accesses are added to the glass tube to allow for example additional thermocouples to be placed at the inside of the glass tube. The set-up is connected to a gas analyzer measuring O_2, CO_2 and CO. Further connections are foreseen, in case it would be desired to add more analyses equipment in the future.

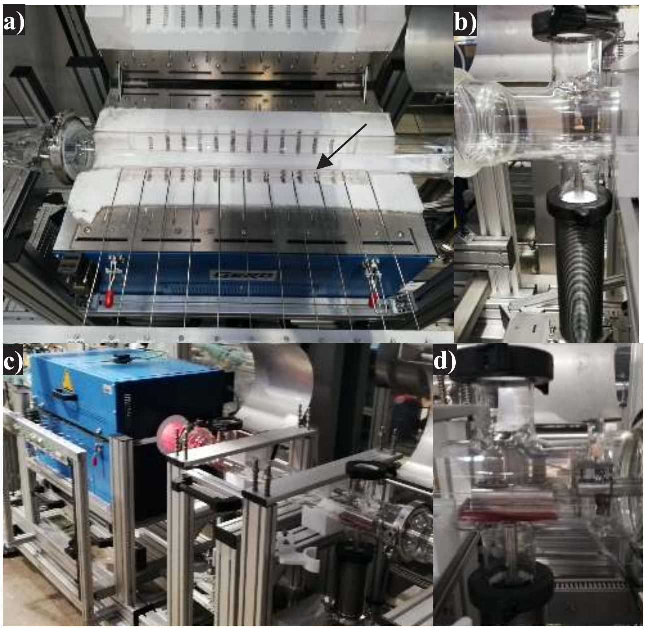


Figure 1. The tube furnace set-up. a) Furnace with quartz glass tube with specimen boat and additional thermocouples at the outside of the tube furnace b) the pivot of the balance system c) overview picture d) pin connected to the load cell

A schematic view of the balance is given in figure 2. A lever allows to install a load cell far enough from the oven to avoid high temperatures at the cell. On the left side of the lever a sample is placed in a specimen boat. This part of the beam is placed in the oven during the experiment. Between the oven and the load cell a pivot is installed. On the left end, the load cell is located. On the weighing unit a pin is installed. Its top is in contact with the balance beam. When the sample on the right loses weight, a force will be exerted on the pin on the left, which will result in an apparent weight change. This last variable is recorded by the weighing cell. This way the weight loss of the sample can be calculated from the apparent weight change. The vertical position of the pivot and the weighing cell can be changed, allowing to decouple the balance beam from the glass tube.

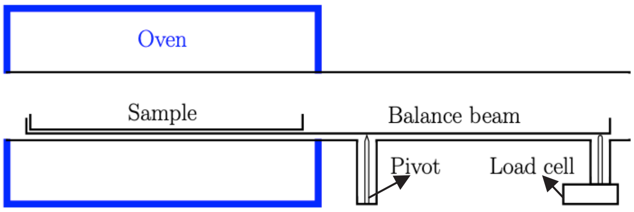


Figure 2. Schematic overview of the balance installed in the tube furnace.

Outline of the contribution

This contribution will give a more detailed description of a new innovative experimental set-up. A detailed temperature distribution of the furnace will be presented and the homogeneity of the temperature and the uniformity of the heating rate will be discussed.

Commissioning experiments of the balance will be presented. These experiments are conducted with $CaCO_3$ powder under nitrogen atmosphere. The advantage of this material is that upon heating the following reaction occurs [2]

$$CaCO_3 \rightarrow CaO + CO_2.$$

This allows to correlate the data from the gas analyzer with the data from the balance and to demonstrate the functionality of the online weighing system and check the plausibility of the results. Additionally, the results from the tube furnace with $CaCO_3$ are compared to mass loss data for $CaCO_3$ in a TGA.

References

[1] International Organization for Standarization (2016). *Controlled equivalence ratio method for the determination of hazardous components of fire effluents — Steady-state tube furnace (ISO/TS 19700).*

[2] I. Galan, F. Glasser, and C. Andrade, "Calcium carbonate decomposition," J Therm Anal Calorim, vol. 111, pp. 1179-1202, 2013.

Environmental Impact of Combustion Gases and Water Run-offs from Electric Vehicle Fires

Full-scale fire tests of electric- and internal combustion engine vehicles

Jonna Hynynen
Fire and Safety
RISE Research Institute of Sweden
Borås, Sweden
Jonna.hynynen@ri.se

Ola Willstrand
Fire and Safety
RISE Research Institute of Sweden
Borås, Sweden
Ola.willstrand@ri.se

Keywords: full-scale fire tests, batteries, sprinkler, water run-offs, emissions

Abstract

Fire incidents that involve battery electric vehicles (BEVs) have attracted considerable attention in the media. However, there is no statistical data that suggests that BEVs are more prone to fire accidents than internal combustion engine vehicles (ICEVs). In 2020 the Swedish fire rescue service performed 3383 rescue operations involving 4470 passenger vehicles. Out of these accidents 34 (~ 0.8%) fires “started in the battery or had the potential to spread to the battery”.[1]

To ensure continuous safe engineering and development of BEVs, fire testing of batteries and vehicles are critical. Large scale fire tests can also provide useful input data for simulations such as emissions and smoke development models. These factors are essential for rescue service personnel to enable development of safe rescue tactics. Another important aspect, that is covered in this project, is the environmental impact of fire water runoffs.

Project Background

This research project is funded by the Swedish Energy Agency and is a continuation of a previous RISE project, ETOX, "Toxic gases from fires in electric vehicles".[2]

Results from ETOX indicated that certain metals (Ni, Co, Li and Mn) and hydrogen fluoride (HF) was found to a higher degree in gas emissions resulting from electric vehicles, compared to emissions from the tested internal combustion engine vehicle.

The continuation of the ETOX project will complement previous results with more data regarding full scale fire tests of vehicles. Additionally, analysis of water run-offs resulting from the use of water upon fire suppression were performed to assess the environmental impact of vehicle fires.

Full-scale Fire Tests

Three separate vehicle (same car make and model) and one battery-only fire test was performed; tests included a BEV, an ICEV, and another vehicle with the traction energy removed as well as a 50 kWh battery.

A sprinkler system was used to study the effect on combustion gases upon water application. The test set-up used allowed for time-resolved analysis of the water run-offs. Additionally, Microtox analysis, and analysis of the biotoxicity of the run-off water towards daphnia magna and green algae were performed.

Results

Ecotoxicity evaluation of the water run-offs indicate a high level of toxicity for the Microtox and green algae for all analysed water samples. For *daphnia magna* the water run-offs from the ICEV were found more toxic than for the BEV. The EC_{50} was found at 16.2 and 58.7 v/v%, ICEV and BEV respectively.

For the combustion gases and soot analysis, results followed the trends seen in ETOX but the concentrations of analysed substances were somewhat lower. Interestingly, no HF could be detected in the combustion gases whilst the sprinklers were active. Indicating that water application was very effective in washing out the HF from the combustion gases. This was further confirmed by the increased fluoride content in the water run-offs.

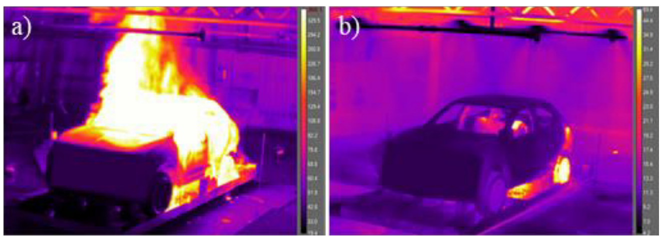


Figure 1. Thermal imaging of the BEV during the fire test, (a) before sprinkler activation (b) sprinklers activated.

References

[1] Webpage IDA MSB, https://ida.msb.se/ida2#page=f43428db-1b2a-4025-abf0-a96b5633771e, accessed 2022-02-16

[2] O. Willstrand, R. Bisschop, P. Blomqvist, A. Temple, J. Anderson, Toxic gases from fires in electric vehicles, RISE report, 2020. Available from: http://urn.kb.se/resolve?urn=urn:nbn:se:ri:diva-52000

Developing of a new test protocol for Quick Suppression Systems (quick reacting water mist system)

Mats Kihlström
Firefly AB
Stockholm
Sweden
mats.kihlstrom@firefly.se

Keywords:
Quick Suppression System, water mist, quick response time, machine protection.

Abstract
In industries handling dry and finely divided material, you will often find risk areas or machines that are highly exposed to dust accumulations or a mix of dust and oil. Even the smallest outbreak of a fire can quickly cause damages and result in a costly production downtime. If the fire is not stopped in time it can rapidly spread to other areas, causing a dramatic increase in costs and severe risk for personnel.

To solve this problem, a fire protection concept were developed for protection of critical machines or high risk areas, based on a protection system with extremely quick response time. The purpose was to develop a system that acts quickly enough to avoid damages and production downtime, thus saving costs and increase safety of personnel.

There were no fire test protocols that addressed this type system/fire hazard. Therefore an ISO/IEC 17025:2005 accredited fire test company were contacted and a test protocol were developed.

The fire test protocol is intended for evaluating the performance of Quick Suppression Systems intended for the protection of certain high risk indoor areas typically found in industry applications such as:
- Planers
- Sanders
- Mills
- Band saws
- Conveyors
- Shredders
- Tissue machines
- Yankee dryers
- Tissue converting machines
- Pellet presses

This paper will describe the concept of the Quick Suppression System and show the relation between the system response time and fire damage. It will explain the new fire test protocol and show results from conducted fire tests.

Digitalization of Fire Safety

Developing webtools to aid the FSE

Melchior Schepers
Jensen Hughes
Leuven, Belgium
ms@fesg.be

Xavier Deckers
Jensen Hughes
Ghent, Belgium
xd@fesg.be

Keywords:* *Digitalization, webtool, CFD, FDS, smoke and heat control

Introduction

In Fire Safety Engineering both the prescriptive and the performance based approach have always been heavily dependent on computational modelling. Ranging from step by step calculations set out in standards for the prescriptive approach to complex CFD-simulations in performance based designs. Jensen Hughes has started developing a series of webtools with intuitive user interfaces to facilitate the usage of such calculations by fire safety engineers. In this abstract two such tools are highlighted and discussed in the light of their advantages and possible caveats. The first webtool presented here focusses on the implementation of BR 368 and the Belgian equivalent NBN S21-208-1. The procedures set out in these standards for smoke and heat control are implemented and incorporated into a web user interface. The second webtool introduced here focusses on the Fire Dynamics Simulator. It enables users to both write and check FDS code and aims to provide fire safety engineers and FDS users with an extra layer of quality assurance.

Quality assurance & computer modelling

Quality assurance is a key factor of any engineering project. It can be implemented on a business level through high level frameworks such as the ISO 9000 family [1] down to the individual validation and verification of calculation procedures and software.

The exponential increase in computing power of the past decades as was famously predicted by Moore [2] has provided engineers with unprecedented modelling capabilities of physical phenomena. It has enabled engineers to transform longwinded hand calculations to a mere click of a button and has allowed them to model structures and fluids to exceptional levels of detail. On the other hand it has also changed a lot of calculations to a black box where a series of inputs result in an outcome which is taken for granted without critical thinking about the underlying assumptions of the model.

A lack of quality assurance and error checking can easily lead to engineering mistakes. Notable incidents from the past attributed to a lack of error checking and quality assurance within the engineering field include the crash of the Mars Climate Orbiter and the sinking of the Sleipnir A offshore platform. The first caused by a mismatch of imperial and metric units [3], the second caused by an underestimation of the shear stresses due to an inaccurate finite element approximation [4]. This goes to show that even though we are able to model physical reality to exceptional levels of detail the models still contain explicit and implicit assumptions that can have a major impact on the results. Limitations on the outcome of a calculation thus rely heavily on the assumptions of the software itself on the one hand but on the user and his inputs on the other hand as well.

The two tools that are presented in the following sections aim to help the fire safety engineer in his daily work processes by streamlining the process of parameter selection and entry and by incorporating error-checking in every step of the calculation. The tools aim to provide an efficient and more resilient approach to fire safety design processes than the current practices.

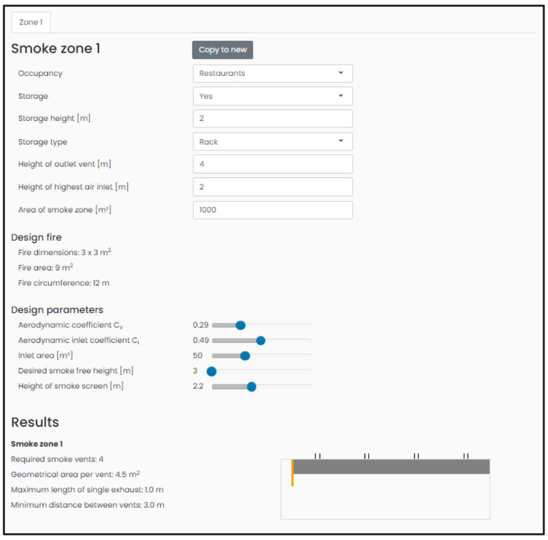


Figure 1. GUI of the webtool implementing different SHC standards

SHC standards

Smoke and heat control is a key factor in enabling safe passage for evacuees when a fire breaks out in a building. The BR 368 'Design methodologies for smoke and heat exhaust ventilation' is a well known reference for designing such SHC systems [5]. In Belgium the basic design of such systems is set out in the NBN S21-208-1 outlining the calculation procedure to be followed [6].

Experience shows that the calculation steps set out in these standards are often implemented in a spreadsheet making them error-prone and tedious to employ. The iterative nature of these calculations additionally makes it hard to optimize towards different parameters. By implementing these procedures in a web environment they become much more accessible and user friendly. Additional advantages include real-time error-checking and the possibility to change different parameters on the fly. The webtool is coupled to an automated report generator providing the user with an efficient manner of reporting the parameters used and the results obtained. The user of the webtool should however be well aware of the inherent limitations of the implemented method and is encouraged to check the limitations through the provided guide or the standard itself.

FDS code facilitator

The Fire Dynamics Simulator (FDS) developed by NIST is one of the most used CFD-tools in the fire safety engineering community. The correct usage of FDS and its intricacies is however not something all fire safety engineers are acquainted with and is usually reserved to a handful of experts within a company. The webtool developed by Jensen Hughes aims to facilitate the interaction of FDS experts and other fire safety engineers and to perform a first automatic quality assurance check. It allows the user to select the relevant technical guideline to be applied (e.g. Belgian best practices for car parks, UK accepted values for fire and smoke parameters,…) and automatically creates a template of FDS code which can then further be altered or supplemented with additional FDS code. The webtool also includes a built-in code validator which allows the responsible quality assessor to validate the FDS code before starting the simulation. This allows in-house teams to make a first assessment whether or not there are obvious contradictions or errors in their code, it also provides authorities having jurisdiction and notified bodies with the ability to check if the simulation they have to evaluate respects the basic requirements of a correct FDS simulation.

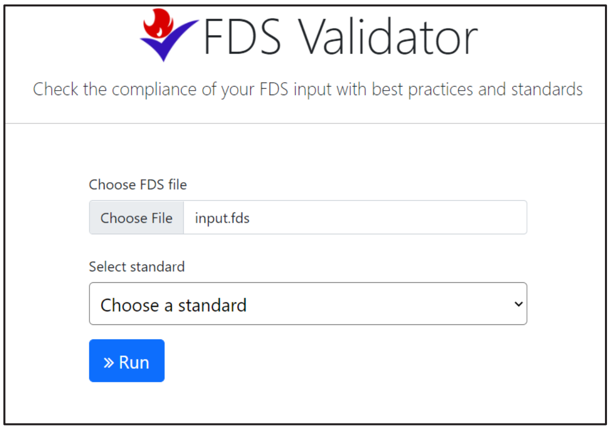


Figure 2. Input screen to the FDS code validator

Conclusion

Jensen Hughes has started the development of a series of webtools which can aid fire safety engineers in the efficient and correct application of calculation procedures. Two such tools were presented here. A webtool replacing commonly used spreadsheets for smoke and heat control purposes and a webtool for the creation and validation of FDS code. The purpose of the tools is to help in error checking and quality assurance of the calculations fire safety engineers have to perform almost daily. The tools provide a time efficient way of reporting the results by automatically importing the results into a report template. Nevertheless it has been highlighted that the engineer should not become complacent as it has been illustrated that the implicit and explicit assumptions of models or calculations can have major consequences for the resulting design.

References

[1] International Organization for Standardization, “Quality Management Systems - Requirements ISO 9001:2015”
[2] G. E. Moore, “Cramming more components onto integrated circuits”, Electronics, 38, no.8, 1965
[3] J. Oberg, “Why the Mars Probe went off course", IEEE: IEEE Spectrum, December 1999
[4] R. G. Selby, F. J. Vecchio, and M. P. Collins, “The Failure of an Offshore Platform”, Concrete International, vol. 19 (8), pp. 28-35, August 1997
[5] H. Morgan, B. Ghosh, G. Garrad, D. Pamlitschka, J. Smedt and L. Schoonbaert, , “Design Methodologies for smoke and heat exhaust ventilation”, London: BRE Press, 1999
[6] Belgisch instituut voor normalisatie, “NBN S 21-208-1: brandbeveiliging van gebouwen – ontwerp en berekening van rook en warnteafvoerinstallaties (RWA) – deel 1: gorte onverdeelde binnenruimten met één bouwlaag”, May 1995

The overall picture of stove fire incidents in Finland and factors endangering stove safety

Kuurne Laura
Finnish National Rescue Association (SPEK)
Helsinki, Finland
laura.kuurne@spek.fi

Lepistö Jukka
Finnish Safety and Chemicals Agency (Tukes)
Helsinki, Finland
jukka.lepisto@tukes.fi

Ojala Tarja
Finnish National Rescue Association (SPEK)
Helsinki, Finland
tarja.ojala@spek.fi

Keywords: (5 key words)
Stove fire, stove safety, fire safety, accident prevention, home safety

Introduction

Stove fires are the most common cause of housing fires in Finland. This poses a significant risk, especially for older people and for those with disabilities [1,2]. Decreased functional capacity exposes to stove accidents, impairs the ability to react and endangers the evacuation safety in the event of fire. Building fire hazards relating to the use of stove may not always be reported to the rescue services if the smoke damages can be handled by the resident. Therefore, the official statistics do not reflect the actual annual number of stove fires.

It is known that stove fires play a significant role in causing fires and building fire hazards [3] but more information on fires, their ignition and prevention are needed to improve safety at home. The aim of this study is to create an overall picture of the factors that endanger the safety of the stove. These include typical mistakes in using stoves, accidents caused by forgetfulness and the materials and stove types that contribute to the accidents.

Materials and Methods

To examine the impact of different factors in the overall picture, information on ignition rates, fire ignition mechanisms and flammable materials, as well as the prevalence of different stove types and stove safety devices was obtained. The analyzed data include investigation reports from the Safety Investigation Authority of Finland (1998-2020, 35 reports)[4:7], data collected from media survey (1.7.2020-31.12.2021, 98 incidents) and accident information from PRONTO (2016-2020,3962 incidents), which is the database of the fire and rescue service's official register of incidents[8].

In addition, a citizen survey was conducted about close call incidents, self-extinguished fires and fires that were reported to the rescue services (101 incidents). In this study, the stove fires include incidents that happened with electric stoves, including traditional cast iron stove, ceramic, and induction stove.

Results

The results indicate that the main causes of stove fire ignition are additional materials stored on or near the stove and unsupervised cooking. In cooking scenarios, accidents often occurred when cooking with oil. Also, accidents occurred mainly with ceramic and cast-iron stoves. According to the survey, three-quarters of stove fires or fire hazards can be extinguished or prevented by a resident of the household and those are not reported to the rescue services. Therefore, the actual number of stoves fires compared to the official records in PRONTO database can be up to four times higher. In addition, the citizen survey indicates that the use of stove safety technology is still low in Finland. The causes of stove fire ignition are similar between the media survey and PRONTO database, but the number of stove fire incidents reported in media is low considering their actual annual occurrence.

Conclusion

Because of the low media coverage on stove fires, citizens have fewer opportunity to learn from the accidents and identify their prevalence and associated risks. However, according to previous studies, the number of stove fires can be reduced with stove safety technology [9]. This should be considered in addition to informing residents about the potential hazards. On the other hand, security technology is still scarce in Finland and its financing has not yet been organized in the municipalities. If the resident is unable to obtain it their self, there is no procedures that guarantee it to those who most need it.

In future, more research is needed to obtain information about fire ignition with different stove types and stove safety devices. There is currently an on-going stove fire project in Finland that aims to fill the gap in research. Also, educational material for citizens on stove safety will be conducted in this year.

References

[1] Karemaker, M., Gill, A., Hagen, R. R., van Schie, C. H., Boersma, K., & Ruiter, R. A. (2021). Elderly about home fire safety: a qualitative study into home fire safety knowledge and behaviour. Fire Safety Journal, 103391.

[2] Korpilahti, U. & Koivula, R. & Doupi, P. & Jakoaho, V. & Lillsunde, P. (2020). Safely at All Ages: Programme for the Prevention of Home and Leisure Injuries 2021–2030, 74-84. Last viewed 31 Jan 2022 [https://julkaisut.valtioneuvosto.fi/handle/10024/163155]

[3] Hu, Y., Chen, J., Bundy, M., & Hamins, A. (2021). The character of residential cooktop fires. Journal of fire sciences, 39(2), 142-163.

[4] Safety Investigation Authority (2003). D1/2003Y School building in residential use catches fire in Jyväskylä rural municipality; Five Other Fires Over The Pe¬riod From April 20 To May 20, 2003. Viewed 31 Jan 2022 https://turvallisuustutkinta.fi/en/index/tutkintaselostukset/other/tutkintaselostuksetvuosittain/muutonnettomuudet2003/d12003yasumiskaytossaolleenkoulurakennuk.html

[5] Safety Investigation Authority (2007). B1/2007Y Fire at Pitkäniemi Hospital in Nokia on 25 January 2007. Viewed 31 Jan 2022 https://turvallisuustutkinta.fi/en/index/tutkintaselostukset/other/tutkintaselostuksetvuosittain/muutonnettomuudet2007/b12007ytulipalopitkaniemensairaalassanok.html

[6] Safety Investigation Authority (2014). Y2014-02 Fire in a block of flats in Turku on 17 March 2014. Viewed 31 Jan 2022 https://turvallisuustutkinta.fi/en/index/tutkintaselostukset/other/tutkintaselostuksetvuosittain/2014/y2014-02kerrostalopaloturussa17.3.2014.html

[7] Safety Investigation Authority (2017). Y2016-03 A fire in a terraced house that led to death of two chil¬dren in Raahe on 13 September 2016. Viewed 31 Jan 2022 [https://turvallisuustutkinta.fi/en/index/tutkintaselostukset/other/tutkintaselostuksetvuosittain/2016/y2016-03kahdenlapsenkuolemaanjohtanutrivitalopaloraahessa13.9.2016.html]

[8] PRONTO. Statistics system of Finnish rescue services. Viewed 31 Jan 2022 [https://prontonet.fi/Pronto3/online3/OnlineTilastot.htm]

[9] Runefors, M. & Frantzich, H. (2017). Nyttoanalys av spisvakt och portabelt sprinklersystem vid bostadsbrander. Rapport 3210. Lund University, Department of Fire Safety Engineering.

Analysis of a devastating fire in an apartment building with municipal housing in Norway

Edvard Aamodt
RISE Fire Research
Trondheim, Norway
Edvard.aamodt@risefr.no

Anne Steen-Hansen
RISE Fire Research and
Norwegian University of
Science and Technology
Trondheim, Norway

Ole Anders Holmvaag
RISE Fire Research
Trondheim, Norway

Keywords:
Fire, safety, investigation, case study, dwelling fire

Background

In the night to 7th of August 2021 a fire started in an apartment building outside the city Bergen in Norway. The building had been built in 2012 and had four floors with a total of 24 flats. Each flat was equipped with smoke detectors and a sprinkler mitigation system. There were balconies covered with wood cladding outside each flat on the façade where the fire started. The building was used as municipal housing for people with drug addictions. The building was continuously supervised by municipal housing personnel or security guards on site.

The fire is described in an evaluation report by Bergen Fire Department [1] and most probably started on a balcony at the ground floor. The fire was spreading to the whole façade with high velocity and intensity. The fire service, arriving on scene 11 minutes after receiving the alarm, had no possibility of extinguishing the fire. However, when the fire service arrived all occupants were already outside the building and nobody was injured. Figure 1 shows the fire development as described two hours after the fire service arrived. Figure 2 shows the building after the fire.

This fire was soon identified as having a great potential for finding learning points that may benefit the fire safety work in the society, and a multidisciplinary group in the Fire Research Centre (FRIC) was established for analysing the fire. The group also included experts outside FRIC. The case study is a part of the FRIC project *Learning from fire investigations*.

Objectives

Two main questions were set as goals for this project to answer:

1. Why did the fire develop so rapidly and grow so large?
2. Given the rapid fire development, why were no occupants injured despite the fact that they are considered as being especially at risk in a fire situation?

Figure 1. The south façade about two hours after the fire alarm (photo: Bergen Fire Department).

Methods and materials

To answer the first main question, it is of interest to assess if the building satisfied the fire regulations at the time when it was built. To do this the documentation of the fire safety design has been analysed. It is also evaluated if relevant revisions of the fire regulations after the fire would have had any impact on the fire safety if they were implemented.

The wood cladding on the balconies was obviously an important factor for the fire spread, and a question is if the fire behaviour of this specific product were comparable to the fire behaviour of ordinary untreated wood. Since the fire occurred after a period of dry summer weather, the moisture content (MC) in the cladding may also have affected the fire spread. The critical heat flux for ignition of the cladding with different MC content has been studied using the method described in ISO 5660-1 2015[2]. The test material was taken from the wooden cladding on the undamaged side of the building. Both the original cladding from 2012 and cladding mounted in 2019 have been tested.

To answer the second main question, a mapping of the evacuation process is made. Information from interviews with the fire service and the police arriving on the scene, and information from their reports after the accident, is combined. Their reports contain interviews with the occupants and the security guard working in the building the night of the fire, which give invaluable insight.

Results

The project is not finished when preparing this abstract, and the final report will be finished during early summer 2022. The report will present the learning points and possible recommendations. Some results are presented below regarding main question 1:

- The choice of wood materials for construction of the balconies and wooden materials were also chosen in the load bearing construction for the balconies contributed to the available combustible material (fuel) for the fire.
- A sprinkler system was not installed on the balconies, this could have prevented the initial fire from spreading to other balconies. It would also have activated a much earlier alarm signal to the fire service.
- Weather conditions such as the wind during the fire and the dry and warm weather in the week prior to the fire are thought to have had impact on the fire spread.
- Occupants of the building were known to accumulate possessions in their apartments and on their balconies and in this way contributing to the available fuel to the fire.

Results regarding main question 2:

- Strong relationship ties made the occupants evacuate each other, however bad the nature of the relationship.
- Having a more nocturnal circadian rhythm resulted in almost all occupants being awake during the fire.
- Only fire on the balcony side of the building and not on the access balconies and stairwell made the occupants able to evacuate through their main entrance doors, which in general would be the first choice of evacuation route.

Figure 2. The apartment building after the fire. Photo: RISE Fire Research.

Acknowledgements

The work has been conducted as part of the Fire Research and Innovation Centre (FRIC), which is funded by the Research Council of Norway (program BRANNSIKKERHET, project number 294649) and FRIC partners.

References

[1] A. Bjørke, B. Næs, K. Øvstedal, and V. Gunstensen, ‘Evalueringsrapport av brannen i Hardangervegen 669’, Bergen Brannvesen, Bergen, Evalueringsrapport, Aug. 2021.

[2] ‘ISO 5660-2:2002 Reaction-to-fire tests - Heat release, smoke production and mass loss rate - Part 2: Smoke production rate (dynamic measurement).’ ISO Copyright office, published in Switzerland, 2002.

Assessing Multiple Natural Hazards

Nils Johansson
Fire Safety Engineering,
LTH, Lund, Sweden
Nils.Johansson@brand.lth.se

Claude Pagnon Eriksson
Fire Safety Engineering,
LTH, Lund, Sweden
claude.pagnon_eriksson@brand.lth.se

Margaret McNamee
Fire Safety Engineering,
LTH, Lund, Sweden
Margaret.mcnamee@brand.lth.se

Keywords: (5 key words)
Wildland fires, flooding, multi-hazards, risk assessment, mitigation, fire and rescue services.

Abstract

A literature review of methods where different hazards are combined into a single multi-hazard assessment method is presented. To directly combine hazards, it is necessary to present them with the same unit of measure. This can be done in a variety of ways, e.g. by normalizing or using weights, to create a level playing field as it were. Maps are often used to gain an understanding of the spatial distribution of the hazard as well as the hazard level. No specific method or tool that can be directly applied directly for relevant hazards in Sweden has been found in this review. However, several general principles and methods that are identified as valuable for future research.

Introduction

The world is facing enormous challenges in terms of access to resources, increasing and diversifying population, and extreme weather events and natural hazards, e.g. the global impact of wildfire is staggering. The Joint Research Centre (JRC) estimates an average number of wildfires of 41 452 and burn area of 333 200 ha annually (2010-2019) in Southern Europe (Portugal, Spain, France Italy and Greece) [1]. Further, the cost of the Swedish summer fires of 2018 were estimated to be 370 million € in net value loss based on final product value of the burnt forest land [2]. Further, global loss due to wildland fire is presently greater than at any time in the past [3]. The impact from wildfires are not only associated with the event itself; for instance, exposure to particulates has an impact of lung conditions, wildfires can also change nutrients in impacted areas and have far-reaching impact on ecosystems in general [4].

Efficient management to minimize the vulnerability of society to hazards requires an assessment of hazards and risks that involves information concerning the type of potential event, the probability of a specific event, and the potential consequences of an event. In the case of wildfire, variables like temperature, moisture content and wind velocity are used to create indices and hazard maps to represent the wildfire danger.

A society's exposure to hazards and the magnitude of potential consequences can be expressed using a so-called risk index. Risk indices can be constructed for different types of hazards and they can be applicable to different areas and levels of the society, from individual buildings or facilities to countries or even entire continents. In a project financed by the Swedish Civil Contingencies Agency (MSB) and FORMAS, a multi-hazard risk assessment tool is being developed to assist prediction of emerging risks on a local, regional, and national level to support various stakeholders for strategic training and resource planning. The tool will combine single hazard indices with a focus on wildfires (forest and WUI) and flooding/storms (urban and coastal).

The objective of the work presented in this short paper is to review different multi-hazard approaches and how different hazards can be combined into a single tool.

Methodology

The methodology applied in this work has also been applied in previous studies of single hazard prediction tools [5, 6] and represents a systematic literature review, see figure 1.

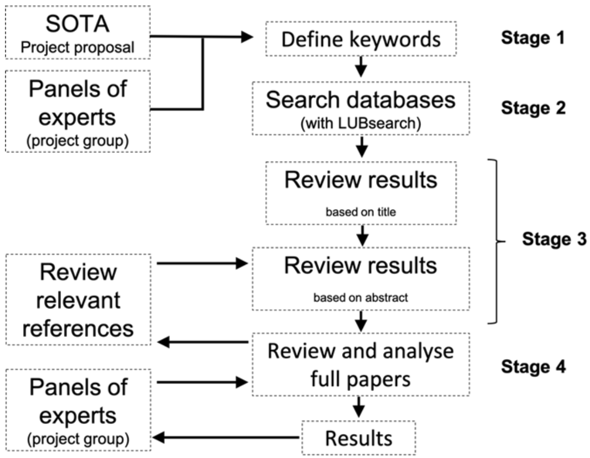


Figure 1. Methodology used in literature review.

A total of 92 titles were reviewed with approximately 30% yielding sufficiently relevant for full review. Selection for full review was based on identification of multi-risk tools with a focus on natural hazards.

Results and Discussion

Based on the review conducted, it is clear that there are a number of methods that have been presented in the literature for the assessment of multiple hazards (see e.g. [7-10]). The short paper will present a summary of principles for standardizing hazards, relationships between hazards, method to combine single hazards into multiple hazards and some examples of existing multi-hazard tools.

Conclusions

This study identifies the need to transform different hazards into the same unit of measure to be able to compare them as one of the main challenges of this type of index. This is typically done using some qualitative nomenclature or by normalising the hazard values. However, there may be no clear maximum value (which could preclude the calculation of normalised values) and in many cases data is lacking causing the adoption of qualitative assessment methods. A less sophisticated way of combining hazards could be to overlay the hazards on a map to illustrate areas where high index values coincide. This is one potential method to combine existing hazard indices without transforming or normalizing them at the start of an analysis. Alternatively, one could combine numerical hazard indices using weighting of the various indices. This latter method has the disadvantage that it may be difficult to identify the different weights of the hazards.

Even though hazard relationships have been studied in the reviewed literature, there is no standardized way to take synergetic effects into account. This needs to be done on a case-by-case basis, and connections between the hazards included in the project should be evaluated to be able to include any significant synergetic effects that might exist.

In most of the studies reviewed, maps are used to illustrate the hazards or combination of hazards. This is a method that makes it easy to understand spatial distribution of the hazard as well as the hazard level. The latter is often illustrated with color codes.

References

[1] J. San-Miguel-Ayanz *et al.*, "Forest Fires in Europe, Middle East and North Africa 2020," 1831-9424 2021. [Online]. Available: https://publications.jrc.ec.europa.eu/repository/handle/JRC126766

[2] Skogforsk, "The Effects on Swedish Forestry of the Summer 2018," Skogforsk, 2019. [Online]. Available: https://www.skogforsk.se/cd_20190502151614/contentassets/8020a8a5edd645c5a7352e5280853eef/arbetsrapport-1012-2019.pdf

[3] D. Thomas, D. Butry, S. Gilbert, D. Webb, and J. Fung, "The Costs and Losses of Wildfires A Literature Survey," *NIST Special Publication,* vol. 1215, 2017, doi: https://doi.org/10.6028/NIST.SP.1215.

[4] A. Bytnerowicz, M. J. Arbaugh, C. Andersen, and A. R. Riebau, "Chapter 26 Integrating Research on Wildland Fires and Air Quality: Needs and Recommendations," in *Developments in Environmental Science*, vol. 8, A. Bytnerowicz, M. J. Arbaugh, A. R. Riebau, and C. Andersen Eds.: Elsevier, 2008, pp. 585-602.

[5] C. Pagnon Eriksson and N. Johansson, "Review of wildfire indices. Indices applicable for a Swedish context," Lund University, Lund, 2020, vol. Report 3233. [Online]. Available: https://www.lu.se/lup/publication/404387de-8dd1-4b72-9c45-fe3e4f431048

[6] C. Pagnon Eriksson and N. Johansson, "Review of flooding indices. Indices applicable for a Swedish context," Lund University, Lund, 2020, vol. Report 3234. [Online]. Available: https://www.lu.se/lup/publication/946f9b81-1e95-428e-bf8d-89679d4f7da3

[7] M. S. Kappes, M. Keiler, K. von Elverfeldt, and T. Glade, "Challenges of analyzing multi-hazard risk: a review," *NATURAL HAZARDS,* vol. 64, no. 2, pp. 1925-1958, 11/01/ 2012, doi: 10.1007/s11069-012-0294-2.

[8] ARMONIA, "A summary of the research undertaken by the ARMONIA (Applied multi risk mapping of natural hazards for impact assessment) research project, funded under the 6th EU FP for Research and Technological Development," Lancaster University, online, 2007. [Online]. Available: http://www.eurosfaire.prd.fr/7pc/doc/1271840032_armonia_fp6_multiple_risks.pdf

[9] F. Pagliacci and M. Russo, "Be (and have) good neighbours! Factors of vulnerability in the case of multiple hazards," *Ecological Indicators,* Article vol. 111, pp. N.PAG-N.PAG, 2020, doi: 10.1016/j.ecolind.2019.105969.

[10] J. Schmidt *et al.*, "Quantitative multi-risk analysis for natural hazards: A framework for multi-risk modelling," (in English), *Natural Hazards,* Article vol. 58, no. 3, pp. 1169-1192, 09 / 01 / 2011, doi: 10.1007/s11069-011-9721-z.

Key issues in the numerical modeling of the structural response of RC elements to accidental actions

Zhaochang Zhang
School of Civil Engineering
Southeast University
Nanjing, China
2975584715@qq.com

Wenqian Liu
Civil and Mechanical Engineering dep.
Technical University of Denmark (DTU)
Kgs. Lyngby, Denmark
weliu@byg.dtu.dk

Luisa Giuliani
Civil and Mechanical Engineering dep.
Technical University of Denmark (DTU)
Kgs. Lyngby, Denmark
lugi@byg.dtu.dk

***Keywords*:** RC elements, numerical analysis, structural response, calculation methods, material behavior.

Abstract

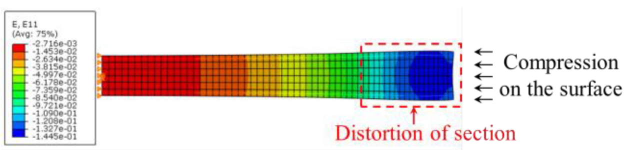
Motivation and background

Reinforced concrete (RC) elements are often vulnerable to accidental actions, such as fire hazards, explosions, earthquake action, etc. The collapse of Ronan Point Apartment Tower (UK, 1968) and Alfred P. Murrah Federal Building (USA, 1995) are just two cases of RC buildings that have collapsed, due to a gas and a manmade explosion, respectively. The demolition of Liverpool car parking UK, 2017 (Mail Online, 2018) or the Paramount Boulevard viaduct in California, USA, 2011 (L.A. NOW, 2011), both due to the extensive damages caused by vehicle fires, are also another indication of the vulnerability of R.C. structure to accidental actions and the significant economic losses they can cause (Qin, et al., 2022).

It is therefore extremely important to account for such actions in the design of R.C. structure. This requires the availability of advanced design tools, such as finite element analysis (FEA), as experimental testing is often impractical in such cases, due to safety concern and very high costs.

However, building reliable nonlinear numerical model of R.C. element is quite complex and requires a high expertise of the user and an extensive validation of the results, due to several computational issues, such as strain localization and objectivity of the solution (Bontempi & Malerba, 1997; Carstensen, et al., 2013)

As a consequence, even simple 2D models of R.C. beams can provide inconsistent results in term of stress and deformation and wrong estimate of the capacity. For example, in Figure 1 (top and middle), an inconsistent deformed shape is obtained, due to inaccurate modeling of the boundary conditions (application of restraint and loads, respectively). In Figure 1 (bottom), stress localization emerges due to inaccurate modeling of the smeared cracking in tension.



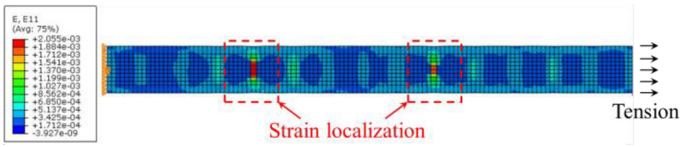


Figure 1 Examples of unreliable results due to localization phenomena

Purpose and method

Aim of this study is to highlight the main factors that can lead to unreliable results when modeling the response of R.C. to collapse and provide practical guidance in setting up accurate yet simple models to investigate the nonlinear dynamic response to R.C. elements to accidental actions.

In particular, a cantilever RC beam is taken as a case study to investigate the effects of the following factors:

1. boundary conditions;
2. material model;
3. grid size.

The analyses are carried out in two different commercial FE codes, where two different users implemented independent models of the same beam. The results are discussed in term of modeling choices and accuracy of the results and a comparison between the two codes is provided with respect to the prediction of the beam bending capacity.

Models and results

A cantilever beam of length 6 m is modeled in Diana and Abaqus (see Figure 2). The beam has rectangular cross-section of dimensions 0.3 m x 0.6 m (width x height) and is reinforced with one top and one bottom steel bar, each having an area of 980 mm^2 and a distance from the centerline of the bar to the closest concrete edge of 0.05 m.

In ABAQUS, a 4-node bilinear plane stress quadrilateral (CPS4) element and a truss (T2D2) element are used for concrete and steel, respectively. In DIANA, a f4-node Q8MEM element is used for the concrete, and embedded reinforcement is used in this model.

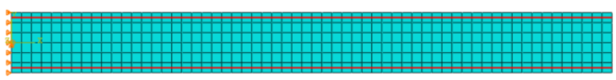


Figure 2: 2D model of the R.C. beam in Abaqus

Firstly, the effect of different modeling of the boundary conditions is investigated. A uniform axial load applied on the free end of the beam is considered and modeled as:

a. distributed load on the elements' surface;
b. concentrated forces on the nodes;
c. load applied to a rigid plate connected to the beam end in such a way, that the adjacent nodes of the beam and the plate must have the same horizontal displacement, but can freely and independently move vertically.

The three numerical results have remarkable differences, as seen in Figure 3 and indicate that a careful modeling of the boundary condition is paramount and that, specifically, the use of a rigid plate can solve issue related to inconsistent deformation and stress localization close to the boundaries.

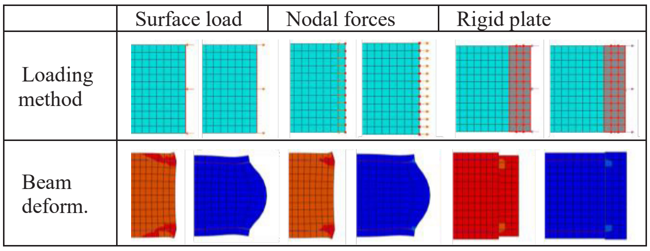


Figure 3: Effect of load modeling on the deformation of the beam end

Secondly, the choice of the concrete material model is investigated and in particular, the following models are used:

i. smeared cracking - tension stiffening definition in strain (abbreviated as "smear-strain");
ii. smeared cracking - tension stiffening definition in displacement (abbreviated as "smear-disp. ");
iii. concrete damage plasticity model - tension stiffening definition in strain (abbreviated as "CDP-strain");
iv. concrete damage plasticity model - tension stiffening definition in fracture energy (ref. to as "CDP-Gf").

For the steel material, an elastic-plastic stress-strain relationship is assumed, as usual. The results indicate that the material model in compression has little influence on the capacity (Figure 4 top), but convergence problems can lead to early abortion of the analysis for some tensile material models (Figure 4 bottom).

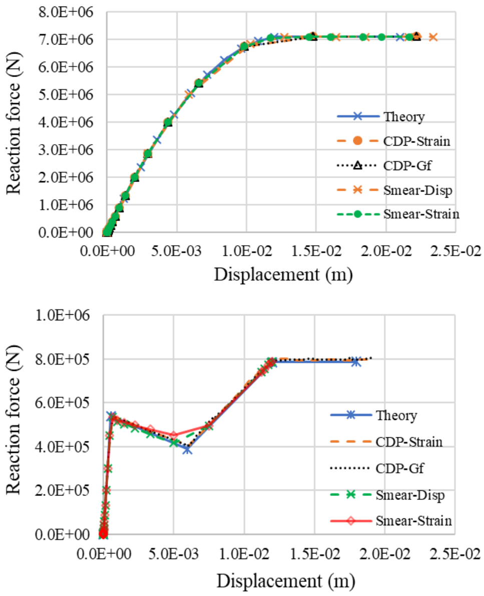


Figure 4: Pushover curve in compression (left) and tension (right)

Thirdly, the effect of mesh size is investigated. It is well known that the modeling of the tensile behavior of concrete cracking through a smeared-cracking approach, as the one typically adopted in most analyses and also considered here, leads to a dependency of the strain definition on the mesh (Cervenka, et al., 1990; Feenstra & De Borst, 1995). Furthermore, limits on the maximum and minimum allowed mesh size arise from interaction with the steel and consistency with the elastic and plastic phase definition of the materials (Carstensen, et al., 2013). The minimum limit is particularly challenging to respect, as it hinders an accurate meshing of the concrete rebar cover and, in general, a good representation of the stress distribution along the section, which, in turn, lead to lack of accuracy in the estimate of the capacity.

The effect of the mesh is shown on the top chart of Figure 5, where the bending capacity of the beam under distributed vertical loads is obtained by means of a static incremental analysis. The bottom chart of Figure 5 reports instead a comparison between the analytically calculated capacity and that obtained with the most appropriate mesh in Abaqus and in Diana. Both numerical models show a little overestimation of the capacity, but are capable of predicting the overall behavior of the beam in bending and are deemed sufficient to be used for further simulation under accidental actions.

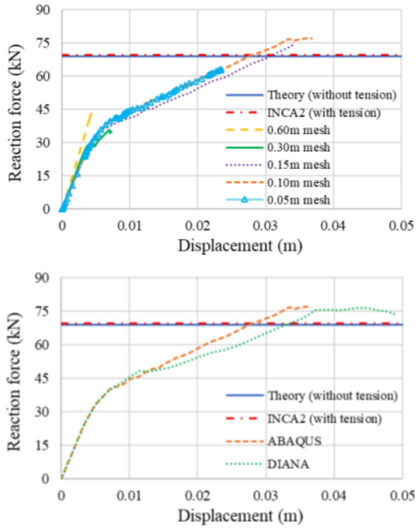


Figure 5 Pushover of the beam in negative bending. Top: Calibration of the mesh; bottom: validation of the two numerical models

Essential References

Bontempi, F. & Malerba, P., 1997. The role of softening in the numerical analysis of R.C. structures. Structural Engineering and Mechanics, 5(6), pp. 785-801.

Carstensen, J., Jomaas, G. & Pankaj, P., 2013. Element Size and Other Restrictions in Finite Element Modeling of Reinforced Concrete at Elevated Temperatures. Journal of Engineering Mechanics, Volume in press.

Cervenka, V., Pukl, R. & Eligehausen, R., 1990. Computer Simulation of Anchoring Technique in Reinforced Concrete Beams. Computer Aided Analysis and Design of Concrete Structures, 1(1), pp. 1-21.

Feenstra, P. & De Borst, R., 1995. Constitutive Model for Reinforced Concrete. Journal of Engineering Mechanics, 121(1), pp. 587-595.

L.A. NOW, 2011. Tanker explosion could bring days of freeway traffic gridlock. [Online] Available at: https://latimesblogs.latimes.com/lanow/2011/12/tanker-explosion-could-bring-days-of-freeway-traffic-gridlock.html [Accessed 21 March 2022].

Mail Online, 2018. Demolition workers finally remove more than 1,000 burnt-out vehicles worth £20m from a torched car park almost a year after New Year's Eve blaze. [Online] Available at: https://www.dailymail.co.uk/news/article-6419171/Work-begins-demolish-Liverpool-car-park-destroyed-New-Years-Eve.html [Accessed 27 January 2019].

Qin, D. et al., 2022. A comprehensive review on fire damage assessment of reinforced concrete structures. Case Studies in Construction Materials, v.16.

Bitumen – a difficult product for university laboratories

Ove Njå
University of Stavanger (UiS)
Stavanger, Norway
ove.njaa@uis.no

Jarle Berge
University of Stavanger (UiS)
Stavanger, Norway
jarle.berge@uis.no

Guzman Cruz Rodriguez
University of Stavanger (UiS)
Stavanger, Norway
guzman.cruz@uis.no

Keywords:
Bitumen; laboratory health and safety; experiments; occupational health; vapor and aerosol exposure; uncertainty

Abstract
This article addresses uncertainties in university laboratories as an important feature to consider in the safety management system. An incident with bitumen heating at a university laboratory implied vapor and aerosol exposure for employees and students. The article is based on a literature review, observations and interviews with the industry involved with bitumen-based products. Universities, like the University of Stavanger are stating visions such as; "challenging the well-known and exploring the unknown", meaning that being innovative is a paramount value of the university. Being successful in this respect might overshadow sound safety precautions at laboratories, and we will exemplify this with the "well-known" substance, bitumen.

Bitumen
Bitumen has been exploited for many decades, obtained from non-destructive vacuum distillation of crude petroleum oil. It is black or brown solid or viscous liquid. Bitumen is a complex mixture of naphthenic, aliphatic and/or aromatic hydrocarbons and heterocyclic compounds containing sulphur, nitrogen and oxygen [1]. The application areas vary from pavement and asphalt layers to construction materials needed for water protection. These applications raise interesting issues for technical university programs involved with the bitumen value chain. At the University of Stavanger these programs are related to the petroleum technology studies, civil and mechanical engineering studies and material technology studies.

University laboratories need access to hazardous substances in their educational activities. The laboratory engineer faces numerous goods of which they need to know associated risks, both related to acute events as well as long term health conditions. Data sheets are important documentation, but this information might be poorly founded, it might not cover the products being processed or it might be neglected by laboratory personnel. There are many challenges, to which job safety analyses could be powerful tools.

Laboratory tasks
The University of Stavanger has many and varied tasks related to bitumen. Some student projects are as follows, partly or entirely executed by laboratory technicians:

- Fraass fracture point (cf. Norwegian Public Road Administration handbook – R210) – is the temperature at which bitumen reaches critical stiffness and breaks. The treatment includes heating of the bitumen binder and working with the material.
- Softening point (R210) is the temperature which a binding material reaches a specific yield strength, under standardize conditions. Again, bitumen is heated.
- Needle penetration of bitumen. The goal of this test is to identify strength responses, under varying loads, temperatures and time scales. These tests are often connected with Fraass fracture and softening points.
- Production and compressing asphalt. Test samples are prepared for Marshall stroke compressions.
- Tensile strength of bituminous materials.
- Identifying bitumen contents of various asphalt samples. The samples are placed in a preheated combustion chamber (>500 ºC), and burnt.
- Bachelor and masters study projects are mostly related to development and testing new construction materials partly based on bitumen-based products, for example asphalt with recycled plastic granulate or paving stones with bitumen-based sealing compounds.

For most laboratories the work on bitumen is an integral part of the total activities involving students, technicians, researchers and supervisors. It could be a highly complex organization with simultaneous activities that might hold hazardous substances produced in an environment with significant uncertainties.

Uncertainty in laboratory works

There are uncertainties present. Uncertainties are often suppressed and given less attention in the laboratory's daily work. The uncertainties could inter alia be based on lack of scientific knowledge, system complexity, erroneous data or insufficient working procedures. Working with bitumen raises concerns about health effects, especially within a university laboratory that consist of confined spaces with sometimes unclear ventilation conditions.

In an effort to go deeper into a more basic understanding of uncertainty our knowledge is quickly challenged. What exists? How do we know what exists? What can we know about it? Aiming these questions at uncertainty reveals that interpreting uncertainty as existing in any ontological sense is difficult to defend. In the laboratory setting working with uncertainty should be connected with the strength of knowledge, which is related to those involved in the activities holding uncertainty.

State of the art – uncertainties of bitumen exposure

Bitumen is a commercial product involving interests that might be seen as biased. Secrecy related to composure, product development and the activities at the various production sites enhances uncertainties. There seems to be an influence in the scientific works as well, with unclear conclusions and often understudied phenomena. A critical review of literature addressing health effects is Kriech et al [2], who concludes: "As part of our analysis, modified Klimisch 'quality' ratings have been adapted and assigned to each of the reviewed human mechanistic studies (Supplemental materials), resulting in only a limited number being considered adequate for assessing the genotoxicity potential of bitumen or bitumen emissions".

Below we present some important findings from the literature:

Bolliet et al found that: "Results showed that composition of bitumen emissions is influenced by temperature under studied experimental conditions. A distinction between the oxidized bitumen with flux oil (industrial specialty bitumen) and the remaining bitumens was observed. Under typical temperatures used for paving (150 ºC –170 ºC), the total organic matter (TOM) and polycyclic aromatic compounds (PAC) concentrations in the emissions were low. However, bitumen with flux oil produced significantly higher emissions at 230ºC, laden with high levels of PACs. Flux oil in this bitumen mixture enhanced release of higher boiling-ranged compounds during application conditions. At 200ºC and below, concentrations of 4–6 ring PACs were ≤6.51 µg/m3 for all test materials, even when flux oil was used." Emission temperature-process relationships are important to guide industry decisions to reduce worker exposure during processing and application of hot bitumen [3].

Exposure to vapours and aerosols of bitumen induce an inflammatory response on the lower airways [4].

Van Thriel & Marchan [5] summarized the human bitumen study with the following statements:

- Bitumen exposure did not cause genotoxicity but subchronic inflammation of the upper airways.
- Quantification of bitumen-derived matter in aerosols still remains a challenge. Differences in sampling and analytical methods should be considered.
- Processing temperature of bitumen is critical for exposure. Therefore, reducing the processing temperature represents an efficient protective measure.
- Urinary levels of polycyclic aromatic hydrocarbons (PAHs) are only of limited value when it comes to the biomonitoring of bitumen-exposed workers, because (1) the PAH content of bitumen is relatively low, (2) cigarette smoking has a strong influence, and (3) additives are increasingly used in asphalt mixtures.
- Overall, it is unlikely that bitumen exposure at the workplaces causes DNA damage
- Bitumen exposure did not cause a relevant increase in micronucleus frequencies in peripheral blood lymphocytes of workers

Schulte claims that uncertainties should not preclude appropriate public health actions to protect workers in the event that asphalt fumes are found to be a carcinogenic hazard [6]. It is a challenge to university management to provide open and unprejudiced decision processes addressing laboratory health and safety.

Concluding remarks on how to deal with uncertainties in laboratories

The incident with bitumen heating that implied vapor and aerosol exposure raised discussions. The event was the starting point of the study, but our concern was the strength of knowledge related to bitumen experiments. The scientific data and how this is acknowledged in procedures and incident investigations are part of the uncertainty picture. Uncertainty as a concept is related to strength of knowledge, but it contains other aspects as well, both reducible and irreducible features. This paper discusses uncertainty aspects using bitumen as an example.

References

1. Health Council of the Netherlands, *Bitumen (vapour and aerosol) : Health-based recommended occupational exposure limit*. Gezondheidsraad. Vol. 2007/01OSH. 2007, The Hague: Committee of the Health Council of the Netherlands.
2. Kriech, A.J., et al., *Assessing cancer hazards of bitumen emissions - a case study for complex petroleum substances.* Crit Rev Toxicol, 2018. **48**(2): p. 121-142.
3. Bolliet, C., et al., *Effect of Temperature and Process on Quantity and Composition of Laboratory-generated Bitumen Emissions.* J Occup Environ Hyg, 2015. **12**(7): p. 438-449.
4. Raulf-Heimsoth, M., et al., *Irritative effects of vapours and aerosols of bitumen on the airways assessed by non-invasive methods.* Arch Toxicol, 2011. **85**(Suppl 1): p. 41-52.
5. Van Thriel, C. and R. Marchan, *The human bitumen study hits the headlines.* Arch Toxicol, 2012. **86**(12): p. 1803-1805.
6. Schulte, P.A., *Gaps in Scientific Knowledge About the Carcinogenic Potential of Asphalt/Bitumen Fumes.* J Occup Environ Hyg, 2007. **4**(sup1): p. 3-5.

Risk assessment and CFD simulations of fire propagation in enclosed parking facilities

A numerical study based on risk assessment and with focus on CFDsimulations utilizing experimental data.

Daniel Gunge Johansen Christoffersen Eriksen
Fire Safety Engineer
MOE
Søborg, Denmark
daer@moe.dk

Pascall Qvistgaard Christensen
Fire Safety Engineer
MOE
Søborg, Denmark
pqch@moe.dk

Frank Markert
Associate Professor
DTU Civil Engineering
Department of Design & Processes
Technical University of Denmark
Kgs. Lyngby, Denmark
fram@byg.dtu.dk

Keywords: *FDS – Parking – Modern vehicles – Pyrolysis model*

Abstract

In the recent years, numerous fire incidents in parking facilities are reported, causing immense damages. Both by an increased number of involved vehicles and structural damages on the facilities. In the same period, the vehicle industry has undergone somewhat of a revolution.

Noncombustible materials are replaced with lightweight alternatives that are often much more combustible, while at the same time the dimensions of the vehicles have increased. Furthermore, new fuel types are introduced to keep up with a more environment friendly society. However, several building codes have not followed this evolution and are still based on decades old standards [1]. Especially when it comes to enclosed parking facilities smaller than 1,000 m^2, the Danish codes only prescribe few requirements to limit fire spread. Thus, the aim of this master thesis project [2] has been to investigate the effect of additional fire protection measures to minimize the risk of high consequence fires.

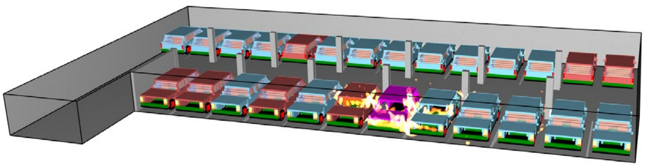


Figure 1: Flame spread in one of the simulated scenarios.

The work of this project has investigated, how the implementation of various fire safety measures effected the consequences, and risks of fire propagation in such enclosed parking facilities. The selected safety measures included sprinklers, mechanical and natural exhaust systems, mechanical fire ventilation and flame shields. The design dimensions and parameters were primarily based on the current Danish legislation [3]. This was done by conducting an initial qualitative risk assessment, to determine which scenarios of the different safety measures would be most relevant to evaluate, by means of expected consequences. The selected scenarios were then simulated in FDS, using a complex vehicle model that was developed, verified and validated, especially for the simulations.

Subsequently, the scenarios were evaluated to quantify the amount of destroyed concrete slabs and directly involved vehicles. These consequences were then used to reevaluate the risk assessments by quantitative measures, as the consequences were more precise. From this, it was possible to compare the different fire safety measures by their risk levels and assess which provided the most effective results.

From the simulations of the base layouts, it was found, that the extent of the fires was dependent on the vehicle loads. It was observed that the base scenario with maximum vehicle load resulted in a fire, with a possible spread to all vehicles. Moreover, it was observed, that the maximum vehicle load in the base layout resulted in significant consequence levels, that possibly could lead to structural collapse. Based on the quantitative risk assessment, it was found, that implementing an automatic fire sprinkler system resulted in the greatest reduction of risk levels. The automatic fire sprinkler systems were able to contain the fire to involve a maximum of four vehicles and was not as dependent on the vehicle load as the base scenarios.

The implementation of flame shields did also show promising reductions of the expected risks. Indications of domain and layout dependencies were observed, thus limiting the conclusiveness of the findings. The automatic fire sprinkler system and flame shields reduced the risk levels to approximately a fifth and a third of the base layout, respectively. Implementation of fire protection measures, where the degree of ventilation was increased, resulted in greater extent of the fires. The fires involved more vehicles and propagated at greater rates, compared to the base scenarios. Ultimately, the risk levels were higher than in the base scenarios.

Temperature profiles at expected times of arrival of the fire services were evaluated. The conditions were found to be inadequate for entry in the base scenarios and scenarios

with increased degree of ventilation. The conditions in the scenarios with a sprinkler system or flame shields were found to be more favorable.

Summary of validation and verification study

The simulation models were initially verified on a sub-level and as complete models. The sub-level verification was carried out by a sensitivity study of each implemented sub-model, where the behavior of the pyrolysis sub-models was analyzed in mesh resolutions of 25 mm, 50 mm, 100 mm and 200 mm. The prescribed (ramp controlled) sub-models were verified against input values in mesh resolutions of 100 mm.

It was found in the verification studies, that the pyrolysis sub-models performed with a mass error of maximum 0.1 %, an energy budget error of maximum 3.25 % and a heat release error with a maximum error of 3 % with respect to the input values, corresponding bulk densities, in a mesh of 100 mm cubic cells.

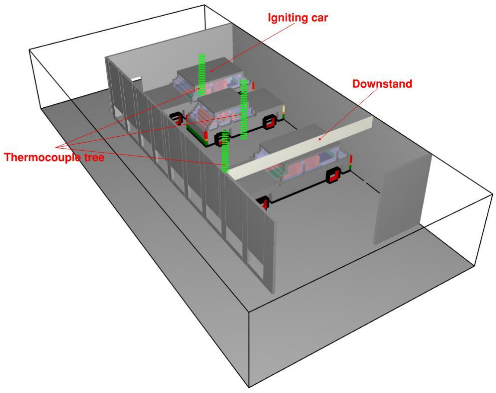


Figure 3: Simulated domain in the validation studies [2] of BRE Tests, recreated from [4]. Green dashed lines are depictions of thermocouple trees.

The prescribed sub-models were verified with a maximum heat release error of 0.4 % in the 100 mm mesh, and with outputted HRR curves being almost identical with the input ramps. It was found that the mass errors determined for the sub-models are in fact scalable to the full vehicle, with mass errors of maximum 0.4 %.

In a validation study against physical, full-scale experimentation carried out by [4], involving fire spread between vehicles the simulated flame spread characteristics, multivehicle PHRR and growth rate was validated during the stages of fully involved fires. Parameters as growth rate, time for ignition and temperature were captured in great similarity with the experimental data. However, the mesh resolution showed incapable of capturing local flame spread within the cabin of the igniting car, which was deemed acceptable due to the scope of the project being related to the flame spread between vehicles – which was recreated sufficiently.

Implementation of sprinklers in the simulation produced fires being controlled at similar levels as the experimental results. Furthermore, the initial part of the decay phase was reproduced in great similarity for sprinklers with activation temperature of 141 °C. Near flame temperatures were reproduced in correspondence to the experimental data during the fully involved fire stages. The peak temperature of the hot gas layer was determined to be exaggerated in the FDS sprinkler simulations by approximately 70 °C 80 °C.

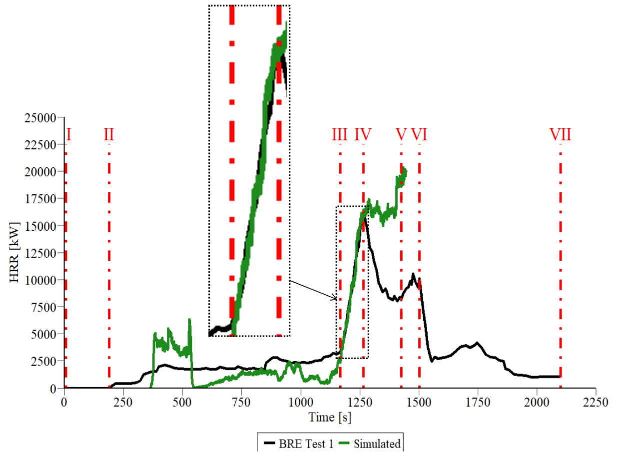


Figure 2: HRR curve from BRE Test 1, reproduced from Figure 2.9.2 in [4] (black), along with simulated data [2] (green).

What has happened since the publication of the thesis?

Since the publication of the thesis that this paper is based on, a large research paper publicized by the National Housing and Planning Agency [5]. The report is done as literature research on the newest studies in the experimental fields of vehicle fires, lithium-ion battery fires and reports from actual fires involving vehicles in parking facilities. The recommendations and conclusions are clear, of those are the following, relatable to this paper and the thesis behind it (freely translated from [5]):

- *"Fire ventilation is not necessarily a useful fire technical installation to prevent fire spread between vehicles."*
- *"A single burning vehicle with a high HRR is not necessarily critical in for parking structures, however, the greater HRR is contributing to fire spread rapidly will become critical.*
- *"The risk of fire spread between vehicles must be lowered. Sprinklers are the most effective and should be used for parking structures greater than 150 m^2.*
- *"It is the entire fleet of vehicles, and not only electrical vehicles, but that also give rise to a reconsideration of the guidelines for fire protection of parking structures."*

All the above conclusions and recommendations are greatly in line with the conclusions and considerations made in the thesis behind this paper.

References

[1] [Klassen, 2020] Modern Vehicle Hazards in Parking Structures and Vehicle Carriers. (July), 60. https://www.nfpa.org/News-and-Research/Data-research-and-tools/Building-and-Life- Safety/Modern-Vehicle- Hazards- in- Parking- Garages- Vehicle-Carriers

[2] [Eriksen, D., et. al, 2021] Eriksen, D., Christensen, P. and Markert, F. Master thesis: Risk assessment and CFD simulations of fire propagation in enclosed parking facilities.

[3] [BR 18, 2022] *Bygningsreglement 2018*. Trafik-, Bygge- og Boligstyrelsen. (Version: 1/1 2022).

[4] [BRE, 2010] Fire spread in car parks BD2552 (tech. rep.). Department for Communities and Local Government. London.

[5] [DBI, TI, 2022] DBI (Dansk Brand- og sikringsteknisk Institut) og TI (Teknologisk Institut). Brandsikkerhed i garageanlæg, oplag af litium-ion batterier og batterier til solcelleanlæg i bygninger. Dato: 2022-01-14 Version: 02.

Production of heat and harmful products from cooktop fires and overheated materials

Simo Hostikka
Emmanuelle Castagnoli
Rahul Kallada Janardhan
Rauli Törrö
Tarique Jhatial
Raimo Mikkola
Heidi Salonen

Department of Civil Engineering
Aalto University
Espoo, Finland
simo.hostikka@aalto.fi

Keywords: (5 key words)
cooking, kitchen fire, electric cooktop, smoke toxicity, overheating

Abstract
Cooking -originated fires form a significant fraction of all home fires or fire dangers. Many of these fires are detected and intervened before the fire spreads outside the close vicinity of the cooktop. In such situations, fire services need to decide if the occupants can stay in the apartment or if they should temporarily leave elsewhere but they are lacking means to estimate life safety after small fires or overheating accidents.

In this work, we measured the ignition and burning characteristics of common food and kitchen items. Produced smoke was collected in a 10 m^3 test room. Concentrations of various gases were measured continuously using Fourier Transform Infrared (FTIR) method and, after a mechanical ventilation, the polycyclic aromatic hydrocarbons (PAHs), volatile organic compounds (VOCs) and carbonyl compounds were measured using active sampling. This presentation shows the experimental method and preliminary results.

Introduction
Half of the US home fires were caused by cooktops in 2013-17 [1]. The Finnish statistics of cooktop fires are presented by Kuurne et al. [2]. Unattended cooking or forgotten materials are the most common reasons for cooktop fires.

Pyrolysis and combustion of cooking substances and kitchen appliances has been found to produce high concentrations of hazardous chemicals and particles [3][4]. Harmful or carcinogenic gases are commonly found, such as formaldehyde, benzene, and polycyclic aromatic hydrocarbons (PAHs) [5][6].

Because stovetop fires are often limited to a part of the apartment, many occupants can stay in their homes once the apartment is ventilated. The lack of information on the quality of the post-fire indoor air means that occupants may unknowingly be exposed to dangerous levels of chemicals. More information is needed to help the rescue services decide whether staying in the household is safe for its occupants.

Materials
Thermal characteristics of three different electric cooktops were first characterized: electric coil (Rosenlew), ceramic glass (Rosenlew) and induction (Electrolux), both alone and with cast iron, carbon steel, or aluminum pans.

Food materials included olive, canola and sunflower oil, sausage, fish fingers, and minced meat. Solid kitchen materials were pizza box, paper towel, Low-density polyethylene bags, and potholders.

Experimental method
Cooktop and (empty) frying pan temperatures were measured with 0.5 mm thermocouples and Infrared camera, along with the time-dependent power consumption of the cooktops. Ignition times of different items were then recorded, and heat release rates measured by leading the fire effluents to the exhaust duct of an ISO 5660 cone calorimeter.

Gas concentrations were measured in a 10 m^3 test room with aluminum paper surfaces, controllable mechanical ventilation, and a mixing fan. Test consisted of 15 min to 60 min heating period, 16 min ventilation (four air exchanges) and post-ventilation gas sampling period, during which the room was closed. During the room tests, we measured cooktop and gas temperatures, continuous gas temperatures using FTIR analyzer. The post-ventilation samples were collected through pipes inserted through the room walls. The samples were analyzed by a certified laboratory. The VOCs were sampled for 20 minutes at 0.100 mL/min (Tenax TA-Carbograph 5 TD) and analyzed with thermal desorber-gas chromatography-mass spectrometry (TD-GC-MS). Compounds were identified from pure reference standard, and NIST and WILEY libraries. Concentrations were reported as toluene equivalent. The limit of quantification (LOQ) was on average 4 ng/sample. Carbonyls were collected for 30 minutes at 1 L/min (DNPH-Silica cartridge). Thirteen carbonyls were analyzed with HPLC-UV according to ISO 16000-3:2011 (LOQ 3 µg/m^3, LOD 1 µg/m^3).

Results
In general, the frying pan peak temperatures were higher with electric coil and ceramic glass cooktops, but the induction

cooktop produced faster response and highest temperatures with aluminum pans. Fig. 1 below shows the measured peak temperatures for plain cooktops (half and maximum power) and three different pans at three types of cooktops.

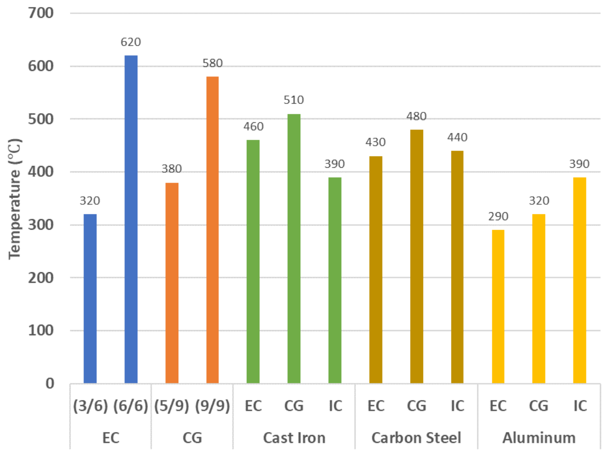


Figure 1. Cooktop and frying pan peak surface temperatures. EC=electric coil, CG=glass ceramic, IC = induction cooktop. Full power was used with the pans.

Post-ventilation concentrations of airborne carbonyls are shown in Table 1 for minced meat, fish fingers and canola and sunflower oils. Formaldehyde, acetaldehyde, acrolein, and hexaldehyde accounted for the highest single carbonyl emissions. Over 60 % of the total carbonyl emissions originated from substances classified from possibly carcinogenic to carcinogenic to humans [7].

Table 1. Post ventilation concentrations of carbonyls with IARC classifications [7].

compounds		IARC group *	concentration (μg/m³)			
			minced beef	fish fingers	canola oil	sunflower oil
formaldehyde	C1	1	95	87	82	83
acetaldehyde	C2	2B	110	75	53	51
acrolein	C3	2A	60	33	95	140
propionaldehyde	C3	-	0	21	28	27
acetone	C3	-	52	31	21	14
crotonaldehyde	C4	2B	< 3	14	7.4	5.2
butyraldehyde	C4	-	47	15	16	19
methacrolein	C4	-	6.1	0	0	0
2-butanone	C4	-	19	10	6.6	6.9
valeraldehyde	C5	-	30	12	23	30
hexaldehyde	C6	-	33	35	60	95
benzaldehyde	C7	-	7.6	19	8.2	8.7
3-methylbenzaldehyde	C8	-	0	0	0	0
Total			462.7	352	400.2	479.8

Total volatile organic compounds (TVOC) concentrations from the same materials varied between 900 and 1900 μg/m³. A large proportion of TVOC concentrations originated from hydrocarbon mixture (630-920 μg/m³) and/or mixture of unidentified compounds (55-370 μg/m³).

Conclusions

The IARC has classified formaldehyde, acetaldehyde and acrolein from possibly carcinogenic to carcinogenic to Humans. All of them were found from the gaseous products of overheated oils and food. Although the indoor air concentration of formaldehyde below 100 μg/m³ (0.08 ppm, for a 30-minute period) are thought to prevent the risk of irritations and cancer among general population [8], for sensitive groups of people, much lower levels may cause health effects [9].

The Finnish residential health guide has set an action limit for TVOC at 400 μg/m³. Here, the TVOC concentrations were 2 to 5 times higher than the action limit. TVOC concentration above the action limit are not indicative of a health risk but suggest that preventive measure should be applied to eliminate or limit the exposure to possibly dangerous chemicals. A large portion of VOCs were classified as hydrocarbon mixture or unidentified compounds. It is impossible to exclude that some dangerous compounds were classified under these categories. In general, concentrations of single compounds were low except for some compounds whose emissions exceeded the action limit for single compounds set to 50 μg/m³.

Acknowledgements

This research was funded by the Finnish Fire Protection Fund (Palosuojelurahasto). Otto Hedström and Janne Hostikka are thanked for assistance in building the test kitchen. Thanks to Juha Laitinen and Marjaleena Aatamila of the Emergency Services Academy Finland for their guidance during the design of these experiments.

References

[1] Tam, W. C., Fu, E. Y., Mensch, A., Hamins, A., You, C., Ngai, G., & Leong, H. va. (2021). Prevention of cooktop ignition using detection and multi-step machine learning algorithms. *Fire Safety Journal*, *120*, 103043. https://doi.org/10.1016/j.firesaf.2020.103043

[2] L. Kuurne, J. Lepistö, T. Ojala. "The overall picture of stove fire incidents in Finland and factors endangering stove safety", submitted to Nordic Fire and Safety Days 2022.

[3] Alves, C., Vicente, A., Oliveira, A. R., Candeias, C., Vicente, E., Nunes, T., Cerqueira, M., Evtyugina, M., Rocha, F., & Almeida, S. M. (2020). Fine Particulate Matter and Gaseous Compounds in Kitchens and Outdoor Air of Different Dwellings. *International Journal of Environmental Research and Public Health*, *17*(14), 5256. https://doi.org/10.3390/ijerph17145256

[4] Sjaastad, A. K., & Svendsen, K. (2009). Exposure to Polycyclic Aromatic Hydrocarbons (PAHs), Mutagenic Aldehydes, and Particulate Matter in Norwegian à la Carte Restaurants. *The Annals of Occupational Hygiene*, *53*(7), 723–729.

[5] Atamaleki, A., Motesaddi Zarandi, S., Massoudinejad, M., Esrafili, A., & Mousavi Khaneghah, A. (2022). Emission of BTEX compounds from the frying process: Quantification, environmental effects, and probabilistic health risk assessment. *Environmental Research*, *204*, 112295. https://doi.org/10.1016/j.envres.2021.112295

[6] Zhao, Y., Liu, L., Tao, P., Zhang, B., Huan, C., Zhang, X., & Wang, M. (2019). Review of Effluents and Health Effects of Cooking and the Performance of Kitchen Ventilation. *Aerosol and Air Quality Research*, *19*(8), 1937–1959.

[7] IARC. (2021). *IARC Monographs on the Identification of Carcinogenic Hazards to Humans*.

[8] WHO regional office for Europe. (2010). *WHO guidelines for indoor air quality: selected pollutants*. http://www.euro.who.int/en/health-topics/environment-and-health/air-quality/publications/2010/who-guidelines-for-indoor-air-quality-selected-pollutants

[9] Salonen, H., Pasanen, A.-L., Lappalainen, S., Riuttala, H., Tuomi, T., Pasanen, P., Bäck, B., & Reijula, K. (2009). Volatile Organic Compounds and Formaldehyde as Explaining Factors for Sensory Irritation in Office Environments. *Journal of Occupational and Environmental Hygiene*, *6*(4), 239–247.

Evacuation strategy – matching the building

Programming the fire alarm system to fit nursing homes, case study

Aldis Run Larusdottir
EFLA consulting engineers
Reykjavik, Iceland
aru@efla.is

Keywords: Nursing home, evacuation strategy, fire alarm system, phased evacuation.

Introduction

In Iceland nursing homes require an automatic fire alarm to be installed [1]. Preferably there should also be a sprinkler system, but that is not mandatory in all cases. The fire alarm system is used to detect a fire and alarm occupants, but also to control related systems, typically shutting down the ventilation system and closing fire dampers and to close fire doors that are held open. It is mandatory for the fire alarm system to be according to relevant standard [2] and guidance documents [3] and to be connected to a security company that has a 24/7 service.

In the past there has been little focus on forming customized evacuation strategies for individual nursing homes and the common procedure has been to have the fire alarm of the whole building going off on detection and then all shall evacuate. This, however, can cause unnecessary trouble in case of false alarms, which can be avoided without compromising safety, even in the case of a real fire.

Case study

The assignment in this case was to make escape plans, evacuation strategy and assist with introducing it and implementing the evacuation strategy.

The building is quite complex and does in fact consist of several connected buildings. Figure 1 shows the layout of floor 4 in the building. The use of it varies and includes individual apartments/rooms to assembly rooms, kitchen, services such as a hairdresser, physiotherapy, group rooms etc. At last, the occupants have very different mobility as well as cognitive skills, which again makes forming the evacuation strategy a more complex task.

It soon came to light that the fire alarm system was programmed for a total evacuation on first detection, no matter in which part of the building the detection occurred. At the same time all ventilation systems were to turn off and close fire dampers and all fire rated doors, which were held open by magnets were set to close. This total evacuation on the very first smoke detection did not suit the building or its functions and therefore the assignment of forming the evacuation strategy grew to also accommodate a new programming manual for the fire alarm system. This would enable the evacuation strategy to base on a phased evacuation and even have some delays built in, minimizing unnecessary evacuations in case of false alarms.

Figure 1. Layout of floor 4 in the building.

Results

The assignment is still in progress, but the idea is to share the approach and the end results in a conference presentation. To shed a light on the fact that it is important to look closely at the building and its users when forming an evacuation strategy and for the fire alarm system to technically support that strategy.

The road leading to this assignment will also briefly be described. For several years the frequent false alarms have undermined the occupants' believe in the system. Staff has been working hard to minimize the negative consequences and to reset the system as fast as possible to let everyone go on with their day.

Hopefully with a new evacuation strategy and a proper introduction to the staff and even some of the residents, the trust in the system will return. At the very least the workload on the staff will be less and focused on right place with more localized alarming during the first phase of evacuation.

References

[1] Icelandic Building Authority. Icelandic building regulation 2012 including later additions 1321/2021.
[2] ÍST EN 54-1: 2021 Fire detection and fire alarm systems-Introduction, 2021.
[3] 6.038 Guidance document on Fire alarm systems V01. Icelandic building autority, 2019.

Functional testing of ventilation systems in schools during activated fire alarm

Coherence with the fire safety strategy

Anne-Marit Haukø[1], Brynhild Garberg Olsø[1], Aileen Yang[1], Andreas Aamodt[1], Per Henning Samuelsen[2], Christoph Meraner[3]

[1]SINTEF Community, Trondheim/Oslo, Norway, [2]Oslobygg KF, Oslo, Norway, [3]RISE Fire Research, Trondheim, Norway

E-mail: anne-marit.hauko@sintef.no

Keywords:
Fire safety, ventilation system, schools, functional testing, smoke extraction.

Abstract

The purpose of this paper is to present results from functional testing of ventilation systems in schools during activated fire alarm. It was investigated whether the results had coherence with the ventilation strategy in the fire safety concept and the function description for the ventilation system.

Functional testing was performed at several schools in three different municipalities in Norway. Results from the preliminary mapping showed that some of the personnel responsible for maintenance of the ventilation systems lacked knowledge about the system's function during fire. Older schools often don't have a fire safety strategy at all, whereas newer schools and renovated schools normally have well documented fire safety strategies, including the ventilation system's function during fire. However, there is little or no information in the building's MOM-documentation (management, operation and maintenance) about how functional testing must be performed.

The functional testing showed several incoherencies with the fire safety strategy of the school buildings.

Introduction

This study is part of the research project BRAVENT– Efficient smoke ventilation of small fires, where it aims to use the existing balanced mechanical ventilation systems, such as ducts and non-fire rated dampers, including variable air volume dampers (VAV-dampers) to control smoke and pressure in the event of small-size fires in schools. Demand-controlled ventilation (DCV) can reduce building energy consumption while delivering good levels of occupant comfort [1]. DCV-systems automatically adjust the air flow rate according to a demand at room level measured by e.g., CO_2 and temperature sensors [2]. Separate ventilation networks are required for exhaust and supply air. Each ventilation network is equipped with a fan to control the total air flow rate. Depending on the configuration, a single fan may serve from several rooms to the entire building. Figure 1 shows the concept of the extraction strategy using the ventilation system. The principle is to increase the speed of the supply and exhaust air to full balanced mode in the event of a fire, so that smoke can be extracted out of the building while mitigating the fire-induced pressure. This concept, if it can be proven safe and effective, can be easily adopted to buildings equipped with balanced mechanical ventilation systems.

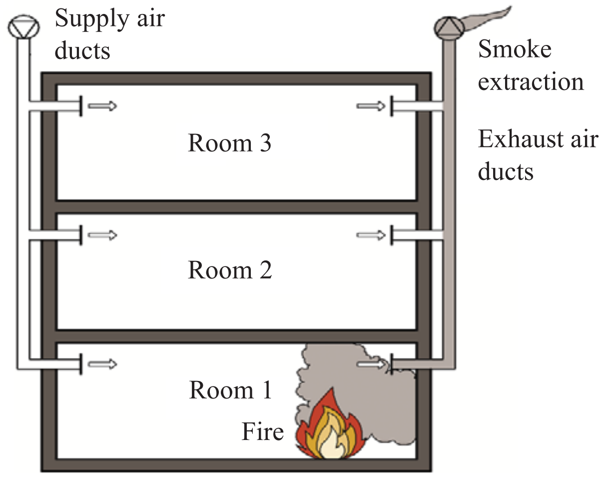


***Figure 1.** Schematic of the extraction strategy using the ventilation system (based on Byggforskserien [3]).*

The Norwegian Building Code is performance-based and sets functional requirements for buildings [4]. Technical installations like the ventilation system, shall be designed and perform in such way that the system does not increase the risk of a fire starting and that fire and smoke are spreading. The companies responsible for building design and construction are responsible for providing documentary evidence of the fire safety. A fire safety strategy is created during the design phase of the building project and describes a main strategy for the ventilation installation.

Methods

To assess whether the extraction strategy can be applied to the existing ventilation systems in schools to handle smoke control for small-sized fires, the first step was to perform a mapping of the fire safety strategies for each school and get an overview of how the ventilation systems in school buildings operate in the event of a fire. Functional tests were done to check if the ventilation system were operating in coherence with the fire safety strategy and the function description for the ventilation system. Functional testing procedures of the ventilation system were developed to investigate if the system functions according to the fire safety strategy. Functional tests were performed in schools in the municipalities of Oslo, Bergen and Trondheim, Norway.

The strategy for functional testing of the ventilation systems included an interview with the operation officer on site, who is responsible for technical maintenance and inspection routines at each school. The purpose of the interview was two-folded; to get overall information about the ventilation system before the functional testing was performed, and to map how familiar each operation officer was with the ventilation system and how well they knew the fire safety and ventilation strategy for the building.

The ventilation system was tested in day mode and night mode, including triggering the smoke detector in the supply air duct to verify if the air handling unit (AHU) stopped. Triggering was executed during normal operation as well as when the fire alarm was already on. The functionality of randomly chosen VAV-dampers and fire dampers was verified by visual inspection upon activated fire alarm.

Results and discussion

The year of construction varied for the schools included in this project and some were also renovated in the later years. Most of the schools included in the functional testing were designed with an extraction strategy, which implies that the normal operation mode of the ventilation system changes to smoke control mode when a fire is detected in the building. This extraction strategy usually includes a bypass fan for the extraction air to ensure safe operation, which prevents hot smoke from passing through filters and regenerators. However, the bypass fan was not present in many of the ventilation systems that were investigated. A few of the schools included in the mapping had a shutdown strategy, where the ventilation system stops, and fire dampers, installed in the ventilation ducts passing through compartmentations, close.

The preliminary mapping showed that some of the personnel responsible for maintenance of the ventilation systems lacked knowledge about the system's function during a fire. For example, they were not sure whether there were fire dampers installed or not, or whether the ventilation system would stop when activating the fire alarm or not. This shows that there may not be enough focus on the topic when it comes to operation and maintenance routines in schools.

Older schools often don't have a fire safety strategy at all, and there is no documented strategy for the ventilation system during fire either. Newer schools normally have well documented fire safety strategies, including the ventilation system's function during fire. However, there is little or no information in the buildings' MOM-documentation about how functional testing must be performed.

The functional testing showed several incoherencies with the fire safety strategy of the school buildings, including:

- VAV-dampers not going in open position
- Opening of supply air and exhaust fan does not start simultaneously, causing unbalance in the extraction strategy
- Delayed/slow start of the supply and exhaust fans, which will disturb the balance and the smoke control
- AHU does not restart during night-mode
- VAV-dampers located in the ducts are not affected by the fire alarm
- The extraction function shuts down the supply air and gears down the exhaust air to 20 %
- After test termination, the AHUs must be physically restarted in the technical room, they cannot be restarted through the central control and monitoring system
- Smoke detection in the supply air gives no signal to the central control and monitoring system or the fire alarm system

The reason for the incoherencies is unknown, but a possible explanation is that the systems are not sufficiently tested after installation.

Conclusion

The functional testing showed several incoherencies with the fire safety strategy of the school buildings. The results indicate that there is a need for better documentation on how the "as built" ventilation system is performed compared to the design solutions given in the fire safety strategy. Clear guidelines for functional testing should be established and implemented in the MOM-documentation.

Acknowledgements

This study is a part of the project "BRAVENT – Efficient smoke ventilation of small fires", and is funded by the Research Council of Norway, project number 321099.

References

[1] M.-L. Maripuu. Demand controlled Ventilation (DCV) Systems in Commercial Buildings: Functional Requirements on Systems and Components. PhD thesis at Chalmers University of Technology. 2009.

[2] M. Mysen et al. (2010) Robustness and True Performance of Demand controlled ventilation in Educational Buildings – Review and Needs for Future Deevelopment. Proceedings, 31st AIVC Conference, "Low Energy and Sustainable Ventilation Technologies for Green Buildigns", Seoul.

[3] SINTEF Byggforsk. Byggdetaljer 520.352, Brannsikring og røyksikring av balanserte ventilasjonsanlegg. Byggforskserien. 2018.

[4] Direktoratet for byggkvalitet. Byggeteknisk forskrift, https://dibk.no/regelverk/byggteknisk-forskrift-tek17/. 2017

Evacuation Modelling of Indoor Playgrounds

Sveinbjörg Sara Baldursdóttir
Department of Fire and Safety
EFLA
Reykjavik, Iceland
ssb@efla.is

Keywords:
Children evacuation, evacuation time, movement time, indoor playground, maximum travel distance.

Abstract

This study was conducted for a master's degree from the department of civil engineering from the Technical University of Denmark.

Data regarding children's evacuation of indoor playgrounds is scarce as most data on children evacuation is obtained with experiments at schools and day-care centres [1, 2, 3, 4]. Furthermore, fire safety design of buildings that contain indoor playgrounds often fails to account for the characteristics of children. Major incidents can occur since playing equipment in indoor playgrounds are made of combustible material and therefore there is a need to investigate children's evacuation in indoor playgrounds. The key aim is to find out how the playing equipment in indoor playgrounds affect children's movement time. The secondary aim is to gain knowledge of the level of detail needed to gain reliable information about children's evacuation in indoor playgrounds, the effect the equipment has on the travel distance and the total evacuation time of both adults and children in indoor playgrounds.

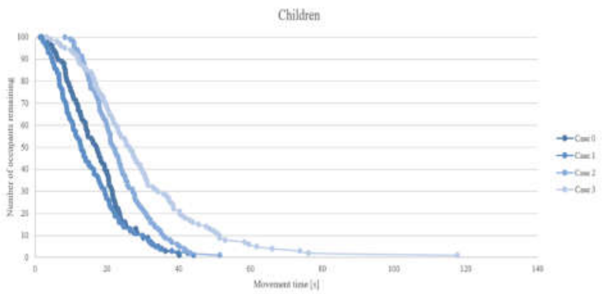


Figure 1. ***As the level of detail increases with each case, so does the children's movement time.***

Method

Information regarding pre-movement time, warning time, travel speeds and the geometry of an indoor playground was gathered. The evacuation computer model Pathfinder was used to model four cases to collect data about children's evacuation in indoor playgrounds. Case 0 represented no playing equipment and persons distributed randomly in the room. For Case 1, outlines of the playing equipment were added, and persons were randomly distributed outside the equipment. Case 2 was the same as Case 1, but persons were distributed randomly inside the playing equipment. The last case, Case 3, was most detailed. The playing equipment was fully modelled, and persons were randomly placed inside and around the equipment.

Results

The result was that the maximum movement time of children, evacuating from the playing equipment was more than three times the adult's maximum movement time from the hallways around the equipment. Figure 1 shows how the children's movement time increases as the level of detail increases with each case. Therefore, it can be concluded that the playing equipment affect children's evacuation in indoor playgrounds. Also, it was found out that detailed modelling of the equipment is needed in order to obtain the most realistic data. The maximum travel distance was then found to exceed the limit of 30 m, according to the Danish legislation, for all cases.

The total evacuation time depends greatly on the pre-movement time as it is about 60% of the total evacuation time. As pre-movement actions have not been investigated in indoor playgrounds, it is questionable whether the movement time should be optimised before the pre-movement time and therefore the searching time are researched as it only represents around 20% of the total evacuation time.

References

[1] A. R. Larusdottir and A. S. Dederichs, "A step towards including children's evacuation parameters and behavior in fire safe building design," Fire Safety Science, vol. 10, pp. 187–195, 2011.

[2] H. Najmanová and E. Ronchi, "An Experimental Data-Set on Pre-school Children Evacuation," Fire Technology, vol. 53, no. 4, pp. 1509–1533, 2017.

[3] A. Cuesta and S. M. V. Gwynne, "The collection and compilation of school evacuation data for model use," Safety Science, vol. 84, pp. 24–36, 2016.

[4] G. N. Hamilton, P. F. Lennon, and J. O'Raw, "Human behaviour during evacuation of primary schools: Investigations on pre-evacuation times, movement on stairways and movement on the horizontal plane," Fire Safety Journal, vol. 91, pp. 937–946, 2017.

Evacuation characteristics of people with alcohol-related impairment

Poulcheria Serafeim
Department of Civil Engineering
Technical University of Denmark
Kgs. Lyngby, Denmark
poul.ser@outlook.com

Artur Storm
RISE Research Institutes of Sweden
Västerås, Sweden
and
Department of Civil, Environmental and Natural Resources Engineering
Luleå University of Technology
Luleå, Sweden

Anne S. Dederichs
Department of Civil Engineering
Technical University of Denmark
Kgs. Lyngby, Denmark
and
RISE Research Institutes of Sweden
Lund, Sweden
anne.dederichs@ri.se

Keywords: Evacuation, alcohol, ship, nightclub

Abstract

The purpose of the current research is to study the behaviour of people with temporary impairments induced by alcohol intoxication during an evacuation process, from buildings, as well as from ships and ferries, broadening the population covered by safety practices. Contrary to the bars and nightclubs where the majority of the attendees are young people, on offshore premises such as ferries and cruise ships people consuming alcohol present a large range of age, culture and impairments. Thus, it is of crucial importance to include a heterogeneous population in the studies. In the current experiment, the aim was to hold in high regard the diversity of the population regarding physical and cognitive impairments, age and culture. A large-scale experiment is carried out in 2022. The findings of the first out of two parts will be presented at the Nordic Fire & Safety Days.

Introduction

Statistics show that fire incident numbers on ships have reached a plateau regardless of the prolonged efforts to develop regulations to eliminate their occurrence. Since 2014, 15 accidents with RORO ships, 14 with ordinary ferries and 15 with cruise ships have been documented [1]. In 2022 a fire on the Euroferry Olympia required a complete evacuation of 281 passengers near the Greek island Corfu [2].

One occupation on the cruise ships is alcohol intake, which may lead to temporary impairments. Studies carried out with permanent and temporary disabled people show that in case of emergencies these categories of people are more likely to suffer [3]. Thus, the need to create safe environments for heterogeneous populations is essential. Research and praxis have provided several studies dealing with evacuation during an emergency, including evacuation from ships [3],[4],[5]. However, there are no studies focused on the evacuation of mixed populations from ships and only a few studies on the evacuation of individuals under the influence of alcohol [6].

The average population of Sweden as described in Table 1, consists of 23% people aged below 19 and more than 25% aged above 60. However, the largest part of the studies so far has dealt with the evacuation characteristics of abled-bodied young adult groups [5]. Consequently, during the evacuation processes in emergency cases, there is a portion of people whose safety remains uncertain.

Table 1: Age distribution of population in Sweden 2021

Age	Number	%
0-19	2 414 374	23
20-39	2 695 902	26
40-59	2 611 707	25
60-79	2 113 592	20
80-99	541 271	5
>100	2 449	0.02

Cruises are a form of vacation that has been increasing in recent years, and for many passengers visiting nightclubs and the alcohol intake on board is part of their entertainment. Alcohol is considered a depressant since it slows down the function of the central nervous system and therefore normal brain functions are delayed. In the nightclub fires that occurred in the past years, many lives were lost[7]. One of the most recent cases is the Kiss nightclub fire in Brazil, which killed 242 people and left more than 600 injured.

The current work is based on two pilot studies. The first study aimed at investigating how alcohol consumption impacts the reaction and decision phase of an evacuation [6]. One focus was the determination of the efficiency of the notification methods. The experiment consisted of two reference experiments, where the participants were sober and two similar experiments conducted under the influence of alcohol (0.46 - 1.08 ppm).

- The two notification methods used in the experiments were verbal warning and tone alarm. The verbal warning experiment was conducted in a silent room and the participants were subjected to a spoken message.
- During the tone alarm experiment, music was playing in the room. The music was interrupted by the tone alarm.

The participants performed tasks and their concentration ability and evacuation characteristics when warned in different scenarios were examined. The participants were given partial information prior to the experiments. The information they had was that the effect of alcohol on evacuation behaviour was studied and that they had to carry out small exercises. 28 students with an average age of 22.5 years participated in the experiments conducted at the Technical University of Denmark.

All participants carried out both the reference and the alcohol experiments. The experiments were conducted in two rooms. The intake of alcohol was undertaken in the Drinking Room. Then the participants changed into the Experimental Room to carry out the exercises and the warning experiment. Reaction and decision time for these experimental conditions was measured, with respect to carrying out the exercises, reacting to the instructions in the Experimental Room and exiting the room.

No significant difference was seen in the measured reaction and decision time with respect to reaction to the warning and exiting the room when the participants were influenced by alcohol. However, a difference was found in the behaviour and the ability to maintain focus on the assignments, when under the influence of alcohol, as well as in the sound level coming from the participants.

The behaviour was changed again when the participants entered the Exercise Room. The sound level decreased. The participants' ability to react to both the spoken message and the tone alarm and start the evacuation changed almost instantly after the warning had been initiated.

These differences in behaviour have a significance for the evacuation of nightclubs onshore and offshore.

A second experiment on the behaviour was carried out using a placebo by Doychinov et al. [8]. Non-alcoholic beer was used as a placebo.

The participants were put through 3 identical exercises, which were aimed at testing their balance, reaction times, concentration, hand to eye coordination, problem-solving skills, cognitive skills and cooperation. In addition to that, they performed 2 evacuations that were used to interrupt their "drunk behaviour" and test their reaction, decision, and overall evacuation times. They were also analysed for signs of drunk behaviour with video and sound recordings.

Some of the participants showed signs of drunk behaviour, such as playfulness and an increase in noise after the placebo was consumed and these were reduced after the environment changed. Based on this it was concluded that even with non-alcoholic beer some of the participants developed drunk behaviour, like that observed in previous experiments with the use of alcohol.

Method

The current experiment is a further development of the previous studies. It involves human beings, who are exposed to alcohol and who will party in a chosen geometry. The design of the geometry, the method for the distribution of alcohol, as well as the run of the experiments, are testing the reaction and decision times, behaviour as well as behavioural patterns of the participants.

The experiment follows the Ethical Codex for evacuation experiments involving human beings and is conducted by DTU BYG [9].

Final comments

The results will be shown at the conference and conclusions will be drawn.

References

[1] FleetMon- tracking the seven seas, 23.10.2019.
[2] Cruise Lines International Association (CLIA) travel report 2018, CLIA, 2018.
[3] D.C. Vassalos, G. & Kim, H. & Bole, Marcus & Majumder, J.. (2008). , Evacuability of Passenger Ships at Sea By., 2008.
[4] M.K. Manley, Yong Seog; Christensen, Keith; Chen, Anthony, Modeling emergency evacuation of individuals with disabilities in a densely populated airport, Transportation Research Record 2205 (2011) 32-38.
[5] A.S.D. J. Gress Sørensen, Evacuation of mixed populations from trains on bridges, 6th International Conference on Bridge Maintenance, Safety and Management (IABMAS 2012), Stresa, Lake Maggiore (2012).
[6] A. Madsen, Hansen, W., M., Dederichs, Anne S.,, The effect of alcohol related impairment on evacuation characteristics Proceedings of the Human Behaviour in Fire Symposium 2015 (2015).
[7] Deadliest public assembly and nightclub fires, 2013.
[8] A.S.D. Simeon A. Doychinov, The development of drunk behaviour during evacuation, , in: G.K. Anne Dederichs, Andreas Schadschneider (Ed.) in Pedestrian and Evacuation Dynamics 2018, Lund, 2018.
[9] A.s. Dederichs, Ethical Codex for evacuation experiments involving human beings and conducted by DTU BYG 2014.

Reliable fire detection systems for the at-risk groups

Jishan Mahmud Rumi[1], Arjen Kraaijeveld[1], Cristina Sanfeliu Meliá[2]

[1]Western Norway University of Applied Science, Haugesund, Norway, 589850@stud.hvl.no

[2]RISE Fire Research, Trondheim, Norway

Keywords:* *Smoke detector, early detection, at-risk group, dwellings, experiment

Introduction:

Western Norway University of Applied Science (HVL) research project BUILDER (Building design for At-risk groups) seeks to improve fire safety for at-risk groups by achieving an understanding of the different challenges & suggesting relevant safety solutions. As a part of the work package (WP-5) of that project, this study is conducted with the cooperation of RISE FR (FRIC project 4.3) to find a reliable smoke detection system solution for the at-risk group. The proposed detection system considers to ensure their life safety and may further be used in housing facilities for residents with drug and psychiatric disorders (ROP) in Karmøy community, Norway.

GAP analysis for the housing for ROP residents and several interviews conducted under the BUILDER project with Fire Service personnel people at-risk group and care services indicates that the technical solutions now provided within smoke detection and fire protection at the dwellings of the residents with substance abuse and mental disorder may not satisfy the requirements of fire safety.

In order to address the challenges and the requirements of the risk group in this study; the reliability, sensitivity, and overall performance of the traditionally used optical detector, combination detector with CO sensors, and aspirating detection system will be assessed experimentally under different relevant fire and smoke scenarios. The experimental assessment of the proposed solution is conducted on an apartment designed for the at-risk group at the Hall of Flame of HVL.

Background of the study

Over the past decades, domestic fire dominates the fatal fire statistics in Norway and at-risk groups are found to be over presented in those fatalities. According to the Norwegian Directorate of Civil Protection reports, almost 75% of victims can be described as vulnerable whereas in official Norwegian documents vulnerability is described as related to factors such as old age, reduced mobility or cognitive abilities, mental health problems, and substance abuse [1,2].

The overall risk picture of the at-risk group can be drawn from the analysis of fatal fires from 2005 to 2014 [3]. The analysis of relevant domestic fire fatalities aspects (victims' age, lifestyle, and psychiatry condition, cause, and consequences of fire, cause of death, etc.) indicates the urge of mitigating fire risk at the societal level through political and organizational measures (such as adequate social housing) along with the improvement of the physical environment of the dwellings according to the need of at-risk group.

The physical environment of the dwellings for at-risk group may be improved by a reliable smoke detector system and it is acknowledged that a smoke detector is an important tool that saves lives through effective & early detection [6]. Previous studies show that 37% of the fire was directly caused by the victim and in most cases, the victim was alone during the incident. In around fifty percent of those incidents, the fire brigade arrives for rescue and firefighting operations when the fire was fully developed [3]. Thus, it indicates the necessity of early detection and notification time, especially for the people at risk group who need assisted evacuation.

Also, the cause of death in the fire fatalities shows 57% of death caused by asphyxiation and 10% by burn and asphyxiation, whereas the toxic effect of carbon monoxide is found in 74.1% of fire fatalities [3]. Thus, it indicates while selecting a smoke detection for at-risk group efficient detectability of CO is a vital feature that shall be covered by the solution.

Under the project "Development of new housing facilities adapted to ROP residents with low capacity to live with an emphasis on user participation" under NORCE Samfunn ved NORCE Norwegian Research Centre AS [4] which is attached with the BUILDER project, 3 small separate houses for citizens with addiction or psychiatric problems will be built in Karmøy community (The ROP project Karmøy). The outcome of this study is to propose solutions with regard to fire safety for this project.

Gap analysis for housing for residents with drug and psychiatric disorders (ROP) [5] under this project shows that there remain a few technical challenges that shall be addressed by the smoke detector which are:

- A smoke detector must not be sensitive to cigarette smoke and other types of pollution (narcotic fume/excessive cooking smoke).
- Detectors or alarms shall be least visible and accessible to the user.
- The smoke detectors or alarms must preferably be able to be tested without having to enter the ROP home and have minimal maintenance requirements.

Previous studies show most of the Norwegian dwellings use photoelectric detector which functions better than ionic detector by the virtue of earlier detection [6, 8]. Other previous studies also show that CO dose may exceed critical value before photoelectric detectors are activated. It may be the combination detectors with CO sensors are more convenient in terms of early detection and with the flexibility of placing anywhere in the dwellings [6]. Aspiration detectors which are mostly used in commercial settlements may be a solution for at-risk groups. Their detection principle is significantly efficient in detecting both smoldering and flaming fire and also it can be installed with the least visibility with a scope of minimal and remote maintenance.

Methodology

For this project, the fire safety objective is life safety in the dwellings for the at-risk group fulfilling the special needs of the residents, and reducing false alarms. A full-scale experiment has conducted in an apartment in the Hall of Flame of HVL, campus-Haugesund to observe the reliability, sensitivity, and performance of the different smoke detectors.

To meet the needs of the target group smoke detector with three different working principles will be used as follows

- Photoelectric smoke detector
- Combination detector with sensors for CO, light scattering, and temperature
- Aspirating detection system

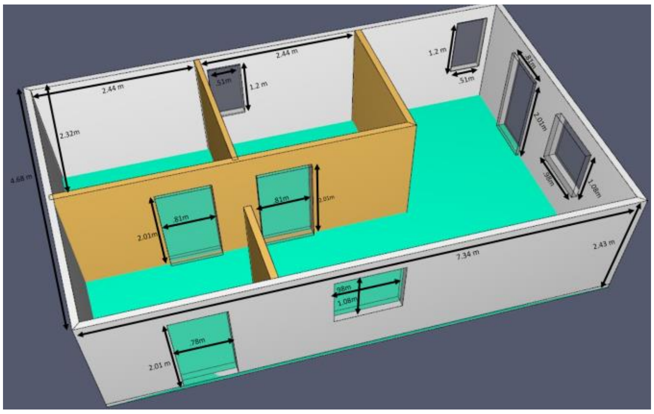


Figure 1. The test room is prepared following a similar layout of the dwellings to be constructed in Karmøy ROP project. The whole apartment has a floor area of 35 m^2.

The detectors were placed following manufacturer guidelines and additionally, a combination detector was placed at the exhaust of the aspiration detection unit. This alternative approach has been taken to assess whether this combination escalates early detection by measuring CO in exhaust air. Also, this detector was programmed with the controller in such a way that it will activate the gas-based extinguishing system (IG-541) only in those cases when both aspirating detection system and the combination detector at the exhaust detect fire/smoke.

As the number of possible fire scenarios is very large in such dwellings thus by interviewing Fire Service personnel, reviewing fatal fire statistics and accident investigations with combining the needs of at-risk groups; those are reduced to a small set of fire scenarios. Considering different conditions such as locations of the fire, status of apartment ventilation, indoor openings, amount of fuel, and the spread of fire and smoke; eight different smoldering and flaming fire scenarios were designed and tested following methods of NS-EN 54-7 (Annex G-J). A total of 33 tests were conducted which includes repeating each scenario four times and a single test with burning tobacco in the apartment.

Result & Observation:

Out of 33 tests, the Aspiration detection system and combination detector were activated in 30 cases and the photoelectric detector was activated in all the cases. The aspiration detection system responded earlier than the combination and photoelectric detectors in 15 cases, especially in the tests with no ventilation. While considering the mean-time of detection, in five out of eight scenarios aspirating detection system was faster and more efficient compared to other detectors. In other tests, it was activated shortly after other detectors. Also, it was not activated during tests 201_3 and 205_1 where the scenarios were similar to the kitchen incidents (with excessive cooking smoke) and indoor smoking which often leads to a false alarm.

Thus, it shows aspirating detection system not only addresses the challenges of being the least visible to ROP residents and being accessible for remote maintenance but also provides early and efficient detection in most situations avoiding false alarms. But its performance was found to be affected considerably by the presence of a ventilation system especially in case of slow smoldering fire with a ventilation system on. An up-gradation of the detection principle in aspirating system may address this issue.

The combination detector placed at the exhaust of the aspiration unit responded significantly slower than all the detectors as the exhaust releases air from all the rooms of the apartment which naturally reduces the smoke particle, CO, and heat present in the air sample. But when the test fire was fully developed/spread of fire occurs it is activated within a short interval. Thus, out of these 33 tests in 18 cases this combination detector was activated and triggered the gas-based extinguishing system (IG-541).

The outcome of the Studies

This study shows aspirating detection system might be a reliable and suitable detection system for the ROP project which can notify fire and rescue services early to initiate assisted evacuation overcoming the existing challenges. Also, the combination of the multi-criteria detector with the aspiration unit at the exhaust provides a considerable time to evacuate and a logical activation of the gas-based extinguishing system (IG-541) in cases of the development of fatal fire/fire spread avoiding false activation.

References

[1] Kristin Halvorsen , Petter G. Almklov, Gudveig Gjøsund Fire safety for vulnerable groups: The challenges of cross-sector collaboration in Norwegian municipalities

[2] Steen-Hansen, A., Storesund, K., & Sesseng, C. (2020). Learning from fire investigations and research – A Norwegian perspective on moving from a reactive to a proactive fire safety management. Fire Safety Journal.

[3] Christian Sesseng, Karolina Storesund, Anne Steen-Hansen "Analysis of fatal fires in Norway in the 2005 – 2014 period" A17 20176:2 , 09.10.2017, English translation of RISE report A17 20176:1.

[4] Project overview: Development of new housing facilities adapted to ROP residents with low capacity to live with an emphasis on user participation" under NORCE Samfunn ved NORCE Norwegian Research Centre AS

[5] B. C. Hagen (2020) GAP analysis for housing for residents with drug and psychiatric disorders (ROP). HVL Report No. HVL report no. 2020-15 ISSN 2535-8103

[6] Christian Sesseng, Nina K. Reitan, Sindre Fjær "Mapping of gas concentrations, effect of dead-air space and effect of alternative detection technology in smouldering fires. VERSION 1 , DATE 2016-03-17.

[7] C. Sesseng and N. K. Reitan, "Kartlegging Av Bruk Av Røykvarslere I Boliger," SP Fire Research AS, Trondheim, SPFR-Rapport A15 20052:1.

[8] NS-EN 54-7:2018, Fire detection and fire alarm systems - Part 7: Smoke detectors - Point smoke detectors that operate using scattered light, transmitted light or ionization CEN-CENELEC Management Centre, Brussels, 2018

Risk-based preventive cooperation between municipal agencies to improve fire safety for vulnerable groups

Åsne Almenning
Western Norway University of Applied Sciences
Haugesund, Norway
584869@stud.hvl.no

Erica Lucia Thunes Hauge
Western Norway University of Applied Sciences
Haugesund, Norway
583625@stud.hvl.no

Ingrid Vedø
Western Norway University of Applied Sciences
Haugesund, Norway
584868@stud.hvl.no

Keywords: ***fire prevention, at-risk groups, cross-sector collaboration, vulnurable groups***

Introduction

Western Norway University of Applied Sciences (HVL) research project BUILDER (Building design for At-risk groups) seeks to improve fire safety for at-risk groups by achieving an understanding of different challenges and suggesting relevant safety solutions. As a part of the work package (WP-1) of the project, this study is conducted with the cooperation of Rogaland Fire and Rescue IKS (RBR).

According to the Norwegian Directorate of Civil Protection reports, almost three out of four of those who die in a fire belong to an at-risk group, in addition 9 out of 10 of those who die because of a fire die in their own home. Elderly people in need of help, drug addicts and people with mental or physical health issues are particularly vulnerable to fire, and many need help to feel safe in their homes.[1]

Many municipal services make a great effort to ensure the fire safety of people in the at-risk groups. This paper, based on a bachelor thesis carried out in spring 2022, will through reviews of earlier literature, an interview with Rogaland Fire and Rescue IKS's section leader, and a comprehensive survey involving different municipal services in Rogaland, review the cross-sector collaboration between different municipal services and its effectiveness.

Problem Statement and Delimitations

The thesis' problem statement addresses how good cooperation between different agencies can contribute to improving fire safety for people belonging to an at-risk group. There has long been great concern regarding the fire safety of this target group, and measures have been implemented at both national and municipal level.

Since people in at-risk groups are particularly exposed to fire and a larger proportion of the population will need services in the home, the following additional question has been prepared:

"What does it take to have a good collaboration, how can municipal services collaborate and what can they collaborate on?"

The aim of this thesis will therefore be to undergo a qualitative and quantitative evaluation to establish and communicate the effect of the project of Rogaland Fire and Rescue IKS aimed at at-risk groups.

The thesis is limited to Rogaland Fire and Rescue IKS's work to improve fire safety for people in at-risk groups, and the collaboration they have with different municipal services around their owner municipalities.

It is important to emphasize that many municipalities in Norway work purposefully and actively to ensure the fire safety of people at-risk, but the thesis only represents measures implemented by Rogaland Fire and Rescue IKS and the cooperation with their owner municipalities.

Earlier Literature and Establishing the At-Risk Group

Previous research has established that elderly people in need of help, drug addicts and people with mental or physical health issues are particularly vulnerable to fire. These people may have both cognitive and physical impairments, they often live alone and generally need help in their everyday life. Implementing effective and helpful fire preventing measures can therefore be challenging. [2]

There are also challenges connected to getting in touch with these at-risk groups. However, in the Norwegian regulations for fire prevention it is stated that the municipality shall determine priority areas and plan cooperation and measures to reduce the mapped risk of fire in an effective manner. The focus areas and measures must be prioritized and justified. [3]

Interview with Rogaland Fire and Rescue IKS

At Rogaland Fire and Rescue IKS untraditional methods have been used to get in touch with members of the at-risk groups.

Targeted information work is one of these methods, for example by seeking out arenas where the vulnerable groups can be reached directly. The section leader at RBR says that, among other things, they visit areas where people with drug problems reside, to provide information about fire prevention. RBR have also held a workshop for the elderly, together with other organizations, to approach this group. The section leader emphasizes that targeted information and motivational work are the most important measures that work best, and relationship building, trust and respect is crucial. In addition, Rogaland Fire and Rescue IKS has focused on getting involved in people's personal lives, showing empathy and being helpful with daily problems to establish trust and connection to members of the at-risk groups. [4]

Furthermore, RBR has had a close cooperation with different health services in their owner municipalities. Among other things they have contributed with training of personnel, informing regarding duty of confidentiality and duty of notification, as well as help carry out home visits and informal inspections.

The section leader explains that it is difficult to get concrete statistics on whether their work has given good results.

Survey of Different Municipal Services

A questionnaire was sent out to various health-related municipal services with which RBR collaborates, to get an insight on the collaboration from their perspective. In total, there are around 200 employees working for the various companies in total, and of these, 79 people responded to the survey.

46 employees state that they have participated in training under the auspices of RBR, and as many as 70% of the participants believe they have good enough knowledge concerning fire safety. Nevertheless, the survey shows that 25% of participants finds it challenging to maintain fire safety of the user in a good way, due to lack of knowledge/training. Home nursing has an especially busy workday lacking in both resources and time, and it is understandable that it is not always within their means to carry put fire preventive work.

Nevertheless, fire safety training should be efficient and simple enough to whereas health and care personnel can know what to look for with the sweep of an eye in regard to fire safety when visiting a patient. Among other things, the survey showed that only 26 out of 79 participants control safe smoking, which is the leading cause of fatal fires amongst the elderly.

As an outcome of the survey, it was revealed that most of the participants know and are aware of the duty to notify, but as many as 41% found it challenging to assess when it is necessary. The findings from the survey suggest that the law may not be concrete enough. The committee from the report «NOU- Trygg Hjemme» proposes to make an amendment to the Health Personnel Act, where the law gives health and care personnel a duty to reduce the fire risk among users by detecting and becoming familiar with flammable conditions.

It is important to emphasize that less than half of total employees responded to the survey, even though several methods were used and a lot of effort was put in to reach them. This could mean that only the most engaged and those who are most concerned about fire safety participated. Due to this, the survey is not necessarily representative of the average.

Importance of Research

The purpose of the thesis is to shed light on the importance of good collaboration across agencies in order to achieve better fire safety for the most vulnerable in society. Statistics show that the problem is very relevant, and that it is necessary to work actively with preventive fire protection work where the risk is greatest. The aim of the thesis is to clarify that risk-based preventive fire protection work has an effect, and the hope is that the thesis can spread this knowledge to other municipalities in Norway and the Nordic countries.

Western Norway University of Applied Sciences

Figure 1. Western Norway University of Applied Sciences (HVL)

References

[1] Direktoratet for samfunnssikkerhet og beredskap, DSB, "Omkomne i brann", January 19th 2022.

[2] Direktoratet for samfunnssikkerhet og beredskap, DSB, «KOMMUNIKASJON OG RISIKOGRUPPER FOR BRANN», 2013.

[3] Forskrift om brannforebygging, Justis- og beredskapsdepartementet, Lovdata, 2015.

[4] Safe At Home: Fire safety for risk-exposed groups, Marie F. Aanestad & Øyvind Nermoen, BOOK OF PROCEEDINGS Nordic Fire & Safety Days, 2018.

[5] Rogaland brann og redning IKS, «BRANNSIKKERHET FOR UTSATTE GRUPPER», rogbr.no, 2022.

Conservation of existing FSE practices through standardization

An appropriate attempt to improve fire safety management or a compensation for underlying challenges in the construction industry?

Henrik Bjelland
University of Stavanger (UiS)
Stavanger, Norway
henrik.bjelland@uis.no

Ove Njå
University of Stavanger (UiS)
Stavanger, Norway
ove.njaa@uis.no

Keywords:
Fire safety engineering; risk assessment; standardization; socio-technical systems; innovation

Abstract

Fire safety engineering and performance-based regulations

Fire safety engineering (FSE) consultants play an important role in assuring fire safety in Norwegian buildings. Specifically, they are typically responsible for the conceptual fire safety design (CFSD). The CFSD is the high-level fire safety solutions, and serves as foundation for detailed fire safety design (DFSD) by structural engineers, HVAC engineers, architects etc. The CFSD includes specification of the location of fire compartments, fire walls, sectioning walls, egress zones and performance requirements for structural and separating construction elements [1]. For instance, a fire compartment wall should satisfy "EI60". It is the responsibility of the architect to design a specific solution and select products that meet the EI60 requirement.

Norwegian FSE consultants are responsible that public requirements are met, i.e., that the design comply with the fire safety regulations. To act as a responsible FSE consultant in a construction project, the company needs a "central approval" by the national authorities [2]. Having central approval makes the FSE consultant company eligible to take on responsibility for the CFSD in a specific project. If the FSE consultant fail to meet regulative requirements, the company stands at risk of both public and private liability charges. Possible consequences include covering expenses of improving the fire safety level in the building, personal responsibility of individual FSEs (which may include prison), and the company losing their central approval. Naturally, it is important for the FSE consultants to meet minimum requirements.

After the introduction of performance-based regulations in 1997, it has been an option to use analyses as a basis to document the fulfillment of regulation requirements. Implementation of performance-based regulations is usually motivated by several benefits, such as simplification of regulations and regulation development, easier trade across national borders and technological innovations [3;4]. Performance-based regulations involves simplifications for the regulator but adds both opportunities and complexity to the FSE consultant. Opportunities include freedom to include new technologies, materials, and design choices, if the safety level is acceptable. The added complexity is about documenting that the safety level is acceptable. Since 1997, there have been several debates in the industry about appropriate risk analysis methods, processes for third party review and controversial design choices, such as the use of plastic materials and high-rise timber constructions. Abstract concepts, such as risk, models and engineering judgment are important tools in a regulation regime based on performance and management principles. Not surprisingly, this leads to different interpretations among different consultant companies. Major construction contractors expect FSE consultants to come up with the optimal cost-effective solutions. One of Norway's major construction contractors have for instance included in their contract terms that "over-dimensioning" is to be regarded as a design error. Consequently, the FSE consultants are, on the one hand, responsible to society for fulfilling minimum requirements, and on the other hand, they run the risk of a private lawsuit if they over-dimension fire safety. This represents a major constraint for the FSE consultants and is also a poor starting point for safety management.

Standardization of risk assessments

Currently, Standards Norway have taken the initiative to revise the standard *NS 3901 Requirements for risk assessment of fire in construction works* [5]. The standard first came out in 1998, shortly after the implementation of performance-based regulations. A second edition was released in 2012. It has always been the intention that NS 3901 should serve as a tool to verify regulation requirements. The guide to the fire safety regulations points to the standard for this purpose. However, the FSE industry does not consider the current standard applicable to support the engineers in the art of balancing safe enough with too safe. The standard's requirements to risk analyses are considered too challenging

for practical purposes, and simpler analyses are preferred [6]. The suggested strategy to improve the standard include inter alia conservation of the industry's current risk assessment practice, conservation of terms and concepts, and standardization of data.

The future of FSE and safety management?

In this paper we ask ourselves if the suggested strategy for standardization will improve fire safety management in the construction industry, or whether it is more directed towards reducing the legal risk of FSE consultants.

In previous works [7;8] we have argued that comparative risk analyses fail to capture important safety issues in design. Generally, the FSE simply assume that the safety level of a reference building is acceptable. The FSE spends time and resources on conducting analyses of both the hypothetical reference building and the specific design, instead of focusing efforts on the design task. The main goal of conducting the analysis is to verify a safety level, which is a poor starting point for adhering to principles of modern safety management, such as internal control, continuous improvements, and operational control.

Why is it possible that major construction companies specializing in turnkey contracts include terms of "over-dimensioning", and how shall outside viewers comprehend such terms? Is it something that the construction company itself assess, and what are the liability grounds for assessment of over-dimensioning phenomena? We need studies that challenge the system within the construction industry to reveal how safety margins are maintained [7].

Furthermore, the fire safety engineering industry has developed their own "dictionary" for terms relevant to the fire safety domain. This is also a way of executing power upon the industry, by conceptualizing terms that restrict or influence safety assessments and measures in the engineering work. An example is how to understand passive fire protection (PFP), which could be regarded as materials added to structures to protect structures, or it could be associated with measures that does not need activation to perform in a fire scenario, such as evacuation rooms in tunnels. Our understanding is that evacuation rooms, as such, falls outside the definition of PFP, and this becomes a barrier for innovation work on the topic. Standardizing terms thus represents a potential safety threat.

Standardization of data for risk assessments sounds very convenient for the FSE consultants. This will contribute to predictability, similar analyses by different consultants, and low risk for the responsible parties, as the consensus-based standardization organization becomes responsible for critical choices. Our view is that standardization of data is a road to conservation of the existing and a barrier to innovations. More importantly, the foundation for standardization of data is also questionable. Fire safety is an emergent property of socio-technical systems, in which statistical variability and epistemic uncertainty associated with the fire phenomena and human behavior are extremely large. Therefore, we argue that verification cannot be the goal of fire safety analyses. The goal of the analyses should be to improve our understanding of the system and how it will perform under different assumptions and loads. In this context it becomes meaningless and counter-productive to standardize data for fire safety analyses.

Conclusions

In this paper we question the rationale behind desired strategies to improve standardization of fire safety risk assessments. We argue that the selected strategy is better suited to solve fundamental problems in the industry, rather than fire safety management issues. Conservation of existing practices, e.g., comparative risk assessments, serves to legitimate methods that has a vague connection to "the safety reality" of future buildings. Conservation of concepts and terms is useful for the FSE community but inhibit flexible understanding and innovation. Standardization of data is a matter of transferring responsibility of critical and difficult decisions from the FSEs' to the standardization organ, which the regulation already points to for guidance.

There are probably not quick fixes to the challenges of fire safety management in the construction industry. We might think that conservation of methods, concepts, terms, and data through standardization is progress. In our opinion it is a step backwards and it serves as a barrier to innovative technologies and solutions, enlightened debate about appropriate fire safety performance and development in the (fire) safety engineering profession.

References

[1] DiBK, *Byggteknisk forskrift 2017 (TEK 17) med veiledning*. 2017, Direktoratet for Byggkvalitet (DiBK): Oslo.

[2] DiBK, *Byggesaksforskriften (SAK10) med veiledning (in Norwegian)*. 2010, Direktoratet for Byggkvalitet (DiBK): Oslo.

[3] TRB, *Designing Safety Regulations for High-Hazard Industries (TRB Special Report 324)*. 2017, Transportation Research Board, National Academy of Sciences.

[4] Lindøe, P.H., J. Kringen, and G.S. Braut, eds. *Regulering og Standardisering - Perspektiver og praksis*. 2018, Universitetsforlaget: Oslo.

[5] SN, *Norwegian Standard (NS) 3901 Requirements for Risk Assessments of Fire in Buildings (in Norwegian)*. 2012, Standards Norway (SN): Lysaker.

[6] Drøsdal, B. & Raastad, O.A. Use of risk assessments for fire safety engineering (in Norwegian). Bachelor Thesis at Stord/Haugesund University College, 2015.

[7] Bjelland, H., Njå, O., Heskestad, A.W. & Braut, G.S., *The Concepts of Safety Level and Safety Margin: Framework for Fire Safety Design of Novel Buildings.* Fire Technology, 2015. **51**(2): p. 409-441.

[8] Bjelland, H. and A. Borg, *On the use of scenario analysis in combination with prescriptive fire safety design requirements.* Environment Systems & Decisions, 2013. **33**(1): p. 33-42.

Effects of external cooling on smoldering fire in wood pellets

An experimental parameter study

Dag Olav Snersrud
Norwegian University of
Science and Technology
and RISE Fire Research
AS Norway

Keywords: Experimental study, smoldering, wood pellets, thermodynamics, Master's thesis.

Abstract

Smoldering fire is a slow exothermic reaction where fuel and oxygen are consumed to generate heat [1]. What separates smoldering from other kinds of combustion's is the absence of a visible flame. Smoldering fires are also significantly easier to ignite, and the persistent behavior of the fires makes them one of the leading causes of casualties in residential fires [3]. The environmental aspect of smoldering is also important because smoldering peat fires are responsible for the destruction of carbon sinks and the release of severe quantities of environmentally hostile gasses [4].

The main goal of the experiments was to explore the effects of external cooling on smoldering fires in wood pellets. This was done by putting a sample of wood pellets inside an insulated steel cylinder heated by an external heating source until a smoldering fire ignited. Around the steel cylinder, water was circulation in a copper spiral. During the tests, the temperature was carefully monitored, along with mass, airflow, and the pressure of the system, which enabled calculations to be made after the tests. A total of 24 experiments were conducted, three of which suffered equipment malfunctions, making the data basis for this thesis 21 tests. Each with a purpose of uncovering more information on the topic of smoldering by investigating different parameters.

The first parameter being heating duration, where ignition was the main focus. The ignition of smoldering under the influence of external cooling was a demanding task. With the flow rate used in this section of the study, a consistent, predictable smoldering fire was impossible to create, and heating duration's up to 30 hours were tested without the initiation of smoldering. Compared to the work by Mikalsen in 2018 [2], this translates to an increase in heating duration equaling a 400% increase of what was needed to initiate smoldering without external cooling. Next, the target was to explore what impact different flow rates of water in the cooling jacket would have, and how this affected the heat transfer. Using a flow rate of 0.29 L/min, the heat loss to water was 103 W. When the flow rate was increased to 0.42 L/min, the heat loss to water only increased to 106 W, indicating that the heat transfer may have reached a stagnation point. This phenomenon was not further investigated due to time restrictions.

The total combustion time was significantly lower in the smoldering cases where external cooling was used, making the fire more rapid, and with a higher heat production rate than in the cases without external cooling. Looking at this result in light of the results from the ignition test series, indicating that when external cooling is applied, the ignition is more difficult, but when ignited, the fire burns more violent and rapid.

This study sheds light on the not particularly well-known phenomenon of smoldering fires, by studying the effects of external cooling on smoldering fires in wood pellets.

References

[1] Rein, G., 2016. SFPE Handbook of Fire Protection Engineering. Springer, New York, NY. doi:10.1007/978-1-4939-2565-0_19. page 581-601.

[2] Mikalsen, R.F., 2018. Fighting flameless fires. Ph.D. thesis. Otto-von-Guericke-University of
Magdeburg. doi:10.13140/RG.2.2.34666.16329. Ahrens, M., 2019.

[3] Home fires started by smoking. National Fire Protec-
tion Association URL: https://www.nfpa.org/News-and-Research/Data-research-and-tools/US-Fire-Problem/Smoking-Materials.

[4] Simon, M., 2021. Underground "zombie" peat fires release 100 times the carbon of wild-fires. Bulletin of theatomic scientists URL: https://thebulletin.org/2021/03/underground-zombie-peat-fires-release-100-times-the-carbon-of-wildfires.

Charging stations for electric vehicles in sub terrain carparks

A study on the extent of emission of hydrogen fluoride gasses from fires in lithium-ion batteries

Jesper Wedel Jensen
Fire Safety Engineer
MOE
Århus, Denmark
jwje@moe.dk

Frank Markert
assoc. prof.
DTU civil engineering
Kongens Lyngby, Denmark
fram@dtu.dk

Keywords:* *(5 key words)
Car-park fire, simulation, battery fires, emission of hydrogen fluoride, Li-ion batteries

Abstract
Since its commercial introduction in 1991, the Li-ion battery has undergone a steady and continuous optimization and has gone on to become profoundly indispensable to the modern societies around the world. Using a variety of different chemical compositions to power everything from mobile telephones, tablets, laptop computers, power tools and now even vehicles, Li-ion technology is literally found everywhere. Although the amount of newly registered electric- and hybrid vehicles (applying Li-ion technology) has risen very rapidly in the past few years *[1]* it has yet to be considered in the building codes. Dividing large spaces into smaller ones, is still a widely applied method to avoid requirements of installing either automatic sprinkler- or fire ventilation systems *[2] – see* ***Figure 1***.

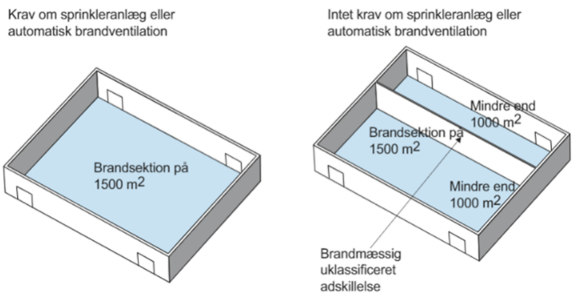


Figure 1 – dividing of large spaces with unclassified structures

Until the technology of the solid-state battery *[3]* is perfected, Li-ion technology is the most effective way to store large amounts of electric energy. The thermal stability of these batteries is recognized as one of the most important challenges of any Li-ion battery, as the occurrence of thermal runaway has caused numerous fires and even explosions. A thermal runaway in even a small battery, will inevitably cause the battery to overheat, and once the battery's protective casing can no longer contain the elevated pressure, a variety of both flammable and toxic gasses are released from it – often spectacularly so *[4]*.
One of these said toxic gasses is hydrogen fluoride (HF), which has a very well documented hazardous impact on human health *[5.]* This gas is the main focus point for this contribution.

The initial research showed that both the risk of the occurrence of thermal runaway, and the quantity of emitted toxic gasses, greatly depend on the battery's general chemical composition, and its state of charge (SOC). It also shows that even identical tests can create rather different results, and that larger batteries do not necessarily emit larger amounts of HF *[6]*. This is why extrapolation of archived results should be avoided and is therefore not used on the results achieved in the simulations of this work.
By applying actual measured quantities of HF-emissions from a full-scale experiment [7] into an FDS-model, this study has investigated different scenarios, where HF is being released from an Li-ion battery pack of a small EV during a fire. The EV is placed in a confined space, in the shape of a real-life underground parking garage, placed in the greater Copenhagen area – see ***Figure 2***. In this specific parking facility, the above-mentioned common practice for avoiding sprinkler and fire ventilation systems was applied, which, when measuring hazardous concentrations of toxic gasses as in this study, is very counterproductive.

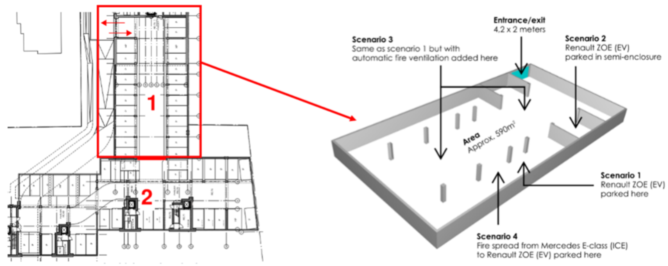


Figure 2 – Floorplan and FDS-model of parking structure

Results, predicted at 1.2 and 1.6 meters above the floor, show that the investigated hazardous HF-concentrations of 30 ppm (IDLH), 34 ppm (AEGL 2, 30 minutes) and 62 ppm (AEGL 3, 30 minutes) occur relatively quickly, when the battery's protective casing is compromised.

It is also shown, that at the time of the fire brigade's assumed arrival, concentrations in the garage exceeds 150 ppm in certain areas of the garage and continue to rise to reach peak values of approximately 800 ppm (measured at 1.6 meters above the floor) in the time firefighters would be expected to be near the burning vehicle – see ***Figure 3***. This because Li-ion battery fires are self-oxidizing, and thereby notoriously difficult to extinguish, using standard firefighting techniques.

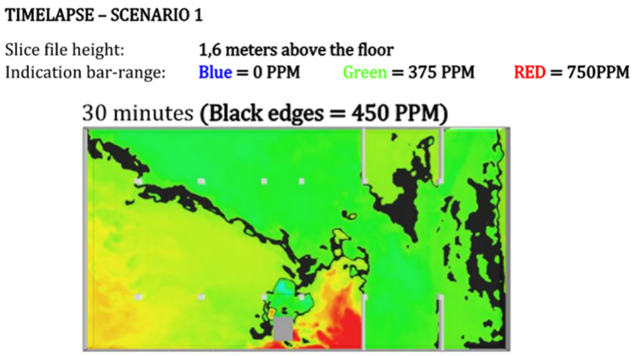


Figure 3 – concentrations of HF after 30 minutes

The results further illustrate the general behavior of the toxic gasses accumulating in corners where ceiling jets collide with vertical obstacles, such as walls and pillars – see ***Figure 4***.
As the HF concentrations predicted at 1.2 meters above the floor are consistently lower than those measured at 1.6 meters above the floor, the combined results of this report show, that firefighters should stay away from corners, and should be operating from lowered/kneeled positions whenever possible.

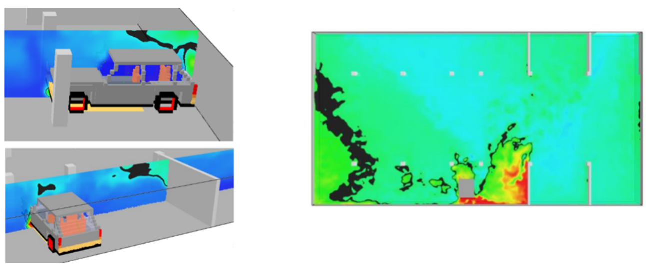


Figure 4 – accumulation of HF-concentrations

The results of this study furthermore show that hazardous concentrations occur by the exit/entry of the garage, where firefighting crew will not necessarily be wearing respiratory protective gear. This means that certain amounts of HF are being vented away during the fire, which would not be the case, if the garage door had been closed. In that case the HF-concentrations inside the garage would naturally have been even higher than the ones obtained in this study.
It is worth considering that the applied experimental measurements in this study are almost a decade old and are established using a Li-ion battery of only 23.5 kWh. The battery packs of today's EV's are considerably larger, and a battery of 23.5 kWh, as the one used in this study can almost be found in the very popular plug-in hybrids.

Though results should not be extrapolated from small to larger batteries, it is conceivable that much larger batteries will emit larger quantities of HF, burn much more aggressively and be much more difficult to extinguish for the firefighters.

Topics, related to the main topic, not considered in the development of this study is:

- The general risk of a fire occurring in alternatively fueled vehicles. Topic is already investigated by RISE, Sweden *[8]*
- Potentially increased risk of fire spread due to jet-flames from battery fires
- Electric vehicles placed in fully automatic- and multilevel parking structures
- Potential sprinkler system effect on acidity of smoke plume
- Alternative extinguishing agents than water
- Acidity of extinguishing water from Li-ion fires

References

[1] S. Dalbro, ""Nye plugin-hybridbiler slår alle rekorder - men de fylder ikke meget" Danmarks Statistik, September 2020.
[2] "Bygningsreglement 2018 (BR 18)" Bolig- og Planstyrrelsen, Janurary 2022.
[3] https://en.wikipedia.org/wiki/Solid-state_battery
[4] Various youtube videos of burning electric vehicles. E.g.: https://www.youtube.com/watch?v=3eFM9JJMH_0
[5] "Facts About Hydrogen Fluoride (Hydrofluoric Acid)", CDC (Center for Disease Control and prevention), https://emergency.cdc.gov/agent/hydrofluoricacid/basics/facts.asp
[6] F. Larsson et.al, "Toxic fluoride gas emissions from lithium-ion battery fires", www.nature.com/scientificreports, July 2017
[7] A. Leqoc et.al, "Comparison of the fire consequences of an electric vehicle and an internal combustion engine vehicle", Ineris (report 00973680), September 2012.
[8] A.W. Brandt and K. Glansberg, "Lading av elbil i parkeringsgarasje", RISE-rapport 2019:123, Safety and trasnport, RISE Fire Research. 2019

Test method for evaluation of fire suppression systems against Li-ion battery fires at sea

Petra Andersson
Fire Safe transport, RISE
Borås, Sweden

Roeland Bisschop
Fire Safe transport, RISE
Borås Sweden

Christian Forsberg
Fire Safe transport, RISE
Borås Sweden

Jonna Hynynen
Fire safe transport, RISE
Borås, Sweden

Keywords: ***Li-ion batteries, Electric propulsion ships, Fire suppression, test method, thermal propagation***

Abstract

Fire safety of ships is a key issue as evacuation and extinguishment is more difficult at sea than it would be on land. There is therefore a long tradition of fire safety regulations at sea.

The current shift to more sustainable transport solutions has now led to the introduction of lithium-ion batteries for ship propulsion. These can offer significant benefits in terms of reducing greenhouse gas and particulate matter emissions, but introduce new risks. If damaged, lithium-ion batteries may go into thermal runaway, a state that produces significant amounts of heat combined with flammable and toxic gases. This is a challenge, and safety is one of the key questions asked when introducing battery propulsion at sea [1].

Electric propulsion at sea was the first application area to require a test that verify that a thermal runaway does not propagate to neighboring cells or modules. The non-propagation can be achieved using passive protection or using a suppression system. This means that there will be a test (series) for each battery/extinguishment combination. For companies/ship owners it would be beneficial to have a test method that can verify a systems performance in a more generic way. Extinguishment system manufacturer would also benefit from a generic test method. This work presents a first step in developing such a method and takes its starting point in the work conducted by DNV in 2019 [2].

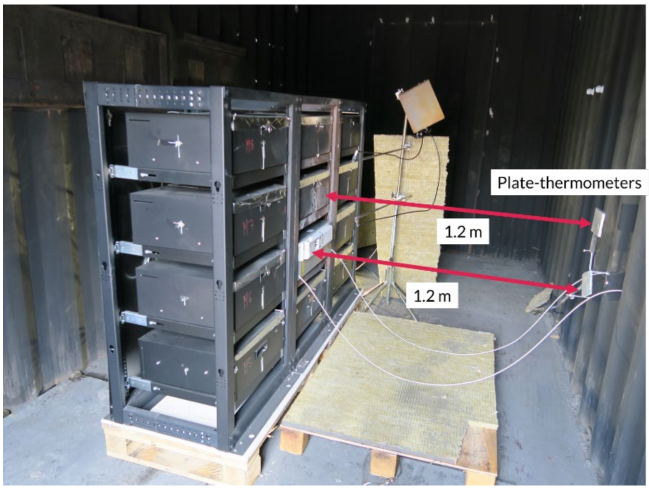


Figure 1. Mock-up placed in container.

Experimental set-up

As the method shall be generic the extinguishing system needs to be applied externally of the pack/modules. The aim will thus be to prevent module-to-module propagation, since cell-to-cell propagation will be impossible to achieve with externally applied suppression. In addition, as there is a risk that the system extinguishes the open flames while the thermal runaway still is propagating and thus pose an explosion danger, the test needs to be designed to be conducted outdoors.

A mock-up consisting of one live module surrounded by 11 dummy modules in a rack configuration was designed to mimic existing installations on ships today. The dummy modules were filled with sand to achieve the same thermal mass as a real module [3].

To be able to evaluate different extinguishing systems performance in mitigating thermal propagation it is important to have a propagation scenario that is very repeatable, i.e. if no system is applied the propagations hould be very repeatable from test to test. In order to reach this, it was decided to use a burner to initiate thermal runaway in a cell.

It is also important to activate the extinguishing system at a time when one is certain that thermal runway will propagate in a repeatable manner if no system is activated. To identify a suitable trigger point, some tests were conducted without using anu extinguishing system. These tests were conducted indoors measuring temperatures, Heat Release Rate etc. but as the final test method should be an outdoor test a suitable trigger time needed to be identifiable through temperature readings. The trigger point should also represent a time where a fire could be detected by an detector outside of the battery/conventional fire detection.

Figure 2. Test running.

Verification

The mock-up rack was tested in a test series where different types of extinguishing systems were used, both water based and non-water based. Two different types of cell chemistries were used. However, to limit the number of tests, some parameters had to be fixed like placement of nozzles. The tests were conducted outdoors but the mock-up was placed in shipping containers (see figure 1 and 2).

The mock-up proved to be robust enough to be used in several consecutive tests. Also, by running only one test per day enough time for cooling the dummy modules was available. However, care must be taken so that water does not enter the sand in the dummy modules in order not to tamper the results of the tests conducted afterwards. The thermocouples used were robust enough to last the entire series, but the placement and number of thermocouples can be further optimized.

In the test series only one type of rack solution was used. The impact of different spacings in the rack on the performance of the extinguishing systems needs to be investigated before deciding on a standard rack.

In these test series NMC and LFP modules were used. The repeatability of the NMC modules was much better than the LFP modules. The trigger criterium was developed to cover both types of modules. As the repeatability of the LFP modules was lower, a later trigger point needed to be chosen. Therefore, the activation time against the NMC modules was later than could have been achieved just considering NMC modules. This emphasizes the importance of using the same type of modules in a test method.

Conclusions

This work provides important input towards the development of a test method for evaluating the performance of fire suppression system under critical battery failures and at lowering the risk for module-to-module propagation. The designed test method performed well and sustained all 18 tests that were done. Overall, repeatable test conditions were obtained which allowed evaluation of fire suppression systems.

The method was verified using different types of extinguishing systems. All fire extinguishing systems had a positive impact in some locations of the modules. However, it was not possible to draw any conclusion on the suppression systems ability to mitigate module-to-module propagation, especially as the test method need further development. The tests showed that mitigating module-to-module propagation can be possible with careful design of suppression systems and perhaps combinations of different means/systems.

References

[1] Andersson, P., Wikman, J., Arvidson, M., Larsson, F., Willstrand, O., “Safe introduction of battery propulsion at sea”, SP Rapport 2017:34, SP Borås 2017.
[2] “Technical Reference for Li-ion Battery Explosion Risk and Fire Suppression,” DNV GL 2019-1025.
[3] Bisschop, R., Andersson, P., Forsberg, C., Hynynen, J., “Lion Fire II – Extinguishment and Mitigation of Fires in Lithium-ion Batteries at Sea” RISE report 2021:111, RISE Borås 2021.

Dafo Energy Storage Protection and Telia collaborates to protect large Li-Ion backup

Author 1
Sören Karlsson
Dafo Energy Storage Protection AB
soren.karlsson@dafo-energy-storage.com

Author 2
Kristoffer Eldin
Dafo Energy Storage Protection AB
kristoffer.eldin@dafo-energy-storage.com

Background

The ongoing digitalization of society is positive in many ways, but at the cost of increased vulnerability where a power outage can have a huge impact on both individuals, businesses, and society at large.

Batteries have been used for decades to backup all kinds of critical infrastructure to create resilience and secure up-time to IT and ICT systems.

One example is telecommunication systems (ICT) which are the backbone of modern information communication with data centers handling various critical tasks to serve the digital society's demand for 7x24 operations.

Availability of non-stop energy in the telecommunication ICT system is therefore extremely important and batteries together with UPS, 48V DC-system and generators thus play a critical role to guarantee 100% system up-time during grid disturbances and power outages.

The role of the battery

As batteries play a crucial role in the system, the selection process puts focus on reliability, functionality, capacity, and lifetime. The choice of battery type is an important part of the system design due to the vital function of the batteries and their impact on the total cost of ownership.

Lead-acid batteries have been the traditional choice until a few years ago when Li-Ion became an alternative battery power backup. Advantages compared with the lead-acid batteries are i.e., space, weight, lifetime, and number of cycles.

The Li-Ion battery

Li-Ion enables the creation of solutions and applications that were unthinkable a few years ago, where the automotive industry and the ecosystem built around it create new opportunities for sustainable solutions in the transport sector.

The same is true for other sectors as well, like the IT and ICT industry, where Li-Ion besides its main function as an ICT-system backup, also will enable the use of stored battery energy as a balancing energy source for the grid. Thus, energy can be used more efficiently on a wide range to meet the growing need for energy backup during grid power peaks.

The beginning with nonconformance in the Li-Ion batteries

The early Li-Ion batteries had problems with issues such as instability, sensitivity to shock, high temperatures and overloads, to mention some areas of concern.

A worst-case scenario can reach a phenomenon known as "thermal runaway" *** where the battery cell enters an exothermal reaction which can be irreversible if not mitigated. At this stage, the batteries release toxic gases (CO is one of them) and may catch fire after a while.

By improving cell technology with safer electrolytes, better anode/cathode materials and using improved battery monitoring systems the Li-Ion battery solution of today are much safer but not safe enough.

Major incidents have caused damage, serious injuries or worse, lost property and not to forget lost credibility. In the last 2-3 years we have had reports on Li-Ion incidents in large energy storage installations in the USA, China, Korea, Australia, and Europe.

In applications that are insensitive indoor environments like hospitals, data centers, central offices, large car garages and other confined spaces the risk is accelerated while quite often the possible dramatic consequences of an incident are not properly addressed, maybe due to lack of knowledge and experience.

The pilot trial between Dafo Energy Storage Protection AB and Telia Sverige AB

Telia is looking and verifying to find advantages for replacing traditional Lead-Acid batteries with Li-Ion batteries as backup in data centers, central offices, and sites. They also have demanding requirements on both safety and availability in their sites as well as requirements to fit these solutions in existing facilities.

Although high safety is available in many Li-Ion solutions today, a thermal runaway*** situation can still accidentally occur. The safety of the system is relying on a well-designed cell as well as a BMS which is the heart of the safety. As both cells and BMS pose a risk, although small, in a worst-case scenario, a catastrophe could happen, and there is a need to enhance the safety (at a reasonable cost).

DAFO and Telia have joined forces and started a trial project, to verify and enhance, the safety of the use of the Li-Ion batteries indoors.

By using a sensor technology patented by Swedish DAFO Vehicle Protection**, a joint venture was established in early 2021 to develop a protection system that will provide early detection of CO-gas from any type of Li-Ion battery known today.

The project has thus been about adapting the vehicle solution to a solution that is adequate for stationary battery applications. This includes setting the level of intervention and includes both shutdown of a cabinet and using a cooling and fire suppression agent. However, using cooling/fire suppression to be effective requires access to each battery module via a pipe/valve system supplying the agent.

Due to the complexity and cost of using cooling agents on a distributed level to each battery module, it was decided that shutdown only would be actual for this project. It will provide a high level of protection at a low level of intervention. The conclusion is that early detection*** with shutdown prior to the thermal runaway is the most cost-effective solution for this project.

By using the same key building blocks as in DVP's vehicle solution we have saved on both project time and development cost. We have also benefited from the investigations and tests made in collaboration with RISE. Knowledge regarding the Li-Ion technology, its construction and the different properties of certain electrolytes and risks with certain electrolytes has been acquired through a combination of own studies and consultation with experts.

The solution will help Telia to maintain high availability in their critical systems in case of a battery incident as only a reduced portion of their battery back-up will be disconnected, and the rest will be kept operational. The algorithms used are based on sensor settings, comparison between sensors, time factors and room conditions. The system also uses temperature and humidity in the calculations. The system is using redundant system controllers and redundant sensors in each battery section.

The system will automatically disconnect a failing battery cabinet to avoid thermal runaway*** and if Telia desire in future, could also be used to control a cooling/fire suppression system.

Project main objectives - features of the solution:

Early detection of CO being released from a Li-Ion cell:
Performed by a super sensitive and self-calibrating CO gas detector (0-1000 PPM)

Ability to recognize and select the battery rack with a failing Li-Ion cell and automatically shut down this rack:
By using algorithms that compare the CO levels, between racks and between racks and a room reference sensor. Comparison is also done by temperature and humidity readings. If there is a conflict or uncertainty in the decision making, the system shuts down all racks as a safety measure.

Independency from the Li-Ion systems internal monitoring and control system (BMS):
The protection system is working totally independent from the battery vendor BMS to ensure that a fault in the BMS will not have an impact on the protection.

High reliability and robustness:
The system uses redundant sensors and control units which communicate by Canbus SAE J1939. Interface to the Scada is through OPC but can be changed to other languages.

Intuitive and easy to navigate human interface:
The system has 2 display screens, one in the actual battery room for service purposes and one placed outside the room for emergency staff. Screens are intuitive and easy to navigate and provide actual status on CO-level, temperature and show warnings and alarms. The screen also shows if a battery rack has been shut down.

Clearly visible warnings:
Each cabinet is equipped with a gas collection and fan assisted hood which includes the sensors and is placed on the cabinet roof. A red/green beacon provides actual status – green or red for normal or gas detected.

Possible to use as a retrofit in existing installations:
The modular approach enables retrofit to standard Li-Ion battery racks and does not require intervention in the battery modules.

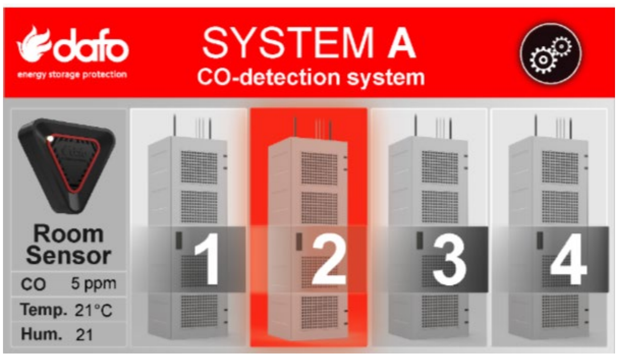


Figure 1. The display shows the affected cabinet in red. A red light is flashing on the affected racks hood.

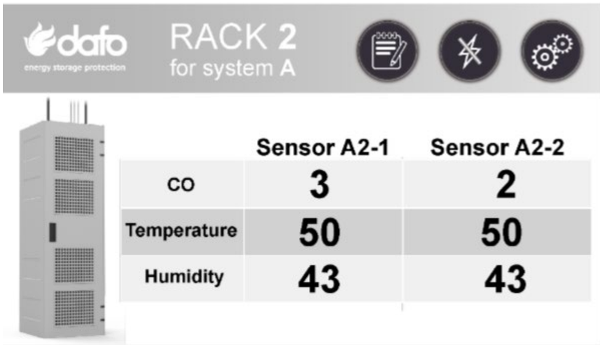


Figure 2. By pressing the affected rack actual details will show up. The rack can also be manually shut down through this panel.

**Dafo Vehicle Protection AB is the parent of Dafo Energy Storage Protection AB.

*** Thermal runaway occurs often when the heat has reached the level of heat which the battery cannot emit. The reaction can also start with mechanical abuse.
Thermal runaway is preceded by a period of increased heat and ventilation with the pre-release of gas. The Dafo sensor can detect this gas (CO) about 4-10 min prior to the start of the thermal runaway.

Figure 3. Picture of actual retrofit hood with sensors

References and documentation

ESS fire incident in Drogenbos Belgium on 11 November 2017
Lessons learned report Engie Laborelec and Federal Knowledge Center for Civil Protection of the Federal public service Interior
Author: Kurt Vollmacher

Four Firefighters Injured in Lithium-Ion Battery Energy Storage System Explosion – Arizona
UL Firefighter Safety Research Institute Columbia, MD 20145
Authors: Mark B. McKinnon, Sean DeCrane, Stephen Kerber

Moss Landing energy storage facility knocked offline after batteries overheat – pv magazine USA (pv-magazine-usa.com)

Tesla Megapack caught fire at Victorian Big Battery site in Australia (cnbc.com)

"Li-Ion is one of the best battery systems, but it is unforgiving in fail-mode. Many Li-ion batteries keep performing even when a fault develops. An analogy is an ageing steam engine that still delivers full power with a boiler that no longer meets safety requirements."
Author: Isidor Buchmann, Assuring the safety of Lithium-ion in the workforce.

IEEE Spectrum 2020: The April 2019 accident near Phoenix put plans on hold to further deploy battery energy-storage systems across Arizona
https://spectrum.ieee.org/dispute-erupts-over-what-sparked-an-explosive-liion-energy-storage-accident

Fire safety of battery-electric vehicles

A pre-study and knowledge gap analysis

Jonas Brandt
Safety and Transport
RISE Research Institute of Sweden
Umeå, Sweden

Artur Storm
Safety and Transport
RISE Research Institutes of Sweden
Västerås, Sweden

***Keywords:* fire safety; battery-electric mining vehicles; fire rescue operations**

Background

The mining industry, as other industries around the world, is facing a major restructuring to meet the environmental goals. As a part of the change, the industry is moving away from fossil-fueled vehicles and moving towards an increased use of battery-electric vehicles. A challenge in underground mines is the environment in which the vehicles operate and the heavy strain on the vehicles but also the fact that accidents underground can be difficult to manage and have major consequences. A rescue operation in underground facilities places great demands on emergency planning and on knowledge on how fires develop in the current environment and may require extensive resources. In the event of fires in underground mines, the response route is often long, and it may take a prolonged period of time before the actual extinguishing operation can begin.

Statistics on fire incidents in Swedish mines show that more than half of the fires that have occurred are related to vehicles [1]. The knowledge regarding the development of fires in vehicles with combustion engines is well established and has to a relatively large extent been translated into the conditions prevailing in underground environments. When converting to vehicles with new energy carriers, other conditions and risks need to be considered in safety assessments and action planning. The majority of the new energy carriers used within the mining industry are battery-electric vehicles powered by lithium-ion batteries and hence the pre-study has focused on the differences between fires in these vehicles and in vehicles with conventional fuels.

Vehicle fires

Fires in heavy duty vehicles are most often caused by technical failures such as electrical faults or short circuits, leakage on hot surfaces in the engine compartment and frictional heat from moving parts such as wheels and hydraulic pumps. Fires can also occur due to a crash and can then be caused by broken fuel hoses, electrical short circuits and the friction heat from the crash itself.

The fire risks with battery-electric vehicles are partly different from the fire risks with internal combustion engine vehicles. Battery-electric vehicles do not have an exhaust system with hot surfaces. Also, they do not have a fuel tank or the combustible fluids in the engine compartment found on conventional vehicles. However, the lithium-ion battery adds risks that are not present in vehicles with conventional fuels. The main risks with lithium-ion batteries are thermal runaway, hazardous gas emissions and the risk of the battery re-igniting after the extinguishment [2]. Thermal runaway can occur if the battery is exposed to, for example, external heat, mechanical impact, short circuit or overcharging.

Thermal runaway means that electrical energy is released in the form of heat inside the battery, warms up the battery cells which in turn increases the thermal runaway. The more the temperature in the battery increases, the faster the thermal runaway accelerates causing a self-generating process. During thermal runaway, there is a risk that the electrolyte of the battery releases, ignites and produces toxic gases [3, 4]. In case of incomplete combustion, there is also a risk that the released battery gases create an explosive atmosphere if they accumulate [5–7].

Gap analysis

Some fire tests on battery-electric vehicles in the form of passenger cars have been performed [4, 8, 9], but no documented full scale fire tests on battery-electric mining vehicles have been found in the literature. When it comes to heavy vehicles with conventional fuels, only a few fire tests with measurements of heat release rate, temperature and gas emissions have been performed in mining environments and then on older machines [10]. The fire load in modern vehicles has increased as a result of the vehicles containing a larger amount of plastics and other combustible materials, which means that these test results are not fully representative of today's vehicles.

The experience and knowledge of how fires develop and spread in heavy battery-electric vehicles and how a fire in other parts of the vehicle affects the lithium-ion battery is still limited. Preliminary subpack tests [11] have shown that fire spread from a burning tire to the battery can take significant amount of time, but at the same time, results from previous full-scale firefighting tests [12–18] indicate that the available time to suppress the fire and cool the battery before it gets involved in the fire will still be shorter than the time required for the BA-firefighters (firefighters with breathing apparatus) to reach the scene of the fire.

The knowledge gap also includes the risk of emissions of toxic and potentially explosive battery gases from a heavy vehicle in a mining environment. It should be investigated if the normal ventilation in mines is sufficient to minimize the risk of a flammable mixture of battery gases occurring or if ventilation measures need to be enforced to ensure a safe environment for rescue personnel and avoid gas explosions in the mine. Response plans for rescue operations in the event of a fire in battery-electric mining vehicles may need to be developed.

A fire and rescue operation in a mining environment is not substantially different during a fire in a battery-electric mining vehicle compared to other mining vehicle fires, and the conventional challenges related to long response routes [12, 13], movement in smoke-filled environment [13–18] and the limitations [19] of the ceiling height remain unchanged. The electrification of the mines does however bring additional challenges to the list, which pinpoints the need of further knowledge in the firefighting community and may require adjustments to the tactics and methods used when dealing with battery fires.

Experience from earlier fire incidents in battery-electric passenger cars [5, 20] has highlighted the difficulties with extinguishing battery fires due to the inaccessibility of the battery, the recurring reignition and the substantial volumes of extinguishing water needed. NFPA [21] recommends that approximately 10,000 liters of water is applied, depending on the size and the location of the battery. The size of the battery in an electrified mining vehicle will be larger than in a passenger car. Given the challenging underground conditions mining vehicles operate in, the protective casing of the battery pack can also be more durable [22]. It can therefore be more difficult to both reach the relevant part of the battery with a water jet and require larger volumes of water to sufficiently cool down the temperature of the battery and control the fire.

In the event of a fire in a mine, evacuation may occur to rescue chambers located near the miners' 'workplaces'. The Swedish requirements for a rescue chamber's air supply are based on knowledge from fires and fire tests with vehicles with conventional fuels [23]. Experiences from a boom truck fire [24] in 2020, which required a 10-hour use of the refuge chambers, indicate that the Swedish air supply requirements should be reviewed, but it is currently not clear what capacity and operational time is sufficient in the event of a fire in large battery-electric vehicle. Further studies are therefore required to be able to plan the preventive fire protection work, carry out the necessary risk analyzes and develop action plans.

Further development is also needed to investigate the extent to which active and passive safety systems cost-effectively can reduce the probability of and mitigate the consequences of a fire in a battery-electric mining vehicle. Protection systems that may be relevant include, for example, thermal insulation of batteries, complementary systems for detecting critical conditions in the batteries in addition to the integrated Battery Management System (BMS) and various types of systems for injection of extinguishing and cooling agents into the battery pack. Other safety measures that might serve a special purpose in mining environments includes, for example, enhanced physical protection of vehicle batteries.

Battery-electric mining vehicles have many benefits. They do not generate exhaust gases, have a higher efficiency, require less maintenance, and could possibly lead to lower fire risks in mines than today's conventional vehicles. However, additional research and development is necessary to reach that point and bridge the knowledge gap described in this paper.

References

[1] ”Årsrapport 2016 Brandtillbud,” Gramko Arbetsgrupp Brand, SveMin, 2016. [In Swedish]

[2] ”Vägledning, räddningsinsats där litiumjonbatterier förekommer,” Myndigheten för samhällsskydd och beredskap, 2020. [In Swedish]

[3] B. Truchot, F. Fouillen and S. Collet, "An experimental evaluation of toxic gas emissions from vehicle fires," Fire Safety Journal, vol. 97, pp. 111-118, 2018.

[4] O. Willstrand, R. Bisschop, P. Blomqvist, A. Temple and J. Anderson, "Toxic Gases from Fire in Electric Vehicles, RISE Report 2020:90," RISE Research Institutes of Sweden AB, Borås, 2020.

[5] National Transportation Safety Board, "Safety Risks to Emergency Responders from Lithium-Ion Battery Fires in Electric Vehicles, Safety Report NTSB/SR-20/01," 2020.

[6] F. Larsson, P. Andersson, P. Blomqvist and B.-E. Mellander, "Toxic fluoride gas emissions from lithium-iion battery fires," Sci Rep 7, 10018, 2017.

[7] M. Henriksen, K. Vaagsaether, J. Lundberg, S. Forseth and D. Bjerketvedt, "Explosion characteristics for Li-ion battery electrolytes at elevated temperatures," Journal of Hazardous Materials, vol. 371, pp. 1-7, 2019.

[8] P. Sturm, P. Fößleitner, D. Fruhwirt, S. Heindl, B. Kohl, O. Heger, R. Galler, R. Wenighofer och S. Krausbar, ”"BRAFA" - Brandauswirkungen von Fahrzeugen mit alternativen Antriebssystemen,” Graz University of Technology, 2021.

[9] S. Recoskie, D. MacNeil, J. Perron, S. Touchette, B. McLeod, K. Hendershot, “Thermal Propagation Testing of Electric Vehicles”, National Research Council Canada, 2021

[10] R. Hansen and H. Ingason, "Full-scale fire experiments with mining vehicles in an underground mine, SiST Research Report 2013:2," Mälardalen University, Västerås, 2013.

[11] O. Willstrand, "Battery Fire Tests," 2021.

[12] M. Kumm, A. Palm, K. Palmkvist, A. Lönnermark and H. Ingason, "Räddningsinsats i tunnelmiljö: Fullskaleförsök i Tistbrottet, Sala," Mälardalens högskola, Västerås, 2014.

[13] H. Ingason, M. Kumm, D. Nilsson, A. Lönnermark, A. Claesson, Y. Z. Li, ... and A. Palm, “The Metro Projekt - Final Report,” Mälardalens Högskola, Report SiST 2012:8, Västerås, 2012.

[14] A. Palm, M. Kumm, A. Storm och A. Lönnermark, ”Breathing air consumption in the fire tests at the Tistbrottet mine,” in Proceedings from the 9th International Symposium on Tunnel Safety and Security ISTSS 2020, 2021.

[15] M. Kumm, "Räddningstjänstens förflyttningshastighet under mark: En förstudie om slangdragning i olika undermarksmiljöer, SiST 2010:05," Mälardalen University press, Västerås, 2010. [In Swedish]

[16] M. Kumm and A. Palm, "The fire and rescue services moving speed in underground mass transport systems, Report SiST 2012:3," Mälardalen University, Västerås, 2012.

[17] H. Ingason, A. Lönnermark, H. Frantzich and M. Kumm, "Fire incidents during construction work of tunnels, SP Report 2010:83," SP Sveriges Tekniska Forskningsinstitut, Borås, 2010.

[18] H. Ingason, L. Vylund, A. Lönnermark, M. Kumm, K. Fridolf, H. Frantzich, A. Palm and K. Palmkvist, "Taktik och Metodik vid brand i Undermarksanläggningar (TMU) – sammanfattningsrapport," SP Sveriges Tekniska Forskningsinstitut, Borås, 2015. [In Swedish]

[19] H. Ingason, A. Bergqvist, A. Lönnermark, H. Frantzich and K. Hasselrot, "Räddningsinsatser i vägtunnlar, P21-459/05," 2005.

[20] R. Bisschop, O. Willstrand and M. Rosengren, "Handling Lithium-Ion Batteries in Electric Vehicles: Preventing and Recovering from Hazardous Events," Fire Technology, vol. 56, pp. 2671-2694, 2020.

[21] R.T. Long Jr, A. F. Blum, T. J. Bress and B. R. T. Cotts, "Best Practices for Emergency Response to Incidents Involving Electric Vehicles Battery Hazards: A Report on Full-Scale Testing Results," 2013.

[22] D. Rulli, "Ontario Mine Rescue: Emergency Response to Battery Fires," One-Day Symposium: Battery Electric Vehicle Safety in Mines, 2020. [Online].

[23] A. Storm, M. Kumm and J. Söderström, "Räddningskammare: översyn och revidering av vägledning, RISE Rapport 2020:35," RISE Research Institutes of Sweden AB, Västerås, 2022. [In Swedish]

[24] S. Holmk and C. Harr, "Incident summary: Onaping Depth BEV fire," Virtual Symposium: Battery Electric Vehicle Safety in Mines, 2021. [Online].

The risks associated with Li-Ion batteries in vehicles.

Electrification of vehicles

The evolution towards a sustainable and carbon free society is reflected in the high speed of change from fossil-powered vehicles to electrical ditto. In Sweden today, 5% of the car fleet consists of rechargeable cars and is expected to grow to 2,5M cars in 2030. The fast change is also reflected by the fact that 50% of the sales (2021) of new cars consists of pure electric or hybrid vehicles (statistics from the public site Elbilsstatistik.se).

This is of course positive news but what about the safety?

- Should we be concerned, or can we relax and fully rely on the battery and car manufacturers safety guarantees?
- Are there any remaining risks associated with the electrified cars, the way we use and maintain them?
- Should we care about the electrical infrastructure and have safety concerns when hundreds of cars are parked side by side?
- Should we have concerns about large Li-Ion energy storage units being installed in densely populated cities, in residential buildings and garages to name a few?

This abstract aims to highlight the safety aspects of using Li-Ion batteries in vehicles and how to mitigate some of the safety gaps with smart solutions.

The challenges with Li-Ion batteries

The Li-Ion battery is slowly becoming more safer to use thanks to the continuous research on its electrical behaviors, new materials, and improved designs. The matureness and quality of course vary between manufacturers and the BMS (Battery Monitoring System), which have a central role in the safety system, can either originate as an OEM product or be supplied from a 3rd party supplier. In vehicle applications the battery must manage a multifold of challenges which we will elaborate on in this document.

In reality, there are incidents with exploding batteries, emissions of hazardous gases and heavy fires. This happens at car accidents, post accidents,in car service stations and scrapyards but also on people's parking lot or in their garage. The main cause is mainly due to a phenomenon called **thermal runaway,** where the battery cell enters an exothermal reaction which, if not mitigated fast enough, will be irreversible. At this stage, the batteries generate their own oxygen, as well as emitting toxic gases (CO is one of them) and eventually they often catch fire.

According to Dafo Vehicle's research and findings over the past years, the main reasons for thermal runaway are:

- Material deformation (aging)
- Incorrect cell settings
- External short circuit
- Mechanical abuse
- Manufacturing defects
- BMS errors and failure
- BMS limitations
- Failing cooling system
- Cell swelling (aging)

Above causes can be categorized into three delimited groups:

- **Thermal abuse** – heat and cold
- **Physical abuse** – mechanical penetration or crushing
- **Electrical abuse –** overloads, overcharging, discharging, internal short in cell

If a thermal runaway has started, there are limited possibilitiesthat can be done to extinguish the abused cell.

Therefore, it is essential to monitor the battery, retrieve data and detect gas as early as possible to enable corrective actions.

This would include switching off power through the cell and cooling the adjacent battery cells to prevent them from reaching the critical temperature. Already at 60 ^{o}C some batteries start emitting vapors. At the same time, the exothermal process in the electrolyte creates an internal pressure which at some point in time will force the battery to open its valve to release the gases (at an elevated temperature) to avoid an explosion.

As mentioned, the emphasis should be to minimize the damage by cooling the adjacent cells to avoid thermal runaway. This is preferably done by cooling with a liquid extinguishing agent/coolant.

Charging and overcharging is a factor to highlight as many batteries are often being charged up to 100% while manufacturers recommend 80%. Overloading and overcharging are well known causes for thermal runaway.

Speed-charging batteries increase the risk that a damaged, or incorrectly manufactured battery will initiate an exothermal process, the pre-phase to thermal runaway.

The challenges with Li-Ion batteries in vehicles

The batteries' behavior and service life in vehicles are impacted in many ways by all the factors listed above. Electrified vehicles are daily exposed to many situations that have various impacts on the battery.

Battery charging is a big challenge for both the batteries and the consumers. The recommendations by the four largest rescue firms in Sweden states that charging of electric cars should be by dedicated Li-Ion battery chargers for electrical cars which should be installed by a qualified electrician. Charging from regular 230V outlets using a Schuko plug cable should only be an exception and is not recommended. The reason is that the Swedish 230V local utility grid is not designed for the high capacity required for charging electric vehicles.

The knowledge of charging requirements is generally too low in Europe. Several of the largest car dealers only ship with a Schuko plug charging cable and often do not inform the consumers about the restrictions (which might be intentionally or due to lack of knowledge).

In the event of a collision between two electric vehicles, the rescue service classifies collisions over 64 km/h (front to front) as a high-energy accident. The same classification applies at a 30 km/h side collision and 0 km/h rear-end collision. When the speed exceeds these limits, the risk is high that the battery pack has been abused and that the vehicle must be monitored and quarantined.

All vehicles where the battery has been subjected to physical abuse must be quarantined. The time required for quarantine varies greatly between different vehicle manufacturers. It can range from 24 hours up to 14 days. Together with the Swedish Police, the author of this abstract has developed national rules for seized vehicles which stipulates that the vehicle must be quarantined for 21 days.

It iss a huge challenge for first responders to an accident involving Li-Ion batteries to understand the status of the batteries – if they are abused, if there is an ongoing exothermal process, and if so, if the thermal runaway is close. In the vehicles there is a BMS whose task is to monitor the battery. Batteries in vehicles are divided into cells, battery modules and battery packs. Several battery cells form a battery module, and several battery modules form a battery pack.

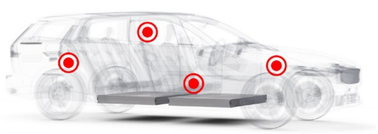
Presently it is almost impossible to know what is happening in an abused battery. Therefore, vehicle service garages must work with quarantine sites, which ought to be mandatory in every service garage that takes care of damaged electric cars.

Ventilation and thermal runaway can occur in the battery when exposed to thermal, physical or electrical abuse. These conditions can occur immediately or with delay and on several occasions. There are many examples where electric vehicles have been involved in collisions and then transported to service garages, where the vehicles have started to burn. It is a huge challenge to know the status of the battery in a vehicle.

Battery abuse forcing cars to quarantine

Leaving a vehicle in quarantine is really demanding from a finance and resource viewpoint. There is obviously a need for a safe and straightforward way to enable work with these vehicles, without compromising the safety.

Based on extensive research conducted by Dafo Vehicle a portable sensor for measuring CO was developed. The solution is designed to work directly at the accident site all the way until the vehicle is handed over to its owner.



By monitoring the vehicle's battery with the portable sensor, also abused batteries that are uncontactable can be transported safely. There are examples in both Europe and the USA where electric cars have started to burn on the flatbed of the tow truck, which has led to several tow trucks starting to burn. An early warning can be given by having a sensor system that can send alarms to a receiver with the driver. Then the driver can stop in a safe place and in the worst case remove the car from the tow truck. It is all about early detection to enable the right measures immediately.

When the vehicle is moved to the service garage for repair, a warning system is required to make the staff's working environment as safe as possible. Since a vast amount of toxic gases can be emitted during Li-Ion battery fires, a new approach to safety is needed. The work environment for service garage staff is crucial with an early warning as the most effective way to protect them.

Research

The innovative high sensitivity CO-sensor (1-1000 PPM) solution is the result of extensive research by Dafo Vehicle Fire Protection in collaboration with RISE. The testing and analysis focused on the behavior of Li-Ion batteries when entering the exothermal process, ventilation, and thermal runaway. Since CO-gas is emitted early on and in a relatively high concentration from all sorts of Li-Ion battery types during the exothermal process, it was decided to concentrate the design efforts on a solution that could be used **regardless of battery type** and in rough environments (i.e. heavy vehicles in mining). Further on is was essential that the sensor could manage a wide operating temperature, having the possibility to measure temperature and humidity, and offer built-in self-calibration and robust communication (CanBus).

Quarantine solution

Dafo Vehicle's proposal for a quarantine site design contains the following specifications:

- No flammable material may be present within a radius of 15 meters from the quarantine vehicle
- The surface should be weatherproof
- Fire alarms should be installed (aging)
- Possibility to back a tow truck and winch vehicles directly into the quarantine site
- Possibility to collect any extinguishing water
- High sensitivity CO sensors installed in areas of specific risks and hazards

Dafo Vehicle, SVFV and the Swedish Police have collaborated on the quarantine site design and developed design drawings of what an adequate site should look like. These are equipped with the Dafo Vehicle CO sensors.

References:

https://www.sbff.se/globalassets/pdf/dokumentbibliotek/pm-627-riskhantering-elfordon.pdf

https://otechworld.com/sony-vaio-laptop-stop-charging/#:~:text=Charging%20the%20battery%20up%20to%2080%25%20is%20good,function%20to%3A%20Increase%20your%20laptop%E2%80%99s%20battery%20recharge%20cycles.

Thermal runaway mechanism of lithium ion battery for electric vehicles: A review Xuning Feng, Minggao Ouyang, Xiang Liu,Languang Lu, Yong Xia, Xiangming He

https://www.nfpa.org/-/media/Files/Training/AFV/Emergency-Response-Guides/Volkswagen/Volkswagen-Emergency-Response-Guide.ashx

Abuse of Lithium-ion Batteries: emergence, composition, and toxicity of vapour cloud

Wojciech Mrozik
School of Engineering,
Newcastle University,
Newcastle upon Tyne, NE1 7RU, UK
wojciech.mrozik@ncl.ac.uk

Malcolm Wise
School of Engineering,
Newcastle University,
Newcastle upon Tyne, NE1 7RU, UK

Neville Dickman
School of Engineering,
Newcastle University,
Newcastle upon Tyne, NE1 7RU, UK

Mohamed Ahmeid
School of Engineering,
Newcastle University,
Newcastle upon Tyne, NE1 7RU, UK

Zoran Milojevic
School of Engineering,
Newcastle University,
Newcastle upon Tyne, NE1 7RU, UK

Prodip Das
School of Engineering,
Newcastle University,
Newcastle upon Tyne, NE1 7RU, UK

Simon Lambert
School of Engineering,
Newcastle University,
Newcastle upon Tyne, NE1 7RU, UK

Paul Christensen
School of Engineering,
Newcastle University,
Newcastle upon Tyne, NE1 7RU, UK

***Keywords:* (5 key words)**
Lithium-ion battery, vapour cloud, safety, hydrofluoric acid, fire

Abstract

Lithium-ion batteries (LiBs) are found in all aspects of our lives - from small portable electronic devices through electric vehicles (EVs) to battery energy storage systems (BESS). LiBs are perceived as crucial to supporting the broad adoption of renewable energy sources. These require BESS to manage the intermittency in their power supply for a reliable electricity grid operation. Applying LiBs in electric traction has initiated a revolution in the automotive industry that is motivated to decarbonize the transport sector and reduce local air pollution.

***Figure 1.** Vapour cloud released from abused (nail penetration) Nissan Leaf II module.*

Like all technology, lithium-ion batteries fail, and the ever-growing number of LiBs in everyday life is likely to result in more failures. Catastrophic events are caused by external factors such as overheating, overcharging, physical abuse, and internal defects introduced during manufacture or ageing [1]. Once exposed to such conditions, the LIB can go into thermal runaway (TR), resulting in toxic gas, fire or even vapour cloud explosion [2]. One of the main factors determining the behaviour during abuse is the State of Charge (SoC). For SOCs, >50%, released gases inevitably ignite in less than 1 min. However, at low SOCs, ≤50%, the vapour may not ignite without sufficient air. Therefore, this phenomenon could lead to flash fire, fireballs developing, or in extreme cases, even a vapour cloud explosion in a confined space.

This work presents the hazards resealed from abused LiBs in confined spaces. In experiments, we used one Nissan Leaf II module, which consisted of 8 pouch cells (total of 1.67 kWh). SoC was set to 40% as we wanted to initiate the vapour cloud without imidate jet flames. Moreover, we had abused the module mechanically (by nail penetration technique) to mimic real scenarios, i.e. car with the tow bar hitting the BESS mounted on the back wall in the garage. The nail was set to punch through the first two cells and allow later to observe the thermal propagation to adjacent cells. Released gases were monitored by the gas sensors (Draeger Xam-5000 – H_2, HCl/HF, HCN, NO_2, SO_2 and CO) and collected via gasbags and thermal desorption tubes for GCMS analysis.

Initially, the thermal runaway was visible by the evolution of a thick, white vapour with black solid particles of ejected cathode material. This vapour is comprised of H_2, SO_2, NO_2, HF, HCl, CO, CO_2, droplets of organic solvent and an extensive range of small chain alkanes and alkenes. Despite the explosion hazard, the white vapour's toxicity must be faced by first responders wherever large LiBs are present in an enclosed space and one or more cells are in thermal runaway. Our tests showed a drastic crossing over safety limits for HF or CO. For instance, for CO, the levels were higher than Imidate Danger to Life and Health (IDLH = 1200 ppm), and for HF, the concentration was about four times higher than IDLH (IDLH = 30 ppm). GCMS analysis shows traces of the electrolyte, its decomomposition producs and various flammable hydrocarbons in the cloud. That has profound toxicity implications for the users and first responders, i.e. proper PPE is needed during intervention and decontamination after.

That leads to concern for places and transportation using LiBs – proper ways of identification, warning systems and ventilation are needed.

References

[1] X. Feng, M. Ouyang, X. Liu, L. Lu, Y. Xia, X. He, Thermal runaway mechanism of lithium ion battery for electric vehicles: A review, Energy Storage Materials, 10 (2018) 246-267.

[2] P.A. Christensen, Z. Milojevic, M.S. Wise, M. Ahmeid, P.S. Attidekou, W. Mrozik, N.A. Dickman, F. Restuccia, S.M. Lambert, P.K. Das Methology, Thermal and mechanical abuse of electric vehicle pouch cell modules, Applied Thermal Engineering, (2021) 116623.

Influence of Sprinklers on the Thermal Exposure of a Tank Exposed to a Hydrogen Jet

Marcus Runefors
Div. of Fire Safety Engineering, Lund University, Sweden
marcus.runefors@brand.lth.se

Robert McNamee
Div. of Fire Safety Engineering, Lund University, Sweden & Research Institutes of Sweden (RISE)

Keywords:* *plate thermometer, hydrogen jets, sprinkler

Abstract

In this paper, a series of experiments are presented to assess the feasibility of using a deluge sprinkler system to prevent tank rupture from an impinging hydrogen jet. In the experiments a simulated tank based on plate thermometer design, was exposed to a small impinging hydrogen jet ($L_f \approx$ 1 m) while simultaneously being cooled by a sprinkler system delivering water densities between 12.2 mm/min and 30.5 mm/min.

The results show that, although the temperature at most of the tank surface becomes significantly lower due to the sprinkler, temperatures can locally remain much higher ($\Delta T \approx$ 600-800K) which might still cause a rupture of a type-IV-tank. It is more likely that a sprinkler system can prevent rupture of a type-I-tank, but this has not been decisively proven.

Note: A full paper version is available, with the same title, in the proceedings of the 10th International Seminar on Fire and Explosion Hazards in 2022.

Background

The low volumetric energy density of hydrogen requires much higher storage pressures (typically 300-950 bar) compared to other gases which causes significant amount of stored mechanical energy which is released in case of a tank rupture. Also, the very high burning velocities of hydrogen causes the combustion of the expanding gas cloud to be on the same timescale as the gas expansion, which are further increasing the maximum overpressure in the pressure wave. Therefore, this scenario leads to very high pressures and needs to be prevented in most situations.

The high storage pressures also result in that carbon fiber tanks with plastic liners (type-4-tanks) are most widely used. In contrast to steel tanks, where a potential tank rupture comes from an increase in internal pressure due to gas heat-up, the rupture of a type-4-tank is primarily linked to degradation of the tensile strength of the composite material above ~130°C. Indeed, internal pressure increase before rupture is typically only in the order of 10%.

Therefore, Pressure activated Pressure Relief Devices (PPRD) can not be used for protection and instead a temperature activated pressure relief device (TPRD) are typically installed. Alternative methods for protections are Leak-Not-Burst-design or possibly intumescent paint. However, these methods have been developed and validated for a hydrocarbon pool fire scenario, which has a significantly different thermal properties compared to a high velocity hydrogen jet flame with a maximum temperature of 2180°C [1]. The effect is also much more local for a jet compared to a pool fire.

An alternative method, that has been applied to some sites in Sweden, is to use a deluge water sprinkler system with the intention to cool the tank and thereby prevent a rupture. However, this approach lacks scientific underpinning and therefore the aim of this presentation is to provide some experimental results to evaluate the effectiveness of such design.

Methods

To measure the thermal impact, a simulated tank was constructed based on a plate thermometer design [2]. The tank was made of 1.5 mm steel with 30 type-KX-thermocouples welded on the inside with a backing of 25 mm ceramic wool with a density of 80 kg/m^3. The measurement points placed at a distance of 100 mm in both the horizontal direction and along the circumference.

The tank was exposed to a hydrogen jet from a 0.6 mm nozzle located 400 mm from the tank. The nozzle was supplied from two hydrogen tanks at 176 bar and 50 l which was allowed to blow down to below 50 bar. At the same time, the tank was cooled by a sprinkler flow of 12.2 mm/min, 24.4 mm/min and 30.5 mm/min. A test without sprinkler cooling was also performed. An overview of the setup can be found in fig 1.

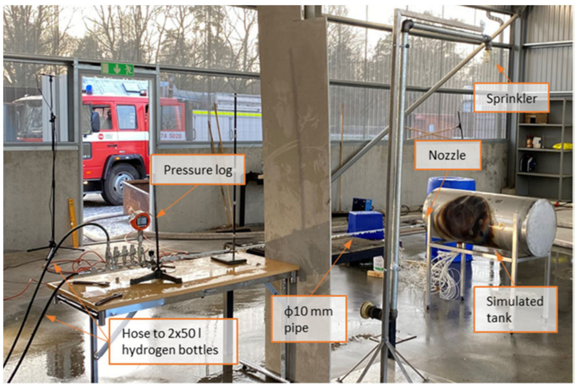


Figure 1. Overview of the experimental setup

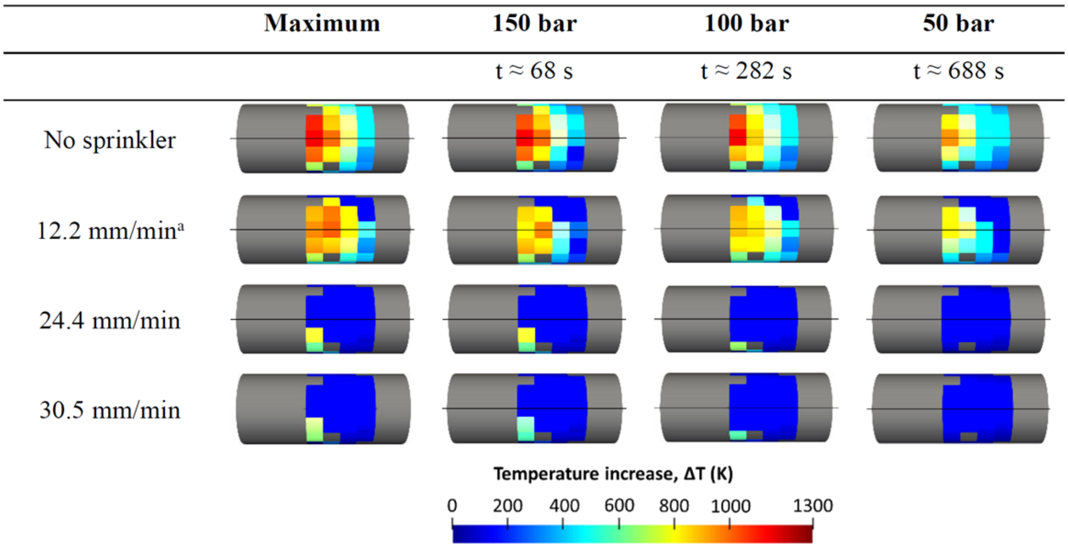


Figure 2. Overview of the temperature profiles of the tank at 150 bar, 100 bar and 50 bar as well as maximum temperature for the different tests.

(a) Note that for this test the sprinkler was placed on the tank centerline while on the other tests it was placed 750 mm in front of it to allow better effect on the point of jet impingement.

Results & Discussion

The target temperature at the different locations are presented in figure 2 at three different pressures during the tank blowdown – 150 bar, 100 bar and 50 bar. This is complemented by the maximum temperature at each location throughout the experiment. Parts of the tank that have colors different from the legend are not equipped with thermocouples (or the thermocouples were damaged during the experiments). For increased readability, only the first of the two iterations at 24.4 mm/min sprinkler flow are presented. It can be seen that the temperature is generally either below 100°C or close to the temperature without sprinkler. This is due to that the cooling is primarily based on a water film being formed at the surface of the tank.

In figure 3, the influence of the water sprinkler system om flame visibility can be found. The effect is most likely due to emission from excited water vapor expected to radiate at the yellow-orange-spectra.

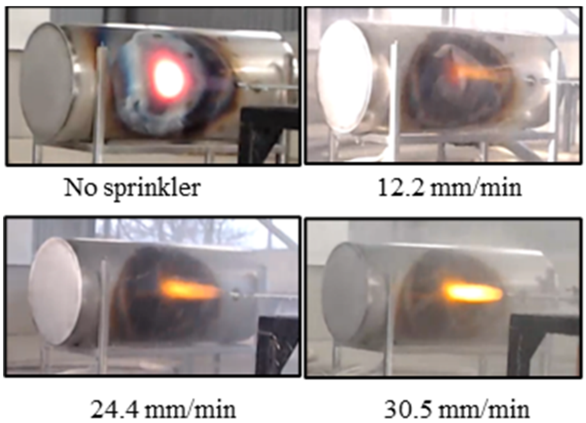


Figure 3. Flame visibility at different sprinkler densities

Conclusions

The results show that a sprinkler system will provide some cooling of the tank, but locally the temperature can still increase 600-800K even for the rather small jet used in the current study. This is higher than what is expected during a bonfire test where type-4-tanks, without TPRD, are expected to fail in less than 10 minutes [3]. Therefore, the use of a water deluge sprinkler system, even at 30.5 mm/min, cannot be used for prevention of a tank rupture for a composite tank.

However, since the average temperature increase across the 28 measuring points decreases from 568K to 90K, it might be possible to prevent rupture of a steel tank (i.e. type-1-tank), but this must be further tested using larger jets.

References

[1] V. Molkov, J.B. Saffers, Hydrogen jet flames, Int. J. Hydrogen Energy. 38 (2013) 8141–8158. https://doi.org/10.1016/j.ijhydene.2012.08.106..

[2] U. Wickström, A proposal regarding temperature measurments in fire resistance furnaces, SP Report 1986:17, Borås, Sweden, 1986.

[3] D. Makarov, Y. Kim, S. Kashkarov, V. Molkov, Thermal Protection and Fire Resistance of High-Pressure Hydrogen Storage, in: Proc. Eighth Int. Semin. Fire Explos. Hazards, 2016..

Impact of firefighting sprays on the fire performance of a structural steel element

Rahul Kallada Janardhan
Dept. of Civil Engineering, Aalto University, Espoo, Finland.

Saani Shakil
Dept. of Civil Engineering, Aalto University Espoo, Finland

Kimmo Partanen
Pieksämäki Fire Station, Pieksämäki, Finland

Marko Hassinen
Pelastusopisto–Emergency Services Academy, Kuopio, Finland

Wei Lu
Dept. of Civil Engineering, Aalto University, Espoo, Finland

Jari Puttonen,
Dept. of Civil Engineering, Aalto University, Espoo, Finland.

Simo Hostikka,
Dept. of Civil Engineering, Aalto University, Espoo, Finland.

Keywords: (5 key words)
firefighting, water monitors, fire spread, FDS, Abaqus, uni-directional coupling

Introduction

Water sprays are most utilised extinguishing agent for fires and especially cellulosic fires [1]. However, the practical efficiency of a water spray depends on several factors such as the ability of the spray to penetrate the flames, the droplet sizes and the actual amount of water that effectively contributes to the extinguishment process. Generally, firefighters attempt to use the available water in the most efficient way to limit the consequences of a fire. During a firefighting operation, the incident commander must choose either an offensive or defensive tactic based depending on the fire severity and resource availability. In large open-frame structures with unprotected structural elements exposed to a travelling/spreading fire scenario, there is a significant risk of structural collapse. Attempting to enter the building can be risky for firefighter safety and the amount of water resources may be insufficient for an offensive attack. An oft employed tactic under such conditions is the structural cooling of load bearing steel elements. And this poses the question: Does structural cooling ensure that firefighters can safely enter a building?

In this work we, investigated the feasibility of using coupled computational fluid dynamics (CFD) and finite element (FE) simulations to aid the planning of fire intervention tactics and the effectiveness of structural cooling approach during firefighting were investigated.

Methods

The characterization of the water sprays was carried out for two water sprays, generated using TFT Blitzfire monitors, using bucket tests in a 24 m x 8.4 m x 5.2 m hall at the Fire and Rescue Services College of Finland and the results were used for calibrating the CFD spray model. The cooling efficiency of the water spray was measured experimentally by applying them on a fire exposed steel beam, and the results were used for validating the coupled CFD-FE model. The validated model was used to simulate fire intervention in a fictitious warehouse with a single large opening and with exposed steel truss beams. The fire intervention was simulated with either one, two or three water sprays for different suppression durations. The sprays were aimed onto the truss beam situated 33.5 m away from the nozzle at a height of 7.0 m with the longest fire exposure as shown in Figure 1. Subsequently, stress analyses of the cooled and uncooled truss beams were performed, and deformation behaviour was studied. A detailed analysis of the fire spread modelling and the structural analysis of the heating phase without fire intervention is reported in [2].

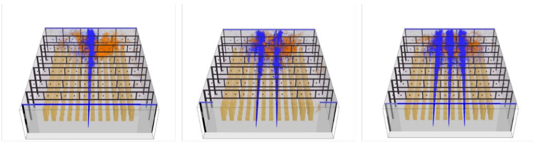


Figure 1: Illustration of the different spray scenarios, their arrangement and region of impact.

Results

The experimental results showed that the cooling power of the spray was proportional to the amount of water used. A cooling period of 10-15 s was sufficient to produce 50 -60 % reduction in steel surface temperatures in the hottest region. The spray modelling showed that the water distribution pattern is highly sensitive to all the modelling parameters and should be carefully calibrated.

In the fire intervention simulations, the results indicate that the cooling effect in this scenario was lower than in the beam experiment due to the longer distance and higher overall temperature. This implies that the pure structural cooling tactic might not be efficient in such buildings as it is extremely difficult to aim the sprays precisely onto the truss beams. However, a significant reduction was observed in the thermal environment around the truss beam when the number of water sprays were increased. In addition to the cooling, the water application also affected the simulated fire spread and power, although this effect was not validated. The results showed that using too small suppression resources can lead to an acceleration of fire development, as the evaporation of the water spray enhances mass flow and turbulence inside the compartment. An important tactical lesson is to ensure that sufficient resources are available before attempting a direct extinguishment of such a strong fire.

FE analysis of the studied truss beam showed that 360 s of water application resulted in the reduction of the steel temperatures to the range of 200 °C to 450 °C. However, insufficient water coverage created turbulent conditions in the warehouse that dramatically increased temperatures in the post-fire period. The cooling of the truss beam at the mid-section successfully prevented further deformations during the suppression. The temperature rise in the post-suppression period did not increase the deformation at the mid-span significantly. However, the truss beam failure is inevitable if it is exposed to such high temperatures for longer time. The relatively large transverse displacements of the truss beams suggest that out-of-plane restraints are critical in fire-safety design. The vertical displacements of the cooled and uncooled truss beams were within the commonly used 'span/20' deformation limit.

Based on the results obtained from the investigated scenario, the structural cooling approach does produce a reduction in temperatures in the cooled region but does not limit the fire spread. Its effectiveness in real scenarios is uncertain especially in large structures. The results also show that the numerical simulations of fire development and structural response provide a safe and powerful methodology for studying and planning fire intervention tactics.

References

[1] G. Grant, J. Brenton and D. Drysdale, "Fire suppression by water sprays," *Progress in Energy and Combustion Science,* vol. 26, pp. 79-130, 2000.J. Clerk Maxwell, A Treatise on Electricity and Magnetism, 3rd ed., vol. 2. Oxford: Clarendon, 1892, pp.68-73.

[2] R. Kallada Janardhan, S. Shakil, W. Lu, S. Hostikka and J. Puttonen, "Coupled CFD-FE analysis of a long-span truss beam exposed to spreading fires," *Submitted to Engineering Structures (under revision),* 2021.

[3] S. Särdqvist, An engineering approach to fire-fighting tactics, Lund, Sweden: Lund Institute of Technology, Department of Fire Safety Engineering, 1996.

FE-analysis as a method to evaluate sustainable materials in fire protection

How is robustness in fire protection affected when traditional building materials are replaced with modern sustainable counterparts?

Lucas Andersson
Fire Safety Engineer
Briab - Brand & Riskingenjörerna AB
Gothenburg, Sweden
lucas.andersson@briab.se

Keywords: (5 key words)
Finite element method, Sustainability, Robustness, Fire protection

Background

The world is moving towards environmental changes in the foreseeable future [1]. As people become more aware of the this, the concept of sustainability permeates both commercial and private practices. The idea of sustained usage over time, with minimal material and energy waste, is becoming a common question for investments both large and small for companies as well as for individuals.

The building franchise is no different – buildings can achieve different certifications depending on their environmental impact. Some examples are BREEAM [2] or LEED [3]. Additionally, as of January 2022 new buildings are required to produce a climate declaration in accordance with Swedish law [4]. These regulatory changes and certification processes invoke constructors to strive for sustainable buildings in a way that the society desires.

When it comes to fire protection in buildings many materials that are traditionally used to achieve adequate levels of fire protection are deemed non-sustainable. To motivate usage of traditional materials from a sustainable point of view it is imperative to achieve a lesser impact by being able to reuse them or to use them over a longer building lifespans. By doing this material lifetimes are extended and thereby the environmental impact can be diluted over time.

An alternative to reusage or longtime usage is the more common option of exchanging the traditional materials to more sustainable options. Using timber in the load-bearing structure or using more sustainable insulation materials like glass wool of wooden fiber insulation can provide more sustainable buildings. These changes can reduce the environmental impact of buildings, but at the same time the robustness of the fire protection may be affected by these material changes. The fire safety robustness is at risk of being compromised as conflicting goals of sustainability generally aims for combustible materials and thereby lesser fire resistance.

But what is robustness? From a structural perspective robustness can be defined as:

” The ability of a structure to withstand events like fire, explosions, impact, or the consequences of human error, without being damaged to an extent disproportionate to the original cause.[5]

Looking into the specific event of fire the fire safety robustness can thereby be seen as how proportional the structural damage may be in relation to an event caused by a fire incident. Furthermore, if a structure, e.g. a steel column, that is part of a system and parts of that system are changed the fire safety robustness, i.e. the damage proportionality in relation to an event caused by the fire, may change as well.

So how can we analyze the changes of fire safety robustness of a system to evaluate if fire safety objectives are met when modifications are done to the system? How can we make smarter decisions regarding adequate fire safety robustness in relation to personal safety?

One answer in certain design situations is the usage of FE-analysis to evaluate thermal penetration of a fire in critical parts of building systems.

FE-Analysis in fire protection

The finite element method (FEM) is a numerical methodology used to solve differential equations for physical phenomena such as heat transfer over a region. The solution is obtained by dividing the region into a finite number of elements [6].

The methodology is commonly implemented in software to extend the number of elements studied. With the use of a transient analysis the thermal response of a building systems, such as an external wall, from a fire can be replicated, see figure 1 below.

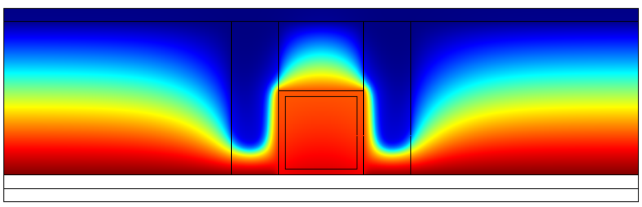


Figure 1. FE-model displaying thermal penetration from a standardised fire exposure

As temperature dependent material properties are assigned to the different parts of the structure thermal responses such as charring of wood-based materials and melting of glass wool can be simulated to some extent [7]. This makes it possible to simulate the effects of a fire furnace test on building systems, such as an external timber stud frame walls, and evaluate the potential consequences of changing components within the system.

Case study

Based on the potential of FE-Analysis in fire and the at times opposing goals of sustainable buildings and fire safety robustness an ongoing case study is conducted. The study aims to quantify the changes in the fire safety robustness when sustainable insulation materials are used instead of traditional ones. The case focuses on the event where protective coverings fall off due to the fire and expose critical parts of the load bearing structures. Does structural damage proportionality to this event change with different kinds of insulation materials?

The aim is pursued by evaluating isotherms and specific temperatures of critical parts within different external wall systems exposed to a transient standardized fire exposure (ISO 834) using FE-Analysis. The changes in fire safety robustness are quantified by the changes in temperatures of the steel column with the different external wall setups. Thermal penetration is analyzed by studying the change of positions of isotherms within the system over time. Charring of timber are estimated to coincide with the 300°- isotherm.[8]

The full extent of the damage proportionally in relation to the protective covering fall off caused by the fire are not evaluated in detail, as only the thermal responses of structures by the fire are studied. Consequently, the mechanical responses are thereby not analyzed. To fully assess the proportionally of the damage the combination of thermal and mechanical responses of the critical parts to the fire needs to be evaluated together. However, higher temperatures and different temperature distributions in critical parts of the load bearing system increases risk of large disproportionate damage in relation to the gypsum fall of due to fire.

The external wall systems studied is a light gauge steel frame and a timber stud frame system. The wall systems are clad with gypsum plasterboards encapsulating a load bearing rectangular hollow sections (RHS) steel column, as seen in figure 2 below.

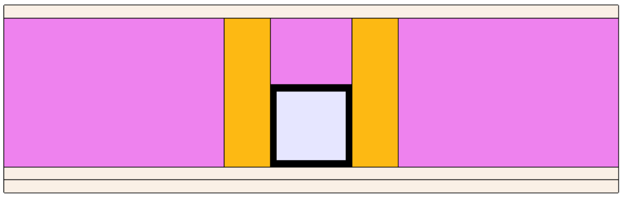


Figure 2. The external wall configuration with timber studs partly used in the FE-analysis.

The two systems are tested with different configurations of insulation materials such as Stone wool, Expanded Polystyrene insulation (EPS), Phenolic Foam (PF) and Wood Fiber Insulation batts.

Conclusions

The thermal penetration from a fire into external wall systems may vary depending on the characteristics of the chosen insulation material. Still, the thermal response of the exposed steel columns from the fire is quite similar in comparison but high. This makes the fire safety robustness unchanged from structural point of view focusing on the thermal response of the column. The damage will still be disproportional to the cause if premature fall off of the protective coverings occurs independent of the insulation material.

However, there are many more fire protection aspects to consider when making changes between different combustible insulation materials in external walls apart from load bearing structures, e.g. external fire spread.

The degree of validation conducted for the different material properties of the insulation materials used in the FE-Analysis vary and it is thereby suggested that further work should involve validation of these by fire furance tests. Furthermore, a fully coupled thermal and mechanical three-dimensional FE-analysis should be done to fully investigate the fire safety robustness.

References

[1] NASA, GLOBAL CLIMATE CHANGE - Vital signs of the planet:Facts, 2022-02-08, https://climate.nasa.gov/evidence/

[2] Swedish Green Building council, “Vad är BREEM-SE?”, https://www.sgbc.se/certifiering/breeam-se/ ,2017-09-06

[3] Swedish Green Building council, “Vad är LEED?”, https://www.sgbc.se/certifiering/breeam-se/ ,2017-09-06

[4] Boverket,“Klimatdeklaration av byggnader”, 2021-10-01, https://www.boverket.se/sv/byggande/hallbart-byggande-och-forvaltning/klimatdeklaration/

[5] Eurokod 1:Laster på bärverk - Del 1-7: Allmänna laster - Olyckslast SS-EN 1991-1-7, SIS, 2006-07-27

[6] N.Ottosen& H, Pettersson "An introduction to the finite element metod, 1992, Pearson education limeted, Edinburgh

[7] Schleifer.V ,Zum Verhalten von raumabschliessenden mehrschichtigen Holzbauteilen im Brandfall, (Dissertation ETH Nr. 18156), 2009, ETH ZÜRICH

[8] Eurokod 5: Dimensionering av träkonstruktioner - Del 1-2: Allmänt - Brandteknisk dimensionering SIS, 2004-12-10

Construction performance in case of fire

Analysis of possibilities using ISO 24679-1

Mahdieh Moghadasi
Department of Mechanical and Industrial Engineering
Norwegian University of Science and Technology
Trondheim, Norway
Mahdiehm@stud.ntnu.no

Anne Steen-Hansen
Department of Civil and Environmental Engineering
Norwegian University of Science and Technology
Trondheim, Norway
anne.steen-hansen@ntnu.no

Keywords:* *(5 key words)
Fire safety engineering, ISO 24679, structure performance, built environment.

Introduction

Demonstrating the adequacy of fire safety measures in the built environment requires assessment a variety of elements, concerning the level of uncertainties in the designing stage. The recently published standard *ISO 24679-1:2019 Fire safety engineering — Performance of structures in fire — Part 1: General* [1]is focusing on the performance of built structure in occurrence of a *real fire*.

There is a low likelihood that a building will face a serious fire, but if it happens, the outcome can be a disaster [2].The process of changes in fire safety in buildings started from plain prescriptive codes developing into rational engineering based on performance goals[3]. In the past, fire resistance in buildings was achieved by designing the building for performing in ambient temperature and in the next step add extra elements like insulation into individual part of structure to enhance the safety of building[2]. These extra elements were defined according to regulations and standards like the Eurocodes. Nowadays, fire safety may be assessed by using engineering approaches, based on the consequences on life and health, property, continuity of operations, the environment, and cultural heritage. Fire safety engineering (FSE) is applied to support performance-based strategies highlighting fire safety objectives, functional requirement sand performance criteria [4]

As it was mentioned earlier, the standard ISO 24679-1 provides a methodology for assessing the performance of structure in the built environment which is developed in compliance with *ISO 23932-1 Fire safety engineering — General principles — Part 1: General* [5]. This abstract presents the outline of a Master's degree project that is performed during the spring 2022.

Objectives

The aim of the project is to describe some steps of the process when applying ISO 24679-1 to a case object. Advantages and weaknesses by using this method compared to traditional methods shall be described, including what kind of obstacles engineers may face during the process, and the efforts required to implement the standard. Which information that is required shall be defined in a sensible and understandable way and finally recommendations that will make it easier for fire safety engineers to apply this standard in their work shall be given.

Methods

A two-storey steel structure called *Nova spectrum* [6]is considered as the case study. In this regard, a review of related published technical reports will be performed:

- ISO 24679-2: Example of an airport terminal [7]
- ISO 24679-3: Example of an open car park [8]
- ISO 24679-4: Example of a fifteen-storey steel-framed office building [9]
- ISO 24679-6 Example of an eight-storey office concrete building [10]

NOVA Spektrum is an arena for trade fairs, exhibitions, congresses, conferences, banquets, concerts and events and conducts business in connection with this. It was established in 1920 with area of over 46000 square metres. This arena includes 9 different halls which it was suggested to consider just one hall with area 7274 square meters called hall B. This hall hosts 6000 people in trade fair event with different stands or 12000 people in concerts without stands and chairs. So, it will be occupied by quite a lot of people. On the other hand, by considering a fire consequence which endanger life, society, environment a construction can be categorized into 4 fire classes [11]. Due the high capacity of this place, the impact of occurring fire can be defined very serious. Therefore, this building is classified into fire class 4. According to "(Byggteknisk forskrift - TEK17)" when a building is considered as fire class 4 it means main load bearing systems in the structure shall be designed to bear completely the load bearing capacity and stability during the event of fire [11]. More detailed information will be provided in the final study.

Figure 1. A landscape picture of case study in this project, NOVA Spectrum [6]

Results

A comprehensive study of the related published technical reports is done so far. In these technical reports, results from analyses of a 2-storey airport terminal, an open car park, a fifteen-storey steel- framework office and an eight-storey office concrete building are presented. Two more technical reports are under development but not published yet. The information from the technical reports will be applied in the analysis of the case study. Final results of the case study and conclusions will be presented in the conference.

Acknowledgements

This study is going to be done with collaboration of Multiconsult. We would like to thank this company for their guidance and help during different stages of this study.

References

[1] ISO 24679-1, "The International Organization for Standardization 24679-1 Fire safety engineering — Performance of structures in fire — Part 1: General." Jan. 2019.

[2] A. H. Buchanan and A. K. Abu, *Structural Design for Fire Safety*. 2016. doi: 10.1002/9781118700402.

[3] V. K. R. Kodur and T. Z. Harmathy, *Handbook of Fire Protection Engineering, Third Edition*. 2016.

[4] M. J. Hurley *et al.*, *SFPE handbook of fire protection engineering, fifth edition*. 2016. doi: 10.1007/978-1-4939-2565-0.

[5] ISO 23932-1, "The international organization for standardization 23932-1 Fire safety engineering — General principles — Part 1: General." 2018.

[6] "NOVA Spektrum," *https://novaspektrum.no/. https://no.wikipedia.org/wiki/Nova_Spektrum*.

[7] ISO/TR 24679-2, "The International Organization for Standardization/ Technical Report 24679-2 Fire safety engineering — Performance of structure in fire — Part 2: Example of an airport ." Jul. 2017.

[8] ISO/TR 24679-3, "The International Organization for Standardization/ Technical Report 24679-3 Fire safety engineering — Performance of structure in fire — Part 3: Example of an open car park." Aug. 2015.

[9] ISO/TR 24679-4, "The International Organization for Standardization/ Technical Report 24679-4 Fire safety engineering — Performance of structure in fire — Part 4: Example of a fifteen-storey steel-framed office building." Aug. 2017.

[10] ISO/TR 24679-6, "The International Organization for Standardization/ Technical Report 24679-6 Fire safety engineering — Performance of structure in fire — Part 6: Example of an eight-storey office concrete building." Dec. 2017.

[11] Norwegian Building Authority, "Regulations on technical requirements for construction works." Jul. 2017.

Experimental study on the mechanical performance of intumescent coatings

Nistor, Ioana
Department of Civil Engineering
Technical University of Denmark
2800 Kgs. Lyngby, Denmark
s202306@win.dtu.dk

Giuliani, Luisa
Department of Civil Engineering
Technical University of Denmark
2800 Kgs. Lyngby, Denmark
lugi@byg.dtu.dk

Lucherini, Andrea
Dep. Struct. Eng. and Building Materials
Ghent University
9000 Gent, Belgium
andrea.lucherini@UGent.be

Keywords:* *(5 key words)
Intumescent coatings; mechanical performance; fire testing; structural fire engineering; steel protection.

Abstract

The use of intumescent coating (IC) to fire protect steel structural elements has significantly increased in last two decades, due to the numerous advantages that IC provides in terms of speed of construction, aesthetics, versatility in application site, and moreover, cost savings and higher insulating efficiency [1]. Despite the increased use, the performance of ICs is still not fully understood, both from the thermal and mechanical points of view.

In particular, it is known that the thermal resistance of the intumescent coating is not only dependent on the temperature, as assumed in current design methods [2], but also on the heating rate [3], substrate [4], shape of the profile [5], and orientation of the element [6]. Furthermore, IC is a concept that involves a wide range of products with quite different compositions and characteristics that are used to protect structures against various fire exposures (cellulosic, hydrocarbon, etc).

However, while an extensive effort has been devoted to study the thermal response of the ICs, in the available literature there is limited research on the mechanical performance of the coating. Some recent experimental studies conducted at DTU have highlighted the possibility of cracking and early detachment of the IC on steel samples protected with epoxy coating subjected to large tensile strain [6] [7] [8]. These results may indicate additional shortcomings in current design methods, which assume that the IC is capable to follow the large deformation of the steel elements and remain in place.

In particular, steel beams are designed against fire by assuming the effective yield strength defined in the Eurocode, which corresponds to the strength value at 2% deformation of the steel [2]. This deformation is quite high and could therefore cause cracking and possible detachment of the IC. However, at present, data on maximum allowable strain in the IC are not available, nor it is investigated to which extent the cracking of the IC can be counteracted by the expansion during fire.

This behavior is seen under high temperatures, but it is not the same when the steel is subjected to large deformations before a fire. This is e.g., the case of fire following earthquakes (FFE), which are at present not considered as accidental design case in codes [9]. Nevertheless, fires during or immediately after earthquake are likely events, as they are often triggered by earthquakes. According to historical records, the damage caused by FFE, frequently outweighs the destructions caused by the actual earthquake. For instance, in the case of the 1906 San Francisco earthquake, the largest urban fire of that time, more than 80% of the damage was caused by post-earthquakes fires [10]. In these cases, the large deformation sustained by the building during the earthquake could damage the passive fire protection, as it is only the steel elements that are designed to sustain the effect of design earthquakes and to dissipate the energy through their structural ductility. Thus, the fire resistance of load-bearing structural systems could be reduced, which would affect not only the safety of the structure, but possibly also of the occupants and rescue services. In particular, information on the building fire resistance is essential for fire fighters, who base their fire-fighting strategy upon it.

Objective and method

The main objective of this project is to find a correlation between the deformation in the steel and damage of the insulation. As it was mentioned before, when it comes to post-earthquake fires (PEF), the aim is to find out the deformation that a building can sustain at ambient temperature (20°C) before having a damage in the coating. On the other hand, the second objective focuses on the reliability of assuming the key deformation values used in fire design for steel structures, as being suitable for sprayed-fire protective materials (SFPM) as well. The deformation must be followed by the IC without causing large cracks or detachment, but it does not exist any indication that the coating will resist without damage.

In this view, two sets of experiments will be conducted on different steel samples coated by two different intumescent coatings: a two-component epoxy-based thick IC (indicated below as E) and water-based thin IC (indicated below as W). The experiments will avail a mechanical actuator and, for the tests at high temperatures, a cylindrical electric oven (Fig. 1). The two possible types of experiments can be differentiated as:

- "transient tests" (noted as TR), where the specimen is first loaded at a given load level and then heated until failure of the specimen or the IC is evidenced;
- "steady-state tests" (noted as SS), where the specimen is first heated to a given temperature and then loaded until failure of the specimen or IC is evidenced.

This terminology is adapted by past literature [11] [12] for concrete, which has a different fire resistance and ductility in the two cases. Similarly, a different behavior is expected for the IC, as a loaded specimen must first be detensioned before cracks appears in the paint.

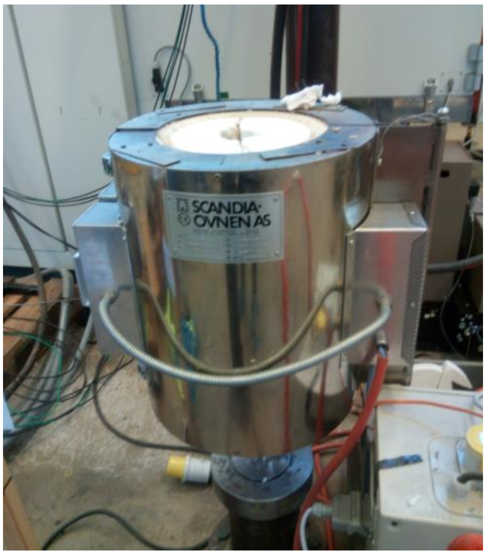


Fig. 1: Experimental apparatus (cylindrical electric oven).

The focus will be on the steady-state tests, where three temperatures will be considered for (20°C, 300°C, 600°C). In particular, the ambient condition tests (at 20°C) are aimed at highlighting the damage that IC could suffer during accidental events other than fire, which can though affect the fire resistance of structural elements to subsequent correlated fire, such as the case of earthquake mentioned above.

Also, two different types of profiles are analyzed: steel rods and steel strips, noted below as R and S, respectively. The SS tests are planned to be carried out on rectangle-shaped profiles as well as on steel rods just for one relevant thickness. Each test will be repeated three times to monitor the variability of the outcome data and to guarantee the reliability and consistency of the test procedures and results.

Acknowledgements

This study is carried out as part of a larger research project on "Mechanical resistance of intumescent coatings" , with the financial support of the COWI FONDEN project, GRANT:A-155.09, Lyngby, DK, 2022.

References

[1] S. Duquesne, S. Magnet, C. Jama and R. Delobel, "Intumescent paints: fire protective coatings for metallic substrates," *Surface and Coatings Technology,* vol. 180–181, p. 302–307, 2004.

[2] EN1993-1-2, "Eurocode 3: Design of steel structures, Part 1-2: General rules - Structural fire design," Comité Européen de Normalization (CEN), Brussels, Belgium, 2005.

[3] A. Lucherini, L. Giuliani and G. Jomaas, ""Experimental study of the performance of intumescent coatings exposed to standard and non-standard fire conditions," *Fire Safety Journal,* vol. 95, pp. 42-50, 2018.

[4] M. Gadgaard and L. Giuliani, "Mechanical performance of intumescent paint protection of steel elements," Master Thesis, Technical University of Denmark, Lyngby, Denmark, 2021.

[5] J. H. Andersen, "Experimental Study of the Thermal Resistance of Intumescent Coatings Exposed to Different Heating Rates," Master Thesis, Technical University of Denmark, Lyngby, Denmark, 2015.

[6] J. Tolstrup, "Fire protection of bridge cables," Cicil Engineering Department, Technical University of Denmark, Lyngby, 2019.

[7] E. Chioti and L. Giuliani, "Epoxy-based fire resistant coatings an experimental study of the mechanical performance," 2019.

[8] A.Arablouei and V.Kodur, "Effect of fire insulation delamination on structural performance of steel structures during fire following an earthquake or an explosion," vol. 84, 2016.

[9] DS-EN 1990, "Basis of structural design. DS-EN 1990 Dansk standard Eurocode 0 : Projekteringsgrundlag for bærende konstruktioner Eurocode," Basis of structural design, 2007.

[10] A. Schiff, C. Scawthorn and J. Eidinger, Fire following earthquake, vol. Monograph no.26, Technical Council on Lifeline Earthquake Engineering-American Society of Civil Engineers, 2005.

[11] Y. Anderberg and S. Thelandersson, Stress and deformation characteristics of concrete at high temperatures: experimental investigation and material behaviour model, Lund, Sweden: Lund Institute of Technology, 1976.

[12] A. Zawadowska, L. Giuliani and K. Dahl Hertz, "Experimental study on the mechanical properties of fire exposed concrete," *Safety Science,* vol. 142, 2021.

Propane flame exposure of concrete elements

Lars Schiøtt Sørensen
Dept. of Civil Engineering
Technical University of Denmark (DTU)
Kgs. Lyngby, Denmark
Lsso@byg.dtu.dk

Frank Markert
Dept. of Civil Engineering
Technical University of Denmark (DTU)
Kgs. Lyngby, Denmark
fram@byg.dtu.dk

Keywords: *Gas flame tests, concrete elements, spalling tests*

Abstract

A test method for gas flame exposure of concrete wall element surfaces. Wall element specimen are forced into a compression state prior to the tests, in order to ensure that concretes susceptible for spalling will show continuous spalling. In this abstract some test results are presented.

Tests performed

A number of screening tests were made using a standard concrete cylinder test setup [1], in which a sudden heat radiation exposure from an oven at 1,000 °C for 30 minutes results in a $T_{SURFACE}$=800 °C. During these cylindrical tests, it was found which concretes were not susceptible for spalling [2]. Next step was to make a propane gas burner test for the concretes that did not show spalling behavior, which is described in the following, starting with a preliminary test.

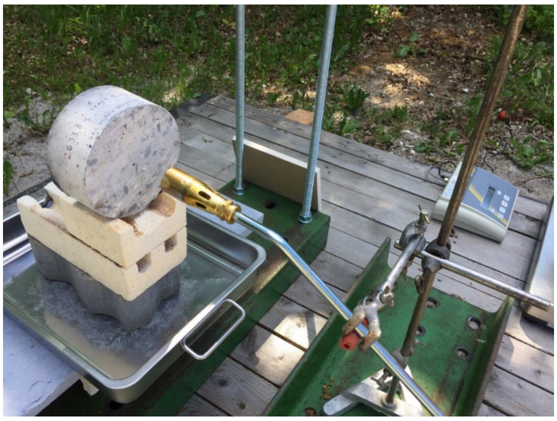


Figure 2. *Preliminary test setup with a common propane gas burner. The flame impinges the surface of the concrete.*

The setup for the propane exposure tests (Figure 3), consist of a frame made of a top and bottom C-profile and four threaded rods (two in each side) shown in Figure 3. The frame is placed on a platform made of timber. The system leveled in place and supported by wedges etc. for achieving a stable system. A concrete wall element (specimen) ready for testing is placed in the frame and adjusted horizontally and vertically to ensure the desired placement in the setup, see Figure 3. The threaded rods are tightened using a torque wrench. The applied tension is adjusted according to the size of the specimen for reaching a desired compression in the concrete. When the specimen is in place, the gas burner placed in front of the concrete surface, with the gas burner head of 50 mm distance to the concrete surface. The type and amount of gas i.e., the burning rate, is selected by the valve according to the test plan. A balance is part of the test setup for measuring the mass loss of gas during the test. In this way, the energy release rate is calculated. The setup ensures that the gas flame exposure made on a concrete specimen of a certain size, compression, representing a small but realistic part of an enclosure or tunnel [3]. The setup includes a data logger for sampling of temperatures via thermocouples (type K). Thermocouples placed in different distances from the concrete surface, and one on the surface as well.

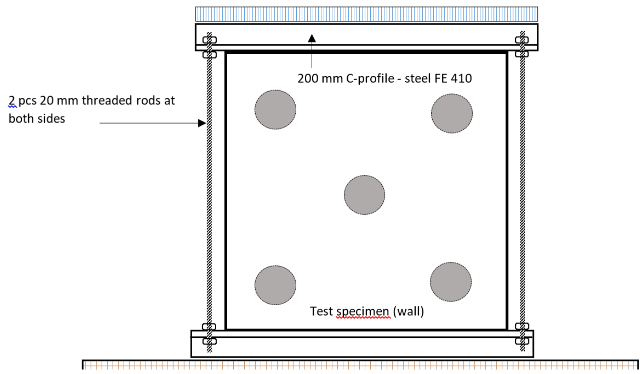


Figure 3. *Test setup for tests of concrete wall elements (in compression), with gas flame exposure [3]. Exposure by propane gas flame 30 min, resulting in $T_{SURFACE}$ >950 °C within 5 min*

After the initial standard cylinder tests, three types of concretes were selected, and tested as wall elements.
Concrete recipes B, C, D (all including PP-fibers):
B: Dense concrete. Probably not susceptible to spalling, at least when PP-fibers added
C: Dense+ concrete. Could be susceptible to spalling, but the amount of fillers are on a relatively low level, so adding of PP-fibers will probably remove the risk
D: Dense+ and high-strength concrete. Experience has shown susceptible to spalling, but reducing of moisture level, and adding of PP-fibers can probably remove the risk.

It is the three concretes with PP-fibers (concrete B, C, D) that were further tested with propane, because none of them showed sign of spalling in the preliminary 1000 ºC heat radiation exposure on standard cylinders.

Table 1Composition of the tested concretes

	Characteristic	w/c-ratio	Micro cilica	Fly ash	Plasti zicer	PP-fiber	Aggr egate
A	Reference	0.45	0%	0%	0	0%	Sea
B	Dense	0.40	1%	0%	+	1%	Sea
C	Dense +	0.35	2%	2%	+	1%	Sea
D	Dense + High strength	0.30	4%	0%	+	1%	Sea

The percentages in table 1 are by cement weight. Curing should be at least 28 days, however longer is better and even more realistic, and we had a curing time of at least 60 days. A water bath (40 ºC) used for accelerated curing for the previously casted and tested standard cylinders, but not for the current "wall specimen". It is relatively important to reach the same moisture level just before the tests, in order to get comparable results. The compressing should be at least 1.2 MPa, ensuring that the concretes susceptible to explosive spalling in fact *are* spalling continuously. If this compression is released, then it is often seen that the spalling stop. For each of the three test items (wall elements) a few propane gas burning exposures performed. The concrete elements for tests by exposure of gas, presented below in Figure 4 and 5.

Figure 4. *Concrete elements, Dim. W x L x T = 1000 x 1000 x 100 mm. Three test items of different concretes recipes (B, C, D) casted for tests*

Figure 5. *Tests with a propane gas burner exposure on one of the wall elements (WE1), w/c=0.40, concrete B, dense*

The temperatures measured by thermocouples placed at different distances from the concrete surface, see Figure 6.

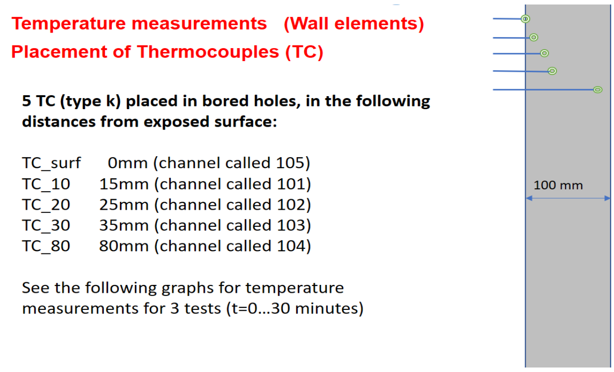


Figure 6. *Temperature measuring points in the concrete wall elements*

Results

Wall Element	w/c (-)	PP-Fibre yes/no	Expo-sure	Gas flow (g/min)	HRR (kW)	Spalling (yes/no)	Cracks
WE1	0.40	yes	Gas flame	16.50	12.65	no	fine cracks
WE2	0.35	Yes	Gas flame	17.75	13.53	no	fine cracks
WE3	0.30	yes	Gas flame	17.60	13,49	(no)*	fine cracks

Figure 7. *Tests of wall elements with gas flame exposure. The first results with propane flame tests. No spalling occurred, just some fine cracks.*

Conclusion

The tests in the first standard cylinder tests [1] found the types of concrete recipes showing spalling or not. The concretes without spalling went to the next level of tests, which was a propane flame exposure in the test setup [3]. None of these propane gas flame tests showed sign of spalling. In the next step these 3 concretes will be further tested using a 700 bar setup for a hydrogen flame exposure simulating impacts of fuel cell vehicles on structures.

Acknowledgements

This project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking (JU) under grant agreement No 826193. The JU receives support from the European Union's Horizon 2020 research and innovation programme and United Kingdom, Germany, Greece, Denmark, Spain, Italy, Netherlands, Belgium, France, Norway, Switzerland.

References

[1] Hertz K.D. & Sørensen L.S. (2005): Test method for spalling of fire exposed concrete, Fire Safety Journal, 40, pp. 466-476

[2] Zaineb, T. Experimental and numerical study of concrete exposed to rapid fire. Master Thesis, August 2020. Department of Civil Engineering, Technical University of Denmark

[3] Sørensen, L.S. Spalling tests – Exposure of concrete walls with gas flame. Subtask 3.4.3 Fire effect on structure integrity and concrete spalling. Presented on HyTunnel-CS project, 6th Project Meeting, held on 15-17 September 2021

Simulations of thermal load in a reduced scale façade test

Karlis Livkiss
Dansk Brand og Sikringsteknisk Institut, Hvidovre, Denmark
kal@dbigroup.dk

Mads K. Hohlmann
Dansk Brand og Sikringsteknisk Institut, Hvidovre, Denmark

Anders Dragsted
Dansk Brand og Sikringsteknisk Institut, Hvidovre, Denmark

Mikkel Thorsdal
Spangenberg & Madsen Rådgivende Ingeniørfirma A/S
Copenhagen, Denmark

Keywords:
ISO13785-1, façade, flame spread, Fire Dynamics Simulator

Introduction

Traditionally in Europe the façade and external wall constructions are approved based on material reaction to fire and fire resistance classification. In general, use of combustible materials is limited. Such restrictions limits the application of bio based materials, that could improve the sustainability in the construction sector.

In order to provide more flexibility in choice of building materials, it is desired to move away from the rigid regulations and substitute them with knowledge based fire safety assessments for individual construction projects. This can be achieved through improving the fire safety competencies and understanding the application and limitations of existing engineering tools. The aim of this study is contributing to understanding of the external façade fire spread. This is done by examining numerical model capabilities for predicting thermal load imposed in ISO13785-1 [1] by using different heat outputs from the burner.

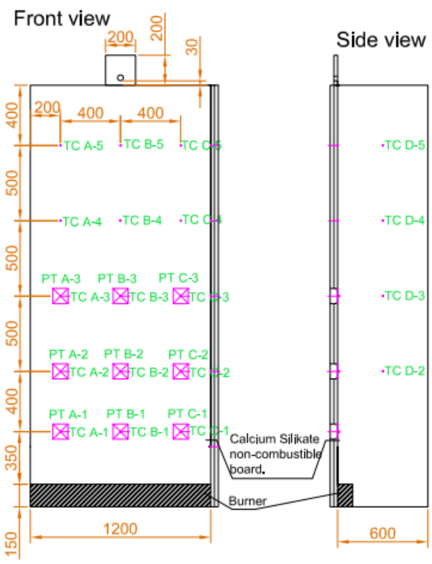


Figure 1. Test instrumentation. PT – plate thermometers, TC – gas phase thermocouples

Testing

A reduced scale façade mock up test, based in ISO13785-1 is used for this study. The test setup consists of corner configuration of non-combustible walls and gas burner with opening dimensions of 100 × 1200 mm2. The corner is set of 1200 mm wide back wall and 600 mm wide side wall. The height of the walls is 2800 mm. This presentation focus on the test data for the numerical model validation. The other aims of the testing programme are investigating the thermal load, repeatability, reproducibility of the method as well as influence of the burner heat output and the presence of the side wall. The test setup is instrumented to determine the thermal load to the façade surface as presented in Figure 1. Nine custom made plate thermometers and 15 gas phase thermocouples are placed in three columns on the back wall. Four gas phase thermocouples are placed on the side wall. Three different propane gas burner outputs are used in this study: 100kW, 75kW and 50kW.

Numerical Model

Numerical simulations are done with Fire Dynamics Simulator FDS version 6.7.7 [2]. Two mesh cell sizes are used in the computational domain: fine mesh near the façade and coarser mesh in areas further away from façade. 20/40 mm mesh and 10/20mm mesh is investigated as a part of the mesh cell size sensitivity analysis and presented in Figure 2 and Figure 3. The figures suggest grid independent result with 20mm mesh cell size near the façade.

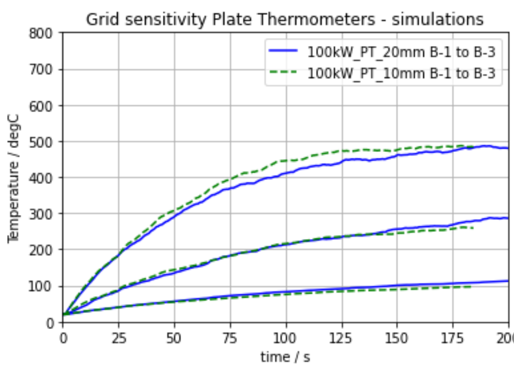


Figure 2. Grid sensitivity to the plate thermometer measurements

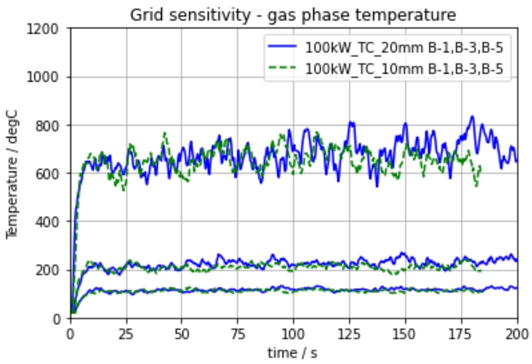


Figure 3. Grid sensitivity to the gas phase thermocouple measurements

Results

A photo from the test and visualization from the simulation are presented in figure 4 and 5 respectively. The gas phase thermocouple measurements increased rapidly and stabilized in a very short time after the beginning of the test. The plate thermometers took longer (approx. 250 to 400 seconds) to reach relatively stable temperatures. Significant differences in gas phase and plate thermometer temperatures were observed between measurements close to the corner and near the open side of the back wall, indicating a strong effect of the corner. In the tests with burner output of 100kW, the measurements in column C were up to 200 % higher than the column A measurements (refer to Figure 1).

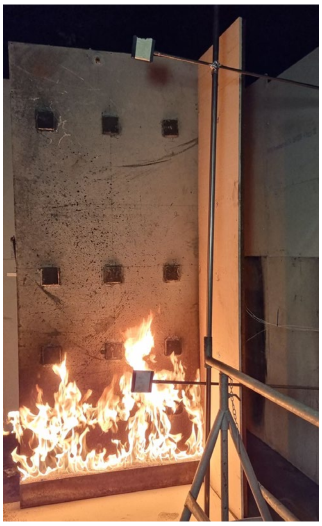


Figure 4. A photo from the 100kW test

The time averaged steady state plate thermometer and gas phase thermocouple measurements are compared with the numerical simulation predictions in Figure 6 and Figure 7, where the blue lines marks 20% and red lines marks 50% error. It can be seen that most of the prediction falls inside 50% error. That numerical model overpredicts the thermal loading in this specific test scenario in most measurement points.

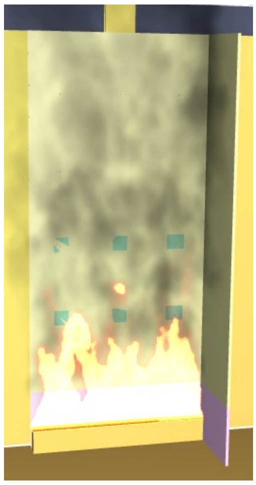


Figure 5. Pyrosim visualization of 100kW test

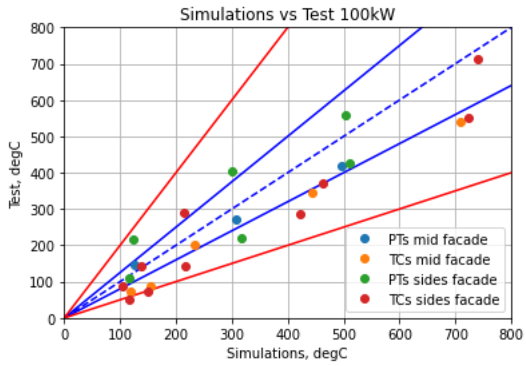


Figure 6. Grid sensitivity to the gas phase thermocouple measurements

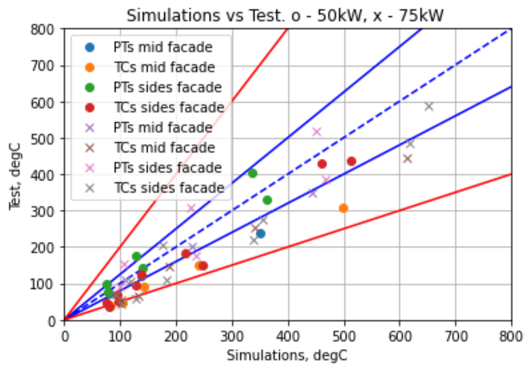


Figure 7. Grid sensitivity to the gas phase thermocouple measurements

The presented results will be used as a step for validating the model for predicting the fire behaviour of combustible, bio based façade claddings.

References

[1] ISO 13785-1:2002 Reaction-to-fire tests for facades – part 1: intermediate-scale test

[2] K. McGrattan, S. Hostikka, R. McDermott, J. Floyd, C. Weinschenk, and K. Overholt, "Fire dynamics simulator user's guide." NIST special publication 1019, no. 6 (2013): 1-339.

Flammable BIO baseded building materials

Can layers of different flammable BIO based building materials be included in wall and roof constructions and meet conservative Danish Fire regulations?

Jess Grotum Nielsen
Assistant Professor
VIA Architectural Technology & Construction Management
VIA University College, Aarhus, Denmark
JEGN@via.dk

Walter Dennis Jackson
Associate Professor
VIA Architectural Technology & Construction Management
VIA University College, Aarhus, Denmark
WATJ@via.dk

***Keywords:* (5 key words)**
Education, Sustainability, Bioconstructions & Fire-testing.

Abstract

National strategy for sustainable building sector

Denmark has formed a national strategy for sustainable buildings in Denmark.[1] The strategy introduces an addition to our Building Regulations BR18, a so called "voluntary sustainable class" that is active on a voluntary basis from 2020-2022. Building designers can adopt this sustainable class during this period and in the process generate and build up a bank of new knowledge that will be required when the strategy is implemented as law. This law will be implemented in 2023 for buildings over 1000 m^2 and for buildings below 1000 m^2 from 2025. In this law there will a requirement for LCA-analysis and limits set for CO_2 emissions, measured in kg. CO_2- equivalent/m^2/year. These CO_2 limits will be reviewed and updated every second year, based upon the experience gained during the process.

The limits set for CO_2-equivalent/m^2/year will initiate the increased usage of sustainable materials and in some cases also renewable building materials. In this context, Biobased products from for example straw, grass & wood fiber etc. which are normally considered to be waste products, will in the future have the potential to be used as sustainable and renewable construction materials and also a means to store CO_2, i.e. contribute to negative CO_2-emissions.

In order for the build environment sector to work with this new strategy for sustainable buildings, the educational sector must also contribute. This project focuses on just that, educating future architectural and construction engineers plus future craft workers on how to design and work with Biobased building materials and Biobased constructions. The showstopper in Denmark so far, has been the need to document that constructions using Bio based materials will meet conservative Danish fire regulations.

Fire classification of Biobased building materials

Many of the Biobased build materials available are today characteristic as having flammable reaction to fire, i.e. classified as E-F according to the European standard 13501-series. This low fire classification, means that in Denmark there is a limited usage of this material with respect to the pre-accepted solutions for fire safety. Therefore, in order to implement more Biobased building materials in the construction of future buildings, the fire safety must be executed by the highest certified fire engineer and a third-party fire engineer with a so called "oriented fire test[2]" performed in accordance with the guidelines for the Danish building regulations. Many companies and test facilities wish to perform these fire tests to help new Biobased products to enter the market. However, before the building industry can use Biobased materials on a wide scale, it is necessary that Bio-construction possibilities are researched, analysed and tested and the results made public to all involved, including the future workforce in the construction industry.

Education of the future workforce for the building sector

Based on the above-mentioned requirement for implementing Biobased building materials and the expected rapid introduction of new materials in the coming years, it is very important that educational institutions support this movement. Therefore, at VIA University College where we educate Bachelor of architectural and construction engineers, we have currently a research project where we include the students in the research process.

At the moment a pilot test project is being conducted with our second semester students, where these students are given lessons in Biobased materials and the pre-accepted solutions

[1] Indenrigs- og Boligministeriet, "National strategi for bæredygtigt byggeri", ISBN: 978-87-971298-8-3

[2] Oriented fire testing is part of the Danish Building Regulations BR18

for fire safety. Using this knowledge, the students then design Biobased constructions for different building parts, such as walls, roof, etc. The preliminary results show several interesting proposals for further analyses.

The next step in the research project is that fourth and seventh semester students will conduct the same study as the second semester students, but here it is required that these more advanced students consider and perform more technical analyses, ensuring that their designs meet the Danish building regulations for moisture, radon, sound, absorption and energy. The students are educated to consider buildings of different heights and if their construction designs are not in accordance with the Danish pre-accepted solutions for fire safety, the students are/will be given lessons, in how different materials such as Bio claddings behave in fires and how construction designs can be put together with fire safety in mind. This educational process will ensure that the student's designs will have the best chance of passing the oriented fire test. The best construction designs will be selected and checked for quality by the educator and also external partners before the selected designs are built as mock-ups for fire testing

The mock-up will be constructed by craft students as part of their education at Technical Colleges institutions such as Aarhus Tech College. In this way the future Danish crafts workforce also participate in this research project, and this segment will gain knowledge on how to physically work with Biobased building materials and hence this segment will also be better prepaered for the increased usage of Biobased building materials in the future.

Fire testing of the mock-ups and presentation of the results

The mock-ups designed by VIA's architectural and construction engineering students and constructed by craft students, will be fire tested by The Danish Institute of Fire and Security Technology.[3] It is expected that the fire results will be presented in the autumn of 2022 and that the education of future students, will be adjusted according to the results obtained in the fire testing. In this way VIA University College, are contributing to the transformation of the building sector to a more sustainable future.

Can layers of different flammable BIO based building materials be included in wall and roof constructions and meet conservative Danish Fire regulations?

The analyses performed so far indicate that the answer to this question will be yes, however the proof will come from the results of the fire test that will be performed later in 2022.

[3] https://brandogsikring.dk/en/fire-testing/

Controlling fire risks due to ro-ro space openings

Alexandra Viitanen, Nikhil Verma, Timo Korhonen, Terhi Kling and Tuula Hakkarainen

VTT Technical Research Centre of Finland Ltd, Espoo, Finland

Keywords:
Ro-ro space fires, ro-ro ships, fire simulation, heat transfer, smoke spread

Abstract

Fires in ro-ro spaces of ro-ro ships form a significant risk to the safety of people onboard. Heat and smoke from a fire can spread through ro-ro space openings to critical areas such as embarkation stations and life-saving appliances, thus endangering safe evacuation.

VTT has studied the fire safety issues of ro-ro space openings and related safety arrangements in the European LASH FIRE project. Fire simulations were performed to study heat transfer and smoke spread from ro-ro space side and end openings to critical areas. The purpose was to evaluate fire risks due to the openings and the effect of possible risk control measures.

Simulations

Fire simulations to study heat transfer and smoke spread from ro-ro space side and end openings to critical areas were performed using the Fire Dynamics Simulator (FDS) software. Real geometries and safety arrangements of existing ro-ro ships were used as the basis of the study.

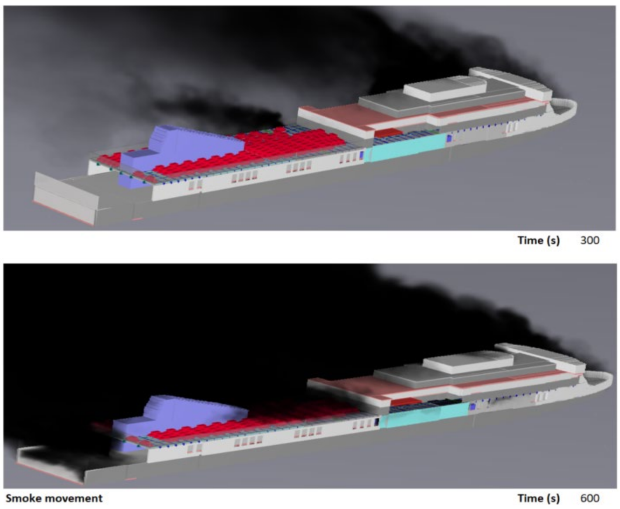


Figure 1. An example of fire simulations showing smoke spread.

Based on statistical data collected in the FIRESAFE I study [1], ship cargo is most likely the origin of fire in the vehicle decks. Thus, a heavy goods vehicle (HGV) fire was chosen as the design fire for the simulations. Heat release rate (HRR) curve for the design fire was formed on the basis of a fire test result by Cheong et al. [2]. The HRR curve from the test was simplified and approximated so that the experimental values remained below the design fire curve.

The studied scenarios included an HGV fire in different locations. Wind direction and speed were varied. Figure 1 illustrates the simulations showing the development of smoke spread in a scenario with portside wind.

The safety of the designs studied was assessed using the life safety performance criteria presented in MSC.1/Circ.1552 [3] in terms of air temperature, radiant heat flux, visibility and CO concentration for humans. For material safety, a heat flux criterion was defined.

Results and conclusions

Potential risk control measures to establish safe design with ro-ro space openings were identified and discussed on the basis of the fire simulation results.

The simulations showed that manoeuvring can be used to direct smoke away from critical areas if conditions are favourable. The necessary condition for this action is that the ship is manoeuvrable, i.e., there is no blackout. Furthermore, the change of the ship's course shall not endanger safe evacuation in rough seas. Wind speed and direction shall be favourable to support the desired outcome after manoeuvring: very low-speed wind cannot push the smoke away efficiently.

Implementing safety distances between ro-ro space openings and critical areas was found to be an effective way to ensure safety of the critical areas. Safety distances were defined separately for side and end openings. It must be noted, however, that simulation results and safety distances are dependent on the assumptions made about the environmental conditions and operational procedures.

In newbuildings, the safety distances can be implemented by means of novel ship designs. For existing ships, the safety distances can possibly be established by closing some openings.

The definition of proper safety distances is challenging, requiring further research work. The goal is that in the future, it would be possible to use either prescriptive values defined in IMO regulations or ship-specific values based on approved calculation or simulation methods in ship design.

References

[1] J. Wikman, F. Evegren, M. Rahm, J. Leroux, A. Breuillard, M. Kjellberg, L. Gustin, and F. Efraimsson, "Study investigating cost effective measures for reducing the risk from fires on ro-ro passenger ships (FIRESAFE) (Final report)," 146 p., 2016.

[2] M. K. Cheong, W. O. Cheong, K. W. Leong, A. D. Lemaire, and L. M. Noordijk, "Heat Release Rate of Heavy Goods Vehicle Fire in Tunnels with Fixed Water Based Fire-Fighting System," Fire Technology, vol. 50, no. 2, pp. 249–266, 2014.

[3] International Maritime Organization (IMO), "MSC.1/Circ.1552. Amendments to the guidelines on alternative design and arrangements for fire safety (MSC/Circ.1002)," 8 p., 2016.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 814975.

Ship evacuation, on equal terms?

A Universal Design problem

Julia Burgén
RISE, Research Institutes of Sweden
Gothenburg, Sweden

Staffan Bram
RISE, Research Institutes of Sweden
Gothenburg, Sweden

Anne S. Dederichs
RISE, Research Institutes of Sweden
Lund, Sweden
and
Department of Civil Engineering and Mechanics, Technical University of Denmark

Per Olof Hedvall
Department of Design Sciences, Lund University
Lund, Sweden

***Keywords:* (5 key words)**
Universal design, inclusive design, accessibility, ship evacuation, passenger ship.

Abstract
Accidents on ships occur and evacuation of passengers of varying age and abilities is a challenge, which needs to be dealt with. The current study on ship evacuations looks into the evacuation process of six ships. Crewmembers with evacuation-related tasks participated in go-alongs on board. It was found that evacuation presents a serious challenge to passengers and crew. Passengers have varying abilities and prerequisites for evacuation. On the visited ships, specialized evacuation procedures primarily focused on a subset of people with mobility impairments while other types of impairments were given less attention.

Background
A large-scale accident such as a fire on a passenger ship may come to require a complete evacuation of all passengers and crew. At the time of writing, the most recent example is Euroferry Olympia, which caught fire near the Greek island Corfu in February 2022. 281 people were rescued from the burning ship but sadly at least eight people lost their lives, with additional persons still missing [1].

The process of ship evacuation can be complex and may involve risks, putting both a mental and physical strain on crewmembers and passengers. The physical and cognitive prerequisites of the passengers vary which has implications for standard evacuation procedures to fit all passengers. For the crew, beyond the apparent pressure of being in an emergency, they are also facing demanding tasks associated with the different phases of an evacuation.

Literature provides knowledge on evacuation – both from buildings and ships [2-6]. However, studies on ship evacuation that account for a realistic passenger demography are scarce.

Method
The present study is based on investigations of six passenger ships. The visits occurred from March 2021- November 2021 and involved ten crewmembers with evacuation-related tasks (or highly ranked in the safety organization). The crewmembers were, to different extent, engaged in go-alongs [7,8] onboard the ship – answering questions while showing equipment and environments related to an evacuation. On two ships, researchers were only able to observe the environments of the ship without any interactions with crewmembers.

In addition to this, nine potential passengers were interviewed on their travel habits and thoughts related to evacuation. Finally, regulations were studied and compared with the results, but were not mapped in their entirety.

The data from the qualitative studies contributed to the description of a ship evacuation as a universal design problem.

Ship evacuation from a universal design perspective
Universal design (UD) is defined as the design of products and environments to be usable by all people, to the greatest extent possible, without the need for adaptation or specialized design [9]. Eight universal design goals are developed with the purpose to improve human performance, wellness and social participation [10]. In the current study, the UD goals and their descriptions were tailored to the specific case of a ship evacuation as:

1. *Body fit:* Accommodating evacuation for a wide range of body sizes and abilities.
2. *Comfort:* Keeping the necessary evacuation activities within desirable limits of body function.
3. *Awareness:* Ensuring that the emergency information is easily perceived.
4. *Understanding:* Making the evacuation activities intuitive, clear and unambiguous.
5. *Wellness:* Prevention of injury while evacuating.
6. *Social integration:* Treating all passengers with dignity and respect while evacuating.
7. *Personalization:* Offering flexible means of evacuation; ensuring legibility, understanding and accessibility.
8. *Cultural appropriateness:* Ensuring that the evacuation activities are taking a wide range of cultural references into account.

To put the goals in relation to the evacuation, the evacuation process is split into different evacuation phases. In research on passengers' behaviors in maritime disasters, evacuation has been described in terms of three phases: pre-movement, motion process and achievement of a safe place

[11]. Within the present study, the evacuation was only studied up until the point of embarkation and the motion process was further elaborated. Sometimes the decision to abandon the ship is not immediately made and the passengers might have to wait at the assembly station for further information. Communication of general safety information (for instance given at departure) was added as a stand-alone phase prior to an accident scenario. See evacuation phases applied in the current work in table 1 together with a description of the main challenges of each phase

Table 1. The different evacuation phases and their main challenges.

Phase	Key challenges
Pre-movement phase	*Getting the attention of the passengers, communicating the emergency information*
Motion phases[1]	*Make sure that all passengers reach the communicated place – both physical challenges and wayfinding*
Waiting phase (at assembly station)	*Keeping passengers calm, comfortable and informed. Life vests is distributed at this point (at some ships they are distributed during some other phase).*
Embarkation	*Getting the passengers into lifeboats and/or life rafts.*
General safety information	*Communicate general safety information to passengers*

Results

The design of all visited ships would only partially account for realistic passenger demographics to evacuate through all phases. On two ships it was told that they would occasionally organize large evacuation drills with invited figurants. There would always be some figurants acting 'difficult' for instance by running away or by resisting. Figurants could also act hurt, but the extent to which they practice evacuating passengers with different impairments is limited.

Passengers with mobility impairments: The discussions about a possible evacuation of the ship easily became centered around passengers with mobility impairments. There are apparent problems if the elevators would be out of service, and activities such as carrying passengers may require a lot of resources. It is common today that a ship is equipped with both lifeboats and life rafts. The life rafts are commonly accessed through a chute. A crewmember explains: *Anyone who can walk of their own would be able to use this.* When options to this is discussed, the person refer to a crane mounted raft that is intended for rescuing people from the water, however this is positioned one deck up, which the elevator does not reach. On other ships crewmember refers to the lifeboats instead of the rafts, which are lowered to deck-level. Whether the safety organization would automatically decide to carry out an evacuation using both lifeboats and life rafts, however, could not be confirmed in the present study.

Passengers with visual impairments: The public address (PA) system is one of the main means of communication emergency information. Upon departure the PA system is also commonly used to give brief safety information. Information regarding wayfinding on the other hand is only observed to be communicated visually and a passenger belonging to this group may be very dependent on the assistance of crewmembers or co-passengers in the motion phases.

Passengers with hearing impairments: The general alarm is, according to regulations, audible and no visual alternative was observed on any of the ships. While the general safety information is available in writing on all ships, the emergency information is communicated over the PA system. At one ship the crew talked about an evacuation bag that the search team would bring, containing pens (among other things). This would allow the crew to communicate through writing if necessary. While this type of bag was only discussed at one ship, it is likely that this is something that the search team could be equipped with on other ships as well.

Passengers with cognitive impairments: Within the current study, there are large uncertainties among crews related to what evacuating passengers with cognitive impairments would implicate.

Conclusion

The results from the field studies and interviews show that ship evacuation presents a serious challenge for both passengers and crew, and that passenger characteristics deviating from the norm, set up through the ship design, are likely to aggravate those challenges. Specialized evacuation procedures normally focused on a subset of people with impairments (i.e. wheelchair users), and for them, evacuation would often involve certain steps (i.e. carrying passengers and assistive products in stairwells) that put a large strain on both the evacuating individual and on assisting crewmembers or co-passengers.

The study also indicates that evacuation arrangements for people with impairments normally focus on physical movement from the muster station to the designated evacuation vessel, while other aspects or phases of evacuation such as safety information, communication and support for wayfinding are not equally developed. In relation to this, demands associated with the different phases of evacuation preparedness and execution do not take sufficient account for variety in the passenger population, such as physical or mental characteristics.

Our results imply that Universal Design could be leveraged to improve evacuation performance. Support for evacuation that is suitable for a large variety of passengers would enable more people to act independently during evacuation, promoting an efficient use of crew resources as well as overall evacuation performance. However, it is also acknowledged that factors such as the ship's age and history of revisions may entail considerable design constraints. In the end, design for evacuation is heavily influenced by regulations that pay too little respect to passenger variations and needs, and thus is not based on realistic passenger demographics.

[1] One motion phase to the assembly station and a second motion phase to the lifeboats (after waiting phase)

References

[1] N. Kitsantonis, "8 Found Dead After Ferry Fire Off Greece as Grim Search Continues", The New York Times, February 26, 2022. [Online]. Available: https://www.nytimes.com/2022/02/26/world/europe/greece-ferry-fire.html [Accessed March 1, 2022].

[2] D. Vassalos, G. Christiansen, H.S. Kim, M. Bole and J. Majumder, *Evacuability of Passenger Ships at Sea,* 2008.

[3] E. Tsychkova, Influence of waves and ship motions on safe evacuation of passenger ships, 2000.

[4] O. Rutgersson, E. Tsychkova, and M. Andersson, Evacuation of passenger ships in rough weather: A study of equipment behaviour and its interaction with human performance, *Naval Architect 2003*, 2003: p. 74-88.

[5] H.D.J.M. May, *Human factors management of passenger ship evacuation.* Human Factors in Ship Design Operation II, 2-3 October 2002, RINA conference, London, 2002: p. 145-156.

[6] C. S. Lu, and C. S. Yang, *Safety climate and safety behavior in the passenger ferry context.* . Accident Analysis and Prevention, 43, 2011 p. 329–341.

[7] M. Kusenbach, "Street phenomenology The go-along as ethnographic research tool", *Ethnography,* 4, 3, 2003: p. 455-485

[8] R. M. Carpiano," Come take a walk with me: The "Go-Along" interview as a novel method for studying the implications of place for health and well-being", *Health & Place,* 15, 1, 2009: p. 263-272.

[9] B. R Conell, M. Jones, R. Mace, J. Mueller, A. Mullick, E. Ostroff, J. Sanford, E. Steinfeld, M. Story and G.Vanderheiden, The principles of Universal Design, NC State University, The Center for Universal Design, 1997. [Online] Available: https://projects.ncsu.edu/ncsu/design/cud/about_ud/udprinciplestext.htm [Accessed February21, 2022]

[10] E. Steinfeld, and J. Maisel, "Practicing Universal Design" in Universal Design : Creating Inclusive Environments, Wiley, Hoboken, NJ, USA, 2012.

[11] C. Casareale, G. Bernardini, A. Bartolucci, F. Marincioni, and M. D'Orazio, Cruise ships like buildings: Wayfinding solutions to improve emergency evacuation. *Build Simul,* 10. 989-1003, 2017.

Performance of a maritime thermal insulation exposed to a realistic ro-ro space fire

Pierrick Mindykowski
Safety – Fire Research
Research Institutes of Sweden - RISE
Borås, Sweden
pierrick.mindykowski@ri.se

Keywords: insulation, ro-ro ships, simulations, experiments

Abstract

Ro-ro ships have been an important component of the commercial maritime industry since their introduction in the 1940's. The ships have a large longitudinal space where cars, trucks and other cargo can be rolled on and rolled off. Despite improved fire protection regulations, many fire accidents have occurred on ro-ro ships and there are no signs of them diminishing in number or magnitude. This was a conclusion at the IMO in 2012 [1] based on a statistical study of ship fire. It has underlined the need for more scientific studies regarding the performance of A class boundaries in case of a ro-ro space fire, especially to prevent fire spread to accommodation spaces. RISE has carried out the RoBound project to answer to this need. The goal of the project was to clarify the performance of "state-of-the-art" fire boundaries between ro-ro spaces and accommodation spaces or other ro-ro spaces, and to give recommendations on how sufficient fire containment is ensured.

To obtain realistic exposure reached during a fire within a ro-ro space, simulations were performed using Computational Fluid Dynamics (Fire Dynamics Simulator [2]). The first step was to model representative ro-ro spaces as well as representative cargo. Two representative ro-ro spaces were then defined: closed and open ro-ro spaces with open ends. Both spaces had the following size, 65 meters long, and 26 meters wide. It was decided to fit it in function of the nature of the cargo. Two types of cargo were chosen:

- Ro-ro space full of trucks with a length of 15 meters, width of 2.5 meters and a height of 4.2 meters.
- Ro-ro space full of cars with a length of 4.4 meters, width of 1.6 meters and a height of 2 meters.

Based on the cargo representation, the height of the ro-ro spaces was:

- Trucks: 6 meters height, giving a free space between the top of trucks and ceiling of 1.8 meters, but only 0.6 meter clearance taking into account the presence of transversal stiffeners having a height of 1.2 meters.
- Cars: 3 meters height, giving a free space between the top of trucks and ceiling of 1.5 meters, but only 0.3 meter considering the presence of transversal stiffeners having a height of 1.2 meters.

The geometry of the ro-ro spaces and the defined above allow for the following cargo arrangement:

- Trucks: 8 lanes of 4 trucks and a total of 32 trucks
- Cars: 10 lanes of 12 cars and a total of 120 cars.

Both representative spaces were designed with one fully open end. The decision to have a fully open end for the closed ro-ro space was based on the RO5 project [4] stating that a fire in a fully enclosed ro-ro space will self-extinguish, and thus representing a less critical scenario for the thermal insulation.

Concerning the open ro-ro space, permanent side openings were assumed and were designed in 3 groups of openings on each side of the ship, 2 groups of 4 openings and 1 group of 2 openings.

The dimensions of the openings depend on the type of cargo in the ro-ro space. In case of trucks, the dimensions were 2 meters by 3.2 meters. With cars the dimensions were 2 meters by 1.3 meters.

The Heat Release Rates for trucks and cars developed were taken from experimental tests done during the project Eureka 499 [5]. With the design fire curves defined, the propagation of fire to involve further vehicles should also be considered. FDS proposes an easy way for how to model fire propagation. It is based on a definition of the thermal properties of target and a heat transfer model, to calculate the internal increase of temperature of the target. When this temperature reaches the ignition temperature of the material constituting the target, ignition of the target is triggered.

In order to keep the approach realistic but simplified, the material as target for ignition was taken to be the same for cars and trucks i.e. natural rubber. This material is used for the fabrication of tires and windows joints, which have proved to be the first materials that ignite in vehicles fires [6].

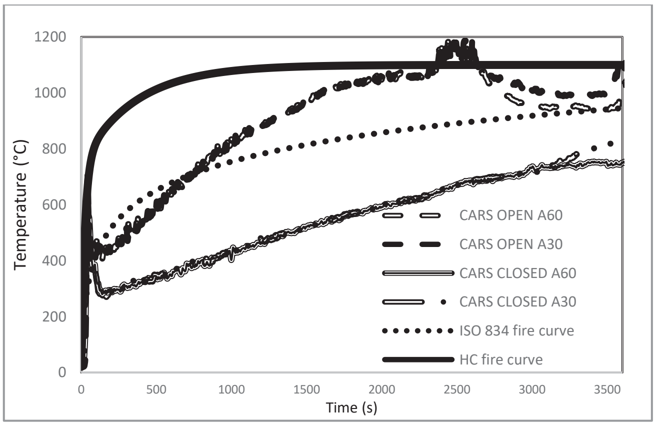


Figure 1. Comparison of the highest temperatures during a simulated fire within a ro-ro space loaded with cars and time-temperature curves

As presented in figure 1, the highest temperature given for each simulated case was then compared with time-temperature curves for designing fire safety. Almost all comparisons showed that the hydrocarbon time-temperature curve fits better to the highest temperature reached in the simulations.

The hydrocarbon time-temperature curve is more severe than the standard (cellulosic) time-temperature curve according to ISO 834, used for type approval of thermal insulation. Experimental tests were then carried out to observe the performance of A class insulation when exposed to the more representative hydrocarbon time-temperature curve in a cubic furnace. The fire insulations were mounted on steel plates with different thicknesses (6 mm and 12 mm).

Tests results showed a significantly reduced fire integrity when exposed to the hydrocarbon time-temperature curve, meaning that it took less time to reach the maximum temperature elevations required by the FTP Code [3] (140 °C for the average temperature elevation and 180 °C for the highest temperature elevation). The reduction, depending on the thickness of the steel plate and thermal insulation, are presented in the table 1. These results apply for stone wool. Glass wool fire insulation was also used in the tests, but it was deteriorated when exposed to the high heat exposure in accordance with the hydrocarbon time-temperature curve.

Steel plate thickness (mm)	Fire integrity based on ISO 834 (min)	Fire integrity based on HC tests (min)	Reduction in fire integrity (HC vs ISO834)
6	60	20	66%
12	60	31	48%

Table 2. Reduction in fire integrity of a A class stone wool thermal insulation exposed to the hydrocarbon time-temperature curve

References

[1] International Maritime Organization, FSI 21/5 Casuality Statistics and investigation, London, 2012.
[2] K. McGrattan, S. Hostikka, J. Floyd, R. McDermott, and M. Vanella. (2020). Fire Dynamics Simulator, User's Guide (NIST Special Publication 1019). National Institute of Standards and Technology.
[3] International Maritime Organization, International Code for Application of Fire Test Procedures, 2010, London: IMO, 2010.
[4] A. Olofsson, P. Mindykowski, Model scale tests of a ro-ro space fire ventilation (RO5 project), 2020.
[5] A. Haack, Fire protection in traffic tunnels: General aspects and rsults of the EUREKA 499 project
[6] T. Marton, A. Dederichs, L. Giuliani, Modelling of fire in an open car park, Applications of structural fire engineering, 2016.

Fire safety strategies for taller timber buildings

Ian Pope
DBI – Danish Institute of Fire and Security Technology
Copenhagen, Denmark
ipo@dbigroup.dk

Leo Willem Menzemer
DBI – Danish Institute of Fire and Security Technology
Copenhagen, Denmark
lwm@brandogsikring.dk

Ahmed Ali Awadallah Ahmed
DBI – Danish Institute of Fire and Security Technology
Copenhagen, Denmark
aaa@dbigroup.dk

Anders Dragsted
DBI – Danish Institute of Fire and Security Technology
Copenhagen, Denmark
and@dbigroup.dk

Keywords: mass timber; cross-laminated timber; fire dynamics; fire safety strategy; performance-based design; tall buildings

Abstract

Combustible building materials such as timber can significantly alter the fire dynamics of a compartment in comparison with non-combustible construction. The consequences of this different performance can fundamentally challenge all components of conventional fire safety strategies for taller buildings. This paper summarises the implications of the fire behaviour of medium and high-rise timber buildings on their egress, compartmentation, structural resilience, and fire service intervention, and demonstrates the need for a holistic approach. Research gaps and future work proposed to facilitate performance-based design are detailed.

Introduction

The desire to reduce the carbon intensity and environmental impact of new building construction has driven a growing demand for mineral-based materials, such as steel and concrete, to be replaced by bio-based alternatives [1]. In Denmark, this change will become increasingly necessary in the coming years, as the government requires new building projects to undergo life-cycle analysis (LCA) and meet ever-stricter carbon budgets [2]. Engineered timber products, particularly cross-laminated timber (CLT) and glue laminated timber (glulam) are widely used bio-based alternatives for primary structural elements in mid- to high-rise buildings, with the potential to replace more carbon-intensive materials.

A fundamental difference between timber and other conventional mineral-based materials is that timber is combustible, and will therefore contribute to the fire as it burns. This has profound implications for the fire safety strategy of a building, and may invalidate current design approaches. In particular, this behaviour challenges many of the assumptions that are inherent to the fire safety strategies for medium and high-rise buildings, for which the time-scales of egress and fire service intervention are longer.

Fire safety strategies in tall buildings

The primary components of a holistic fire safety strategy are the egress strategy, compartmentation provisions, structural resilience, and fire service intervention. The performance of each of these components can be characterised in the time domain, and this forms the basis of fire safety engineering analyses that compare the available safe egress time (ASET) against the required safe egress time (RSET) [3]. The ASET is defined by the time at which a fire creates untenable conditions for building occupants, due to exposure to smoke and/or heat, or as a result of structural collapse. The RSET is the time required for occupants to egress to a place of safety, which may be a protected space within the building or somewhere outside, depending on the strategy chosen. Once adequate safety factors are applied, proportionate to the uncertainty in calculating these times, the following design requirement arises:

$$\text{ASET} \gg \text{RSET}$$

For low-rise buildings, the time taken for all occupants to safely egress from the building is typically in the order of minutes, while the time to failure of compartmentation and the structure are substantially larger. Responding fire service personnel also have easier access to the building and can suppress the fire from outside. In this case, eventual breaches of compartmentation or even total structural collapse may be acceptable, depending on the risk to neighbouring properties. However, for taller buildings, the time required for egress and fire service intervention can be in the order of several hours, or a 'stay-put' strategy may be followed, in which occupants remain within the building. Moreover, structural collapse of medium or high-rise buildings is generally unacceptable due to the risk to neighbouring property. Consequently, failure of the compartmentation or structure must be entirely avoided.

Fire behaviour of timber buildings

In a building made from non-combustible materials, the fuel load comprises only the 'moveable fuel' within a compartment, i.e. the combustible furnishings and contents. These moveable fuel loads can be estimated with confidence, and burnout of the fire can be achieved once these fuels are exhausted, as long as the fire is prevented from spreading to adjacent compartments. This is the basis of the *fire resistance* framework, which prescribes *fire resistance* ratings that are intended to ensure that tall buildings endure the full duration of a fire to burnout [4].

In a timber building, design for burnout is complicated by the contribution of the combustible structure to the fuel load, and its effect on the fire dynamics. If the compartment is not designed to ensure self-extinction of the timber, it may continue to burn until the entire structure is consumed [5,6]. This cannot be evaluated through standard *fire resistance* testing, which makes no allowance for the contribution of the timber to the fire severity, or for continued burning of the structure after consumption of the moveable fuel load [7]. The additional fuel load and configuration of burning surfaces may also alter the fire dynamics in comparison with a non-combustible structure, promoting fire growth and spread between compartments. For laminated timber materials, failure of the bond lines at elevated temperatures can result in char fall-off that enhances the burning rate and potentially prevents self-extinction [5]. The effects of these contributions from exposed timber on the fire behaviour in a compartment are summarised in Figure 1.

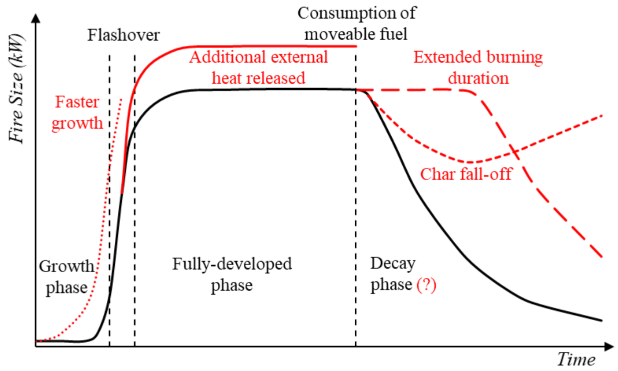


Figure 1. Phases of an under-ventilated compartment fire, and the impact of exposed timber surfaces.

Egress

The egress strategy for a building is usually defined by its height and occupancy, however there are implications of the use of combustible building materials that may challenge this. Firstly, in a large compartment, an exposed timber ceiling may accelerate the growth of a fire if the ceiling ignites, due to the additional thermal feedback from the ceiling to the rest of the room [8]. This faster growth could significantly reduce the ASET for occupants to reach a protected space, and it cannot be quantified by conventional approaches that rely on prescribed 'αt^2' growth rates alone. The potential effect of combustible building materials on the behaviour of occupants and their perception of risk is also unknown, but adherence to a stay-put strategy may be impacted by these attributes. Moreover, if indefinite performance of the structure and compartmentation is not ensured, then any 'stay-put' strategy would be invalidated, and total evacuation of the building must be required.

Compartmentation

In a tall building with a stay-put strategy or extended egress times, the horizontal and vertical compartmentation must be sufficient to prevent fire spread throughout the duration of the fire. For timber compartment boundaries, this requires an explicit design for self-extinction, or a level of encapsulation that prevents the timber from becoming involved in the fire [9]. Vertical compartmentation should also account for a more severe exposure to the facade from external flaming, due to the excess fuel provided by combustible building elements. Timber façade elements may also facilitate fire spread, which must be considered when devising an adequate egress strategy.

Structural resilience

If the fire safety strategy for a tall timber building relies on the structure retaining its capacity indefinitely, then the structure must be designed to withstand the full duration of the fire, including the cooling phase. A pre-requisite of this is to ensure that the timber elements will self-extinguish early enough that they retain sufficient residual capacity at the end of the fire. Furthermore, timber structural elements may also lose some capacity during the cooling phase, after the extinction of the fire, due to the continued propagation of the thermal wave and elevated moisture content through the depth of the cross-section [10]. If indefinite performance cannot be established, then it must be assumed that the affected elements will eventually fail – with consequences for the stability and compartmentation of the building [7].

Fire service intervention

The activities of the fire service are critically dependent upon the behaviour of occupants and the performance of the building. Failure of compartmentation or structural stability will challenge the ability of the fire service to intervene, while additional water resources and suppressing capabilities may be required to manage the increased fire severity. The importance of the cooling phase and related phenomena of continued smouldering and incipient fire spread may necessitate extended fire service intervention and monitoring following the initial extinguishment efforts.

References

[1] G. Churkina, A. Organschi, C.P.O. Reyer, A. Ruff, K. Vinke, Z. Liu, B.K. Reck, T.E. Graedel, H.J. Schellnhuber, Buildings as a global carbon sink, Nat. Sustain. 3 (2020) 269–276. https://doi.org/10.1038/s41893-019-0462-4.

[2] National strategi for bæredygtigt byggeri, (2021). https://im.dk/nyheder/nyhedsarkiv/2021/mar/ny-aftale-sikrer-baeredygtigt-byggeri.

[3] A. Cowlard, A. Bittern, C. Abecassis-Empis, J.L. Torero, Some Considerations for the Fire Safe Design of Tall Buildings, Int. J. High-Rise Build. 2 (2013) 63–77.

[4] A. Law, L. Bisby, The rise and rise of fire resistance, Fire Saf. J. 116 (2020) 103188. https://doi.org/10.1016/j.firesaf.2020.103188.

[5] R.M. Hadden, A.I. Bartlett, J.P. Hidalgo, S. Santamaria, F. Wiesner, L.A. Bisby, S. Deeny, B. Lane, Effects of exposed cross laminated timber on compartment fire dynamics, Fire Saf. J. 91 (2017) 480–489. https://doi.org/10.1016/j.firesaf.2017.03.074.

[6] C. Gorska, J.P. Hidalgo, J.L. Torero, Fire dynamics in mass timber compartments, Fire Saf. J. (2020) 103098. https://doi.org/10.1016/j.firesaf.2020.103098.

[7] A. Law, R. Hadden, We need to talk about timber: fire safety design in tall buildings, Struct. Eng. (2020). https://www.research.ed.ac.uk/en/publications/we-need-to-talk-about-timber-fire-safety-design-in-tall-buildings.

[8] S. Nothard, D. Lange, J.P. Hidalgo, V. Gupta, M.S. McLaggan, The response of exposed timber in open plan compartment fires and its impact on the fire dynamics, in: The University of Queensland, 2020. https://doi.org/10.14264/5d97785.

[9] H. Xu, I. Pope, V. Gupta, J. Cadena, J. Carrascal, D. Lange, M.S. McLaggan, J. Mendez, A. Osorio, A. Solarte, D. Soriguer, J.L. Torero, F. Wiesner, A. Zaben, J.P. Hidalgo, Large-scale compartment fires to develop a self-extinction design framework for mass timber—Part 1: Literature review and methodology, Fire Saf. J. 128 (2022) 103523. https://doi.org/10.1016/j.firesaf.2022.103523.

[10] F. Wiesner, L.A. Bisby, A.I. Bartlett, J.P. Hidalgo, S. Santamaria, S. Deeny, R.M. Hadden, Structural capacity in fire of laminated timber elements in compartments with exposed timber surfaces, Eng. Struct. 179 (2019) 284–295. https://doi.org/10.1016/j.engstruct.2018.10.084.

Evacuation training as a part of fire strategies for timber buildings

Leo Willem Menzemer[1,2]
[1] Division of Fire Safety Engineering, Lund University, Sweden
[2] The Danish Institute of Fire and Security Technology (DBI)
Hvidovre, Denmark
lwm@brandogsikring.dk

Keywords: ***evacuation training; human behaviour in fire; fire safety strategy; timber buildings; serious games;***

Abstract

With biobased buildings making the transition into mainstream construction, the safety of their occupants needs to be adequately ensured, since the introduction of combustible building materials is bearing fundamental ramifications for fire safety strategies of such buildings. The present work introduces a research project on safe evacuation of timber buildings. More specifically, it targets to investigate the effects from evacuation training of building occupants on the required safe egress time (RSET).

Introduction

To reduce the carbon emissions of the construction industry, an increasing emphasis is placed on the use of sustainable, biobased building materials, like timber, in Denmark and globally, due to their potential to emit up to 75% less CO2 compared to commonly used building materials (e.g., steel), while also sequestering carbon in even larger amounts [1].

While this will potentially have a great impact building sustainability [2], many unknowns remain for their implications on fire safety. Biobased building materials affect the fire dynamics in compartments through additional energy release [3] resulting in accelerated fire growth, spread, and increased intensity [4, 5], with further implications on the decay phase [6]. Therefore, building designers are faced with novel challenges that must be solved when evaluating the interactions between the fire, the building, and its occupants in detail to ensure safety when employing green materials.

Egress Safety Strategies

A successful evacuation relies on the availability of sufficient time to reach a safe place, meaning it is necessary to ensure tenable conditions until the evacuation is completed. In this context, two parallel approaches exist to improve safety in hazardous fire scenarios, namely 1) to make sure that the conditions are tenable for a longer time or 2) to decrease the time to reach a safe place. Since for the combustible nature of biobased materials, their use may impede solutions aimed at improving the tenability of the environment, subsequently affecting the time available for evacuation, it is important to counterbalance their use with solutions aimed at ensuring adequate evacuation. A more holistic approach to evacuation safety for buildings including combustible materials is currently missing, as most of the research emphasis in the field has been put on ensuring tenable conditions for longer times rather than systematically identifying solutions aimed at reducing evacuation times in parallel.

Evacuation Training

The evacuation process can be characterized in many ways and terminology way vary across sources, but it is often described using two distinct periods: a pre-movement phase, and a movement phase. Possible solutions to reduce evacuation times are, for example, increasing movement speeds and wayfinding for evacuation.

However, the entire evacuation process consists of a chain of complex decision-making processes, which are described using psychological behavioural models, for instance, the behavioural sequence model by Canter et al. [7] (included in Figure 1) and the Protective Action Decision Model (PADM) by Lindell and Perry [8]. The role of decision-making in evacuation becomes evident considering the pre-movement time and its dependence on the time to reach a decision to evacuate. Hence, this decision governs the evacuation process in the first place, but also during the movement phase evacuee behaviour could be improved. For example, the effect from affiliation behaviour could be reduced, where people tend to stick to known exit routines rather than the most suitable or shortest egress solution in emergencies [9].

Thus, a key aspect to lower egress times is the identification of solutions aimed at improving human risk perception and decision-making for evacuation. In this context, evacuation safety training can play a fundamental role by affecting the components underlying of the evacuation process to ultimately reduce time scales to reach an evacuation decision and the overall RSET (Figure 1).

However, only limited research has been conducted on quantifying the effect of training on evacuation and the benefits that it can have on individual and group decision making [10]. In fact, many national regulatory frameworks focus on egress drills to prescribe the assessment of evacuation performance or evacuation training [11]. However, the regulations are highly inconsistent with one another in terms of objectives, training requirements, and documentation [11], while seemingly also lacking a clear scientific basis that informed their implementation.

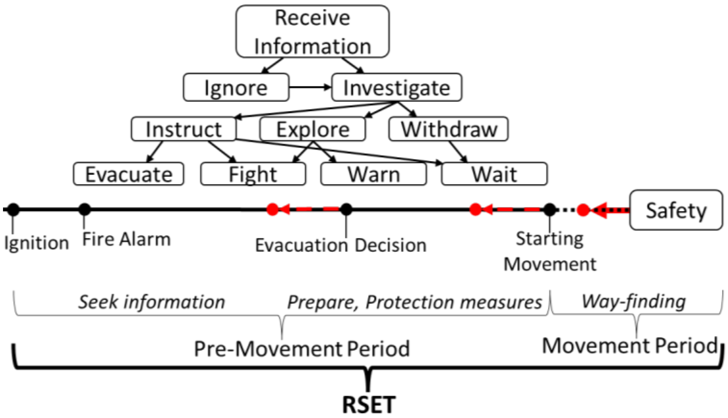


Figure 1. The evacuation process (black) and potential impacts from evacuation training (red) on decision-making processes and behavioural actions during emergencies and fire evacuation. Partly based on illustrations in [7] and [17].

A current approach for fire evacuation training is the application of 'serious games' [12,13]. Training methodologies include the use of simulation tools in the context of serious gaming for evacuation, such as Virtual Reality [14] and Augmented Reality [15], whose potential have been well documented in the literature [16]. Practical issues linked to their implementation, on the other hand, are scarcely investigated.

Research Project

With the goal to generate a scientific basis for the employment of evacuation training, a research project is carried out by DBI in cooperation with Lund University. The aim of this work is to review and analyze existing training methodologies and to study their effect on building evacuation.

Aspects this research will investigate, employing both qualitative and quantitative methods, include the scientific state of the art of behavioural training and training methodologies, the perception of risk and fire safety in timber buildings among occupants, as well as the quantification of the effects from evacuation training and their translation into knowledge applicable to building design.

Outlook

The use of innovative training methods would require a careful assessment of their potential users since the level of familiarity with new technology may vary greatly among building users. Therefore, a systematic study of the validity and quantification of the impact of innovative evacuation training methods for different contexts, like building types (e.g., office or residential), populations (e.g., adults, elderly, residents, visitors), and environments (e.g., working space, dwellings), is a key milestone towards their successful implementation in buildings. This will contribute towards rapid evacuations [18] and subsequently ensure an adequate safety level in biobased buildings.

Acknowledgements

The author acknowledges financial support for the research project from the Innovation Fund Denmark.

References

[1] G. Churkina, A. Organschi, C.P.O. Reyer, A. Ruff, K. Vinke, Z. Liu, B.K. Reck, T.E. Graedel, H.J. Schellnhuber, Buildings as a global carbon sink, Nat. Sustain. 2020 34. 3 (2020) 269–276.
[2] K. Lokesh, A.S. Matharu, I.K. Kookos, D. Ladakis, A. Koutinas, P. Morone, J. Clark, Hybridised sustainability metrics for use in life cycle assessment of bio-based products: resource efficiency and circularity, Green Chem. 22 (2020) 803–813.
[3] A. Law, R. Hadden, Burnout Means Burnout, SFPE Eur. Mag. (2017).
[4] C.G. Putynska, A. Law, J. Torero-Cullen, An Investigation into the Effect of Exposed Timber on Thermal Load, (2016).
[5] R.M. Hadden, A.I. Bartlett, J.P. Hidalgo, S. Santamaria, F. Wiesner, L.A. Bisby, S. Deeny, B. Lane, Effects of exposed cross laminated timber on compartment fire dynamics, Fire Saf. J. 91 (2017) 480–489.
[6] A. Law, R. Hadden, We need to talk about timber: fire safety design in tall buildings, Struct. Eng. (2020).
[7] D. Canter, J. Breaux, J. Sime, Domestic, Multiple Occupancy and Hospital Fires, in: Fires and Human Behaviour, John Wiley & Sons (1980) 117–136.
[8] M.K. Lindell, R.W. Perry, The protective action decision model: theoretical modifications and additional evidence, Risk Anal. 32 (2012) 616–632.
[9] J.D. Sime, Movement toward the familiar: Person and Place Affiliation in a Fire Entrapment Setting, Environ. Behav. 17 (1985) 697–724.
[10] S. Gwynne, M. Amos, M. Kinateder, N. Bénichou, K. Boyce, C. Natalie van der Wal, E. Ronchi, The future of evacuation drills: Assessing and enhancing evacuee performance, Saf. Sci. 129 (2020).
[11] S. Gwynne, E.D. Kuligowski, K.E. Boyce, D. Nilsson, A.P. Robbins, R. Lovreglio, J.R. Thomas, A. Roy-Poirier, Enhancing egress drills: Preparation and assessment of evacuee performance, Fire Mater. 43 (2019) 613–631.
[12] Z. Feng, V.A. Gonzalez, R. Amor, R. Lovreglio, G. Cabrera-Guerrero, Immersive virtual reality serious games for evacuation training and research: A systematic literature review, Comput. & Educ. 127 (2018).
[13] J. Ribeiro, J.E.J.E. Almeida, R.J.F.R.J.F. Rossetti, A.L.A.L. Coelho, A.L.A.L. Coelho, Using Serious Games to Train Evacuation Behaviour, 7th Iber. Conf. Inf. Syst. Technol. (CISTI 2012).
[14] F.M. Williams-Bell, B. Kapralos, A. Hogue, B.M. Murphy, E.J. Weckman, Using Serious Games and Virtual Simulation for Training in the Fire Service: A Review, Fire Technol. 51 (2015) 553–584.
[15] R. Lovreglio, M. Kinateder, Augmented reality for pedestrian evacuation research: Promises and limitations, Saf. Sci. 128 (2020).
[16] M. Kinateder, E. Ronchi, D. Nilsson, M. Kobes, M. Müller, P. Pauli, A. Mühlberger, Virtual reality for fire evacuation research, in: Proceedings of the 2014 Federated Conference on Computer Science and Information Systems. January (2014) 313–321.
[17] E.D. Kuligowski, Human Behavior in Fire, SFPE Handb. Fire Prot. Eng. Fifth Ed. (2016) 2070–2114.
[18] E. Ronchi, Design buildings for rapid evacuation, Nature 528, no. 7582 (2015) 333.

Charring rate of CLT products

Experimental approach

Mika Alanen
Faculty of Built Environment
Tampere University
Tampere, Finland
mika.alanen@tuni.fi

Mikko Malaska
Faculty of Built Environment
Tampere University
Tampere, Finland
mikko.malaska@tuni.fi

Mikko Salminen
Markku Kauriala Ltd
Fire Engineering and Fire Safety Design Consultants
Tampere, Finland
mikko.salminen@kauriala.fi

Pyry Paavola
Faculty of Built Environment
Tampere University
Tampere, Finland

Keywords:
Timber, CLT, charring, charring rate, fire test

Abstract

Current version of EN 1995-1-2 [5] does not include a method to determine the charring of laminated multi-layer timber products and the charring rate values applicable to the fire resistance design of CLT building components. Tampere University has an ongoing research project to investigate the experimental methods to assess the charring rate values of different lamella layers and to derive the design values for structural fire design. In this paper the main observations from a fire test on vertical test specimens are reported.

Introduction

Cross-Laminated Timber (CLT) is a relatively new mass timber product that is widely used in structural walls and floor slabs due to many reasons, such as sustainability, speed of construction, aesthetics, and robustness.

For all building materials and construction elements, fire safety is an important issue that needs to be addressed. It is widely recognized in the structural fire community that there are several knowledge gaps in the field of timber fire design. The applicability of standard fire test and so-called fire resistance framework for timber fire design has been questioned e.g. in [1]. Moreover, it has been shown that the widely used Reduced Cross-Section Method (RCSM) together with so-called zero-strength layer may lead to unsafe results in many cases [2]. It is also evident that there are some key differences in the behavior of CLT products when compared to solid timber elements. At elevated temperatures the timber-adhesive interaction weakens and can lead to debonding, which can be classified as char fall-off or as delamination. In the case of delamination and char fall-off before or at the adhesive line there will be an increase in charring rate as residual timber cross-section is exposed prematurely as new fuel [3].

Even though there is lot of discussion, criticism and room for development related to the current practices in timber fire design and testing, the fire-resistance framework i.e. using standard fire exposure in furnace test as well as RCSM are still (and will probably remain) widely used concepts for structural fire design of timber structures. Irrespective of the fire exposure and the applied design method, the charring rate and char depth will probably remain the most important parameters in the structural fire design of timber. Therefore, it is extremely important that the fire test results will provide the needed information for the design process and that the charring rates and char depths are determined consistently for different products in the fire tests.

In Europe, CLT is not yet part of a harmonized standard. There are European Test Assessments (ETA) for some products available, but the specified properties are often based on small-scale ad-hoc tests and extrapolation which may result in unsafe values for char depth [4]. Moreover, the current version of EN 1995-1-2 [5] does not include a method to determine the charring of laminated multi-layer product that can delaminate, such as CLT. Therefore, consistent guidelines how the charring rate and char depth of CLT-product should be determined from test results are needed to enable more efficient, realistic and safe structural fire design of CLT-products.

Tampere University has an ongoing research project to investigate the experimental methods of determining the charring rate values applicable to the fire resistance design of CLT building components. The aim of the research is to assess how the charring rate values (β_0) representing the performance of different lamella layers, especially the layers behind the first exposed lamella layer should be experimentally determined. There are several issues affecting the measured temperatures the rate values are based on, and all these should be controlled and standardized by the test method. In this paper, the main observations from a fire test carried out using specimens in vertical position are reported. The size of the two specimens was 850 mm x 905 mm (height x width) and they consisted of five 20 mm thick layers. The specimens had polyurethane (PUR) adhesive in their main bond line without edge gluing. Specimens were subjected to the standard fire exposure conditions of SFS-EN 1363-1:2020 and heated according to the standard ISO-834 curve.

Test results and observations

In the two specimens of similar construction five thermocouples were installed in each interface between the lamella layers prior to the gluing of the panels. The measurement points at the different lamella interfaces overlap and the overlapping points at consecutive depth form a measurement station. The positioning of the thermocouples relative to the joints between neighboring lamellas vary as shown in figure 1. The joints are likely to affect the results, but there are no standardized instructions on the positioning of thermocouples relative to the joints.

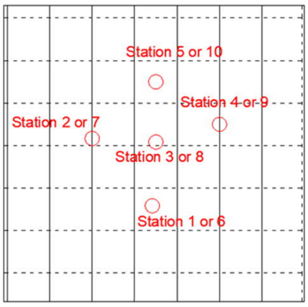


***Figure 1.** A schematic diagram of the placement of the thermocouples on one interface between two lamella layers*

Figure 2 shows the temperatures measured at different thermocouples. The position of the char-line in a test specimen is assumed as the position of the 300 °C -isotherm. The results clearly show that there is a significant variation in the time at which the 300 °C limit is exceeded, especially in the layers behind the first lamella. This is likely to increase the variation at the charring rate values determined by the measurements.

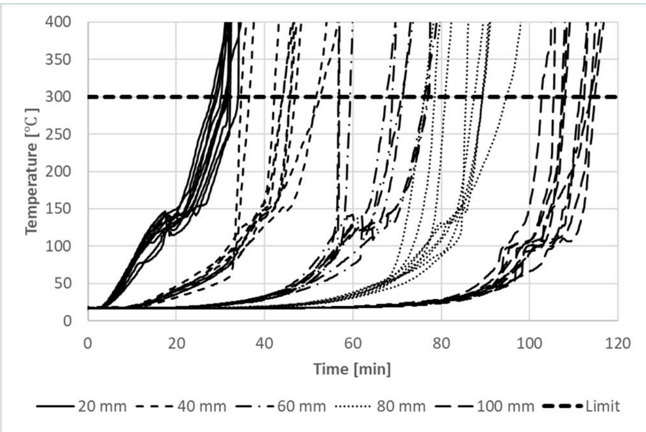


***Figure 2.** Experimental temperature distributions of 100 mm thick panels with five 20 mm thick lamella layers.*

Figure 3 provides a plot of the calculated charring rates at different lamella layers. The horizontal lines represent the average rate value of a layer and the red vertical lines the variation of the rates in the layer. There is practically no variation in the first layer whereas the variation in the second layer is significant. From the fire design point of view, it is difficult to justify a single design charring rate representing the performance of the layers behind the first lamella. The average charring rate of the second layer may provide a safe estimate, but the value is almost double that of the layers behind.

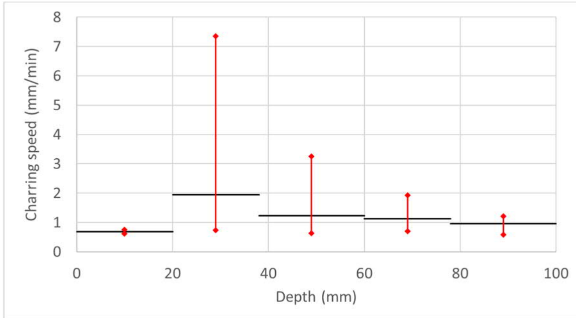


***Figure 3.** Average values and the variation of charring rates at different lamella layers based on ten different measurements at each layer.*

Conclusions

The results obtained from the tests were consistent with earlier studies conducted for CLT. The char depths, charring rates and their scattering varied significantly depending on the considered layer.

This part of the study focused on the challenges in determining the design values for char depth and charring rate experimentally. The main conclusions are listed below:

- There is no standardized test procedure for layered timber structure, such as CLT, in Europe. The procedure should specify e.g. the number and location of the measurement points and how the scattering is addressed in the final results (e.g. if the use of average values is acceptable).
- The measured charring rate at the first layer was consistent with the value of solid wood, and the scattering of the results was small, as expected.
- The charring rate and the scattering of the results were the highest at the second layer, as has been observed in other related studies also.
- There is no standardized procedure how to determine the design value for charring rate of layers behind the first layer so that it will lead to conservative solutions, and it is simple to apply in structural fire design.

References

[1] F. Wiesner, L. Bisby, A. Bartlett, J. Hidalgo, J. Santamaria, S. Deeny, R. Hadden, Structural capacity in fire of laminated timber elements in compartments with exposed timber surfaces. In: Engineering Structures, vol. 179, pp. 284-295. 2019.

[2] J. Schmid, A. Just, M. Klippel, M. Fragiacomo, The Reduced Cross-Section Method for Evaluation of the Fire Resistance of Timber Members: Discussion and Determination of the Zero-Strength Layer. Fire Technology, 51 1285-1309, 2015.

[3] A. Colic, F. Wiesner, L. Bisby, J. Hidalgo, Delamination and Char Fall-Off in Fire-Exposed Cross-Laminated Timber Loaded in Shear. AOSFST 2021 – 12th Asia-Oceania Symposium on Fire Science and Technology, The University of Queensland, Brisbane, Australia, 7-9 December 2021.

[4] Brandforsk 2020:10. Fire Safety in Timber Buildings – A review of existing knowledge. Brandforsk – Swedish Fire Research Foundation. 2020.

[5] EN 1995-1-2. Eurocode 5: Design of timber structures – Part 1-2: General – Structural fire design. CEN, Brussels, 2004.

Fire development in the cavity behind exterior wood cladding
An experimental study

Anne Steen-Hansen, Reidar Stølen, Mikael Bergius, Janne Siren Fjærestad
RISE Fire Research
Trondheim, Norway
anne.steen.hansen@risefr.no

Christian Sesseng, Finn Drangsholt, Geir Drangsholt
Safezone
Trondheim, Norway
christian@safezone.no

Keywords:* *Fire safety, wood cladding, façade, cavity, FDS

Background
In 2020 the Norwegian Building Authority performed an audit of exterior claddings of fire retardant wood, and in connection with the audit it was revealed that certain treated (non-FR) wood products erroneously were declared with classification D-s2,d0 with reference to the CWFT procedure (classified without further testing) [1]. However, these products obtained classification E or F in tests. The cladding in question was so-called *royal oil* treated wood. This is salt impregnated wood that is boiled in linseed oil; leaving a surface layer of 1-3 mm of wood soaked with oil, which increases the cladding's resistance to degradation caused by moisture and weather exposure. Based on these findings two experimental projects were performed.

In the first project fire spread on the exterior façade of wood claddings with different types of non-fire retardant treatments was studied in a series of a total of 30 large-scale tests [2]. Then the fire development in the cavity behind the wooden cladding was studied through a new series of large-scale tests [3], and the results from this second project are presented below, together with results from simulation of fire development in the cavity using Fire Dynamics Simulator (FDS) [4].

Objectives
The objectives were to study how a fire may spread in the cavity behind wood cladding and how the fire spread is affected by different parameters. The main parameter to be investigated was oil treatment of the wood cladding (known as *royal oil*) versus untreated wood. Other parameters were types of lathing and type of wind screen material. Would higher combustibility of the materials in the cavity lead to a faster fire spread than materials with a lower combustibility? Would cross mounted laths give better ventilation and a faster fire spread in the cavity than vertical laths?

Materials
Façade test specimens were constructed of pine cladding with a shiplap profile. Two types of cladding were tested: Untreated wood, and royal oil treated wood. Two types of windscreen boards were used in the cavity: One satisfying Euroclass A2 the other one satisfying Euroclass F. The cladding was mounted on untreated pine laths with profiles 23 mm x 48 mm and 36 mm x 48 mm. In some of the tests the bottom opening of the void was covered with a steel mouse grid with 50% opening, and a steel plate was used to cover the top opening in some of the tests.

Experimental setup
The cladding was mounted as façade elements, all setups with a cavity behind the cladding. The specimen width varied between 0.6 m and 4.8 m, and the height between 2.4 m and 4.8 m. The interior surface of the cladding was smooth. Four test series were performed with vertical cladding nailed to a grid of cross mounted laths. Two test series were performed with horizontal cladding mounted on vertical laths.

The ignition sources were pools of heptane with different surface areas and different depths of the heptane, with averaged HRR of 39 kW, 222 kW, and 1359 kW respectively. The duration of the ignition sources varied between 190 s and 780 s. For the two smallest ignition sources, the flames were "forced" into the cavity by a flame shield at the bottom of the façade, to avoid fire spread on the exterior surface.

Several measurements of temperatures were made at several different heights inside the cavity, the number of measurements varied between the test series. Concentrations of CO_2 and O_2 were measured at the top of the specimens, and the pressure was measured by a bidirectional probe in the center close to the top of the cavity.
The experiments were recorded on movie and photographs. Observations of events of importance, e.g., flames emerging from the top of the specimen, were registered. Photos from the testing are shown in Figure 1.

Figure 1.* *Fire testing of vertical cladding. Right photo: Flames emerging at the top of the façade specimen

Test results

Based on measurements of gas concentrations, pressure and temperatures, HRR was estimated.

Two parameters were assessed as relevant for assessing the severity of the fire spread: Time to 200 °C was reached at a height of 2.3 m, and time to flames were observed on top of the specimens.

Fire simulations

Maximum HRR in the cavities behind the wood cladding was calculated using Fire Dynamics Simulator (FDS) [4].

Simulations with combustible wood panel indicate that inside the cavity, the oxygen supply controls the heat release and the fire spread. To get an idea of what the maximum HRR in the cavity would be, a simplified model of a wall was made (600 mm x 2400 mm) where the combustible panel was replaced with 8 gas panels (burners) stacked upon one another, each measuring 600 mm x 300 mm. Maximum gas supply corresponds to a HRR of 100 kW/m^2, which yields a total HRR of 144 kW if all the gas is ignited.

Two models have been tested, one with a cavity depth of 25 mm and one with a cavity depth of 35 mm. The cavity was open in the bottom and top for ventilation, the sides were closed.

Each panel was heated up linearly from 0 to 100 kW/m^2 over a 10 seconds period if sufficient oxygen concentration was available. The gas supply to each panel was activated sequentially, i.e., first the bottom panel was activated, then the subsequent panels were activated until the top was reached. The gas was ignited spontaneously given that there was enough oxygen to establish combustion.

Results from the simulations show that steady state conditions occurred after about 30 seconds for a cavity depth of 25 mm and after about 40 seconds for a cavity depth of 35 mm. The HRR at steady state conditions was calculated to be 55 kW for the 25 mm cavity and approximately 80 kW for the 35 mm cavity. Non-combusted fuel, due to lack of oxygen, was transported to, and released at, the top of the cavity, where it would ignite spontaneously if the temperature was high enough, or if there was an ignition source present.

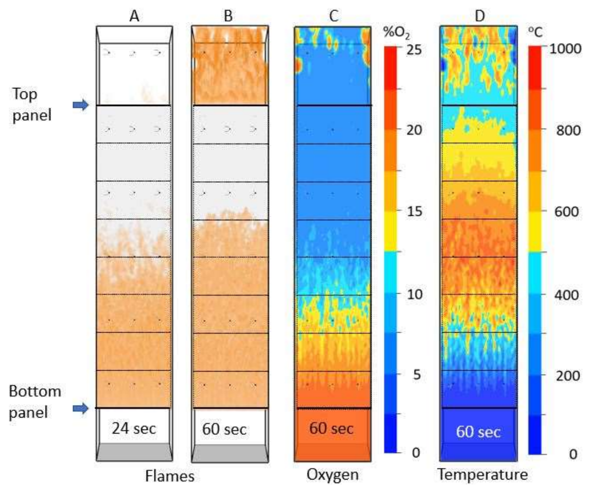


Figure 2. Colour maps showing the situation inside the cavity at steady state conditions

Figure 2 shows colour maps of flames, oxygen concentration and temperatures inside the cavity for the model with 25 mm cavity depth. After 24 seconds (A) we can see some flames at the top of the panel, i.e., the fire is about to get ventilation-controlled. Steady state condition is shown in figure B, C and D.

Discussion and conclusions

The test results were analysed using factorial Anova, applying a p-value of 0.05 [5].

The analysis showed that the size of the ignition source and the type of lathing geometry were significant for the time to reach 200 °C, while the type of windscreen was just outside the criterion for significance for this parameter. For the observations of flames above the test specimens, none of the analysed parameters were found to be significant, but type of windscreen and type of lathing geometry were close to the criterion limit. It was not possible to detect any significant effect on the fire development of the tested oil treated cladding compared to the untreated cladding.

Based on the results we conclude that the ventilation conditions in the cavity is the governing parameter for flame spread. This is also supported by the FDS simulations. The results also indicate that the material in the windscreen may affect the fire spread. This may be due to the combustibility of the material or the thermal insulation properties, or a combination of these. Fire development in the cavity is a complex phenomenon that should be reflected in the guidelines to building regulations.

Acknowledgements

The authors want to thank the sponsors of the project for approving publishing of the project results: Talgø MøreTre AS, Alvdal Skurlag AS, Marnar Bruk AS and Boligprodusentenes forening.

References

[1] COMMISSION DECISION of 6 March 2006 establishing the classes of reaction-to-fire performance for certain construction products as regards wood flooring and solid wood panelling 74 and cladding (notified under document number C(2006) 655) (Text with EEA relevance) (2006/213/EC). 2006.

[2] A. Steen-Hansen and R. H. Mostad, "Vurdering av branntekniske egenskaper til fasadekledning av tre - Branntesting av trekledning med ulike typer behandling," RISE Fire Research, Trondheim, Norge, RISE Rapport 2021:61, 2021.

[3] R. Stølen, M. Bergius, and J. S. Fjærestad, "Brann i holrom bak royaloljebehandla kledning av furu," RISE Fire Research, Trondheim, Norway, RISE Report 2022:05, 2022.

[4] McGrattan et al, Fire Dynamics Simulator User's Guide, FDS 6.7.7, Nov 2021

[5] J. Fox and S. Weisberg, *An R Companion to Applied Regression*, Third. Thousand Oaks CA: Sage, 2019. [Online]. Available: https://socialsciences.mcmaster.ca/jfox/Books/Companion/

Travelling fires with exposed CLT surface

Planning of full-scale test

Andreas Sæter Bøe
Norwegian University of Science and Technology (NTNU)
Trondheim, Norway
andreas.s.boe@ntnu.no

Kathinka Leikanger Friquin
Dept. of Architecture, Materials and Structures
SINTEF Community
Trondheim, Norway
Kathinka.friquin@sintef.no

Keywords: *CLT, COMPARTMENT FIRE, FIRE SPREAD, TRAVELLING FIRE*

Abstract

The use of engineered wood products, like glue laminated timber and cross laminated timber (CLT) has increased massively over the last years. The increased popularity is caused by the many advantages of building with wood, like the possibility of prefabrication, the low carbon footprint, the easy handling and mounting of wood, and its aesthetic look. With the increased popularity, CLT is now used in large compartment buildings, public buildings and office buildings.

However, most experiments studying the fire performance of CLT buildings have been carried out on relatively small compartments with small window openings, resulting in ventilation controlled fires [1-3]. Most modern buildings have large open-plan spaces and large window openings to allow for natural light. A fire in this type of compartment is likely to become fuel controlled, and not ventilation controlled. It can also travel through the room.

Fire dynamics of large open-plan spaces with large window openings is often characterized as travelling fires [4]. Travelling fires are recognized with a steady propagation and burnout of the fire through the room.

Several full-scale travelling fires have been conducted over the last years, but only in compartments with non-combustible surroundings [5]. However, recently tests have also been carried out with a CLT ceiling. These tests have provided new knowledge about how an exposed CLT surface affects the fire dynamic and fire spread rate.

In a 1/8-scale test, Nothard et al.[6] studied the effect of having the ceiling exposed, and reported a more rapid fire spread with an exposed ceiling.
In the *CodeRed#01* test [7], a fire test was conducted in a 380 m^2 combustible compartment with a CLT-ceiling. Initially, the fire spread slowly along a wood crib. But, after the fire plume hit the ceiling, the fire spread rapidly across the exposed ceiling. The intense burning of the ceiling then caused radiation down to the woodcrib, and caused the fire to spread across the entire 174 m^2 wood crib area within 5-6 minutes. The fire developed faster than what is considered an ultra-fast fire spread.

In the X-ONE fire test [8], which was an almost identical test, but with no exposed ceiling, the fire spread across the room in about 25 minutes.

Through the few tests performed with a combustible ceiling, it is evident that there is a need for more knowledge on how different exposed CLT surfaces affects the fire spread and fire safety in large compartments.
How fast a fire spreads is highly relevant for several aspects within fire safety, like: Available time for people to evacuate safely, the size of the fire when the fire brigade enters the building, extinguishing tactics etc.

In order to better understand how an exposed surface affects the fire spread in a large CLT compartment with large window openings, two full-scale tests will be carried out in Autumn 2022 in the FRIC-research centre.

Method

The fire compartment is 19.4 m x 4.8 m x 2.4 m (l x w x h) (see Figure 1), which is approximately the same size as several other travelling fire tests with non-combustible surfaces [9]. The compartment is almost completely open with four large window openings located on the front wall, except from three columns supporting the weight of the ceiling. The window configuration corresponds to an opening factor of 0.18 according to the method of Eurocode 1[10].

A 3 m high inert façade is attached above the window openings in order to study the external flame from the windows.

The fuel load density is 380 MJ/m^2 (per floor area), and is distributed in the room in a continuous wood crib. The wood cribs are built up of 4 layers with 2.8 m long woodsticks with a 50 mm x 50 mm cross-section. The wood crib is located in the centre of the compartment with 1 m distance to each wall.

Two different tests will be carried out, one with exposed CLT ceiling, and one with an exposed CLT wall.

The non-exposed surfaces are protected with 2 layers of gypsum boards.

The compartment will be instrumented to give data on temperature distributions, incident heat flux at different locations in the compartment, on the façade and at a distance away from the fire.

The different sensors installed will give valuable data on fire spread rate, temperature distributions, charring rates, and heat fluxes at the façade.

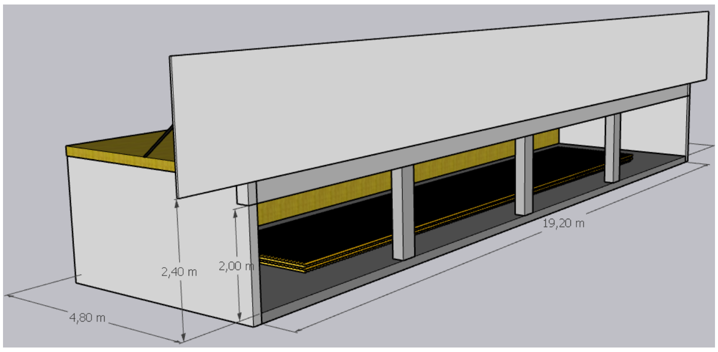


Figure 1. Sketch of the compartment.

References

[1] D. Brandon, J. Sjöström, E. Hallberg, A. Temple, and F. Kahl, "RISE report - Summary report - Fire Safe implementation of visible mass timber in tall buildings - compartment fire testing (2020:94)," 2020.

[2] D. Brandon and B. Östman, "Fire Safety Challenges of Tall Wood Buildings – Phase 2: Task 1 - Literature Review," NFPA, 2016.

[3] G. Ronquillo, D. Hopkin, and M. Spearpoint, "Review of large-scale fire tests on cross-laminated timber," *Journal of Fire Sciences,* vol. 39, no. 5, pp. 327-369, 2021, doi: 10.1177/07349041211034460.

[4] J. Stern-Gottfried and G. Rein, "Travelling fires for structural design–Part I: Literature review," *Fire Safety Journal,* vol. 54, pp. 74-85, 2012/11/01/ 2012, doi: https://doi.org/10.1016/j.firesaf.2012.06.003.

[5] V. Gupta, J. P. Hidalgo, D. Lange, A. Cowlard, C. Abecassis-Empis, and J. L. Torero, "A Review and Analysis of the Thermal Exposure in Large Compartment Fire Experiments," *International Journal of High-Rise Buildings,* vol. 10, no. 4, pp. 345-364, 2021.

[6] S. Nothard, D. Lange, J. P. Hidalgo, V. Gupta, and M. S. McLaggan, "The response of exposed timber in open plan compartment fires and its impact on the fire dynamics," presented at the Proceedings of the 11th International Conference on Structures in Fire (SiF2020), 2020.

[7] P. Kotsovinos *et al.*, "Fire dynamics inside a large and open-plan compartment with exposed timber ceiling and columns: CodeRed #01," *Fire and Materials,* vol. n/a, no. n/a, 2022, doi: https://doi.org/10.1002/fam.3049.

[8] E. Rackauskaite *et al.*, "Fire Experiment Inside a Very Large and Open-Plan Compartment: x-ONE," *Fire Technology,* 2021, doi: 10.1007/s10694-021-01162-6.

[9] V. Gupta, A. F. Osorio, J. L. Torero, and J. P. Hidalgo, "Mechanisms of flame spread and burnout in large enclosure fires," *Proceedings of the Combustion Institute,* vol. 38, no. 3, pp. 4525-4533, 2021, doi: 10.1016/j.proci.2020.07.074.

[10] *EN 1991 1-2 (2002) Eurocode 1: Actions on structures - Part 1-2: General actions - Actions on structures exposed to fire*, Brussels, Belgium, 2002.

A CFD analysis of smoke development in an enclosure of unprotected CLT elements

Jeyad Mohammad Baig
Department of Civil Engineering
Technical University of Denmark
Ramboll A/S Denmark

Anne S. Dederichs
Dept. of Civil Engineering DTU,
Kgs. Lyngby, Denmark
RISE, Research Institutes of
Sweden e- Anne.Dederichs@ri.se

Keywords:* *Smoke developement, CLT, CFD simulation, Critical condition, Combustible lining

Abstract

The smoke contribution of unprotected Cross Laminated Timber (CLT) surface elements in an enclosure was investigated in the current work using computational fluid dynamic (CFD). A series of seven simulations revealed that wood surfaces influence on critical time and smoke development is governed by their location to the fire source. Adjacent combustible walls can spread the fire, causing the pyrolysis process to begin, contributing to smoke and shortening the safe egress time.

Introduction

Concerns about the environmental impact of building constructions lead to an increase in the use of wood. This replacement shall diminish a building's CO_2 emissions by 50%[1]. However, the use of wood implies fire safety issues, which need to be solved. The use of wood has an impact on the structural safety as well as the time until critical condition, affecting the safety for the building's users.

Most literature on enclosure fire dynamics deals with non-combustible enclosures [2]. When using wood, such as Cross-Laminated Timber (CLT), the fire dynamics in combustible wooden enclosures needs to be understood.

Knowledge process of pyrolysis [3] and subsequently combustion of wood are needed for ensuring the fire-safe use of exposed structural timber elements. The findings of experimental and numerical studies show that the timber in an enclosure contributes to fire growth. The time to flashover was shortened [4]. Hence, parametric models for enclosure fire dynamics account for the contribution of unprotected combustible compartment linings.

Studies have shown that the fuel position and distance to combustible linings influence the contribution to the production of pyrolysis gases [4],[5],[6],[7],[8]. The fire dynamics in an enclosure was shown to be affected by whether the char layer of CLT falls off or not [4],[6],[8]. A *fall off* will result in exposing a fresh layer of timber, allowing the production of higher fuel load and rapid pyrolysis. However, if the char layer does not fall off, the remaining layers will stay protected by the char layer, and the fire will automatically extinguish when all exposed combustible material is consumed. The experimental studies therefore highlight that wood has a complex pyrolysis process that may be unpredictable and vary from experiment to experiment.

It was found that the two-zone model fails to account for the placement of exposed timber linings in relation to the fire [7]. The model was found to rely exclusively on the percentage of wood ratio rather than its positioning. Fire behavior, flashover time, ventilation effects, and structural abilities of enclosures with exposed wood linings have been examined (table 1). The current study investigates the smoke produced by exposed wood linings and its potential effect on personal safety during an evacuation.

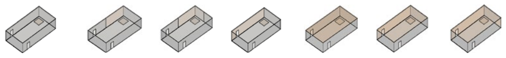
Table 1: *previous work on fire safety of timber constructions*

Objective	Enclosure size (W×L×H)	Approach	Exposed wood surfaces	Fuel Load	Reference
Effect of CLT on compartment fire dynamics	2.72m×2.72m×2.72m	3×experiment	2×walls (15m^2) 1×wall, 1×ceiling (14m^2) 2×walls, 1×ceiling (22m^2)	56 kg wood cribs 132 MJ/m^2	Hadden et al., 2017 [4]
Comparing effect of opening factor in an enclosure with CLT ceilings vs. concrete ceilings	6m×4m×2.52m	6×experiment	None (×3) 1×ceiling (×3)	Wood cribs and heptane 891 MJ/m^2	McNamee et al., 2021 [5]
CLT panels contribution to development, duration and intensity of room fires	3.5m×4.5m×2.5m	5×experiment	None (×3 protected CLT) All CLT (×2)	Propane 379 MJ/m^2 Furniture 529 MJ/m^2	McGregor et al., 2015 [6]
Fire Dynamics of timber in compartment	4.5m×3.5m×2.5m (×5) 2.72m×2.72m×2.77m (×3)	8×Two-zone model	None 4×walls, 1×ceiling 2× walls (adjacent) 2×walls (opposite) 1×wall 1/2×wall, 1/2×wall 1/4×wall, 1×ceiling 1/2×wall, 1/2×wall, 1×ceiling	Wood cribs/furniture 92-366 MJ/m^2	Wade et al., 2018 [7]
Gas temperature development and charring behavior of CLT compartment	4.5m×4.5m×2.5m	4×experiment	None (×2 protected CLT) None (protected wood studs with insulation) All CLT	Wood cribs 720 MJ/m^2	Hakkarainen 2002 [8]

Method

Seven simulations has been conducted to study the correlation between the quantity and location of combustible linings in an enclosure (table 2). A 250 kW room-corner fire in a standard office compartment was used. The smoke contribution was measured to determine the time to critical condition in a pre-flashover fire enclosure. The smoke reaching the critical height of 2 m was set as acceptance criteria in an enclosure height of 4 m and examined through the vertical profile of smoke layer height and temperature in Pyrosim.

Table 2: *Simulation configuration*



	S1 (Reference)	S2 (W1/2)	S3 (W2x1/2)	S4 (W)	S5 (R)	S6 (WR)	S7 (Wx2R)
Combustible surfaces	None 0	Wall ½	Walls ½+½	Wall 1	Roof 1	Wall+Roof 1+1	Walls+Roof 1+1+1
Timber surface area [m^2]	0	40	60	80	200	280	320
Timber surface ratio [%]	0	6.25	9.38	12.50	31.25	43.75	50
Area average thermal inertia [$J/(m^2 \cdot K \cdot s^{1/2})$]	1243	1184	1155	1126	951	835	776

Results

Previous studies suggested that the critical time would be inversely proportional to the amount of wood. The current study found a disparity between the simulations but no direct correlation to the quantity of combustible surfaces. However, a connection to the location of the combustible lining was found. In figure 1, the relevant simulations are sorted by the position to the fire to show the correlation.

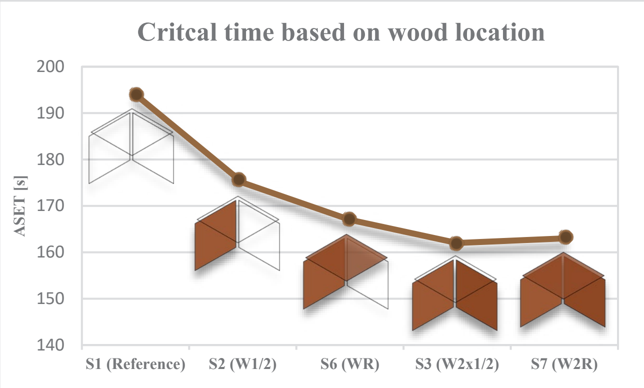


Figure 1: *Graphical representation of ASET correlation to wood location in an enclosure*

The ASET is reduced when more wood lining is placed close to the fire. However, case S7 (3 wood linings close to the fire) does not follow this trend. When comparing the smoke height as a function of time for S3 and S7, S7 begins to decline faster at first, indicating more smoke, but since the difference in the simulations is the combustible roof, it is highly unlikely that the roof will undergo pyrolysis and emit smoke so early due to limited fire spread at that stage. Since the device is influenced by temperature measured across the diagonal axis, it can cause the layer height to vary, and therefore, it is more probable that the data at the start is inaccurate.

Conclusion

The simulations demonstrated that wood surfaces can affect the critical time and it contributes with smoke development and increased temperature. It was found that the amount of wood but also the orientation and location affects the formation of the smoke gas layer.

When one wood surface is adjacent to the fire, the time until critical smoke condition is reached, is reduced by 10%. When a wall and a roof are adjacent, the reduction is 16%. When two or more surfaces are nearby, a 20% reduction is to be predicted.

References

[1] Træbyggeri er godt for klimaet, 2019. https://www.skovforeningen.dk/wp-content/uploads/2019/01/faktaark-traebyggeri-er-godt-for-klimaet_skovforklima.pdf.

[2] B. Karlsson, J. Quintiere, Enclosure fire dynamics, CRC press1999.

[3] L. Berard, P. Otxoterena, A. Dederichs, Compounds Produced by the Pyrolysis of Powders and Dusts Present in the Alimentary Industry, Combustion Science and Technology (2021) 1-15.

[4] R.M. Hadden, A.I. Bartlett, J.P. Hidalgo, S. Santamaria, F. Wiesner, L.A. Bisby, S. Deeny, B. Lane, Effects of exposed cross laminated timber on compartment fire dynamics, Fire Safety Journal 91 (2017) 480-489.

[5] R. McNamee, J. Zehfuss, A.I. Bartlett, M. Heidari, F. Robert, L.A. Bisby, Enclosure fire dynamics with a cross-laminated timber ceiling, Fire and Materials 45(7) (2021) 847-857.

[6] X. Li, X. Zhang, G. Hadjisophocleous, C. McGregor, Experimental Study of Combustible and Non-combustible Construction in a Natural Fire, Fire Technology 51(6) (2015) 1447-1474.

[7] C. Wade, M. Spearpoint, C. Fleischmann, G. Baker, A. Abu, Predicting the Fire Dynamics of Exposed Timber Surfaces in Compartments Using a Two-Zone Model, Fire Technology 54(4) (2018) 893-920.

[8] T. Hakkarainen, Post-flashover fires in light and heavy timber construction compartments, Journal of Fire Sciences 20(2) (2002) 133-175.

[9] J.M. Baig, Fire safety in an enclosure of unprotected CLT elements- CFD analysis of critical smoke conditions, Master thesis, Technical University of Denmark, Lyngby, Denmark, 2022

Assessing Community Vulnerability to Wildland Fires

Jonathan Wahlqvist
Fire Safety Engineering,
LTH, Lund, Sweden
Jonathan.wahlqvist@brand.lth.se

Claude Pagnon Eriksson
Fire Safety Engineering,
LTH, Lund, Sweden
claude.pagnon_eriksson@brand.lth.se

Margaret McNamee
Fire Safety Engineering,
LTH, Lund, Sweden
Margaret.mcnamee@brand.lth.se

Nils Johansson
Fire Safety Engineering,
LTH, Lund, Sweden
Nils.Johansson@brand.lth.se

Keywords:* *(5 key words)
Wildland fires, vulnerability, risk assessment, fire and rescue services.

Abstract

Since the introduction of modern forestry practices in Sweden in the late 1800s the number of wildland fires in Sweden has been relatively low. In recent years, however, the increase in warm dry weather during the summer has lead to increased fire danger. This short paper provides a description of work underway to create a methodology to assess community vulnerability to wildland fires, as part of a broader initiative to understand multiple natural hazards in Sweden and necessary Fire and Rescue service capabilities associated with these emerging natural hazards.

Introduction

Wildfires are a serious concern to communities around the world. Traditionally this has been of greatest concern in the south of Europe, the USA or Australia; but in recent years the issue of wildland fires and wildland fire vulnerability has gained traction even in Sweden. The number and consequences of wildland fires in Sweden have increased in recent years from relatively low values since the introduction of modern forestry [1]. Recent research indicates that Swedish buildings in the wildland urban interface (WUI) are not sufficiently protected from wildland fires [2]. Fire and Rescue Services (FRS) need support in understanding the wildland fire hazard, their exposure risk and vulnerability in order to be able to plan capability needs. The fire danger in Sweden is assessed by the Swedish Hydrological and Meteorological Institute (SMHI) using the Fire Weather Index (FWI) developed in Canada [3]. A recent publication indicates that the FWI provides a good method to assess fire danger in Sweden [4]. Assessing the fire danger, is not, however, sufficient for FRS planning. The index values need to be combined with other hazard and exposure assessments together with an understanding of capability needs.

In recent years, numerous methods of vulnerability analysis have been developed and applied to the WUI [5-7]. There is, however, some uncertainty concerning the applicability of such methods to the Swedish context [8]. The work presented in this short paper provides a framework for FRS to understand community vulnerability as input to their capability needs. The work has been conducted within the MSB and FORMAS funded research project EXTREME-INDEX: A new multi-hazard vulnerability index, grant number 2019-06053.

Methodology

A multistep approach to understanding fire danger has been developed with the aim to assist FRS with training and planning through improving their understanding of when extreme natural hazards occur, see Figure 1. The methodology is being developed in a modular manner to foster the inclusion of multiple natural hazards, such as wildland fires, flooding, earthquakes, etc. The method presented here is specific to wildfires but "Hazard n" in Figure 1 indicates the possibility to expand the model to include additional hazards.

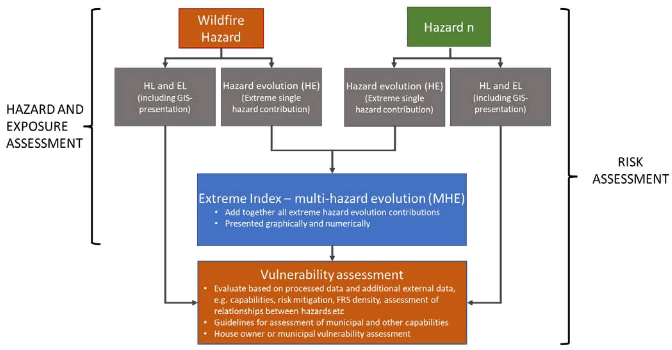


Figure 1. ***Flow chart showing multistep methodology for assessment FRS capability needs for training and planning.***

The "Extreme Index" part of the tool developed will be based on the combination of hazard and exposure evaluations for each individual hazard. Figure 2 illustrates the "Extreme Index" concept, where the "extreme contribution" is determined as area of overlap between two hazards in this case.

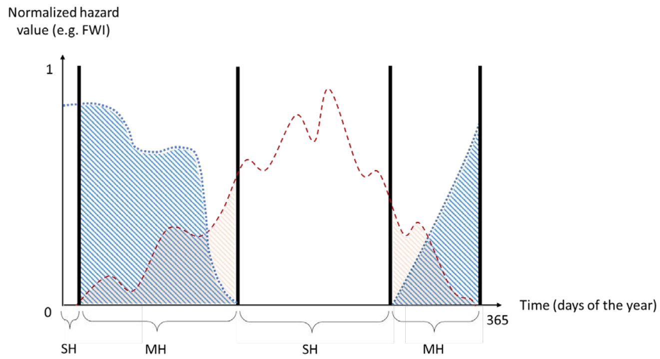


Figure 2. Schematic figure illustrating the concept of estimating extreme natural hazards as input to planning for the FRS. SH=single hazard, MH=multiple hazard.

The full Extreme Index tool will display information in the framework developed as part of the WUI-NITY initiative [9]. The parts of the methodology in Figure 1 that will be implemented are those that offer generic information. Many parts of a vulnerability assessment will require local information.

Results and Discussion

The project is still in the early stage of development of the Extreme Index tool. Efforts are presently underway to apply the methodology to a specific community (Ljungby). This includes, e.g. the preparation of a fuel map applicable for Sweden (step 3 in Figure 1) based on recent work done in Canada [7]. It is anticipated that more details will be available by the NFSD.

Conclusions

Municipal resources are finite and decisions concerning capability needs in the fire service are crucial to their planning to ensure that these resources are properly used. Improved understanding of fire danger, hazard level and exposure level are important data points as input to an overall community vulnerability prediction. The development of such community vulnerability predictions will improve FRS planning and support vulnerability mitigation in the future.

References

[1] J. Sjöström and A. Granström, "Skogsbränder och gräsbränder i Sverige - Trender och mönster under senare decennier (Wildland fires and grass fires in Sweden - Trends and patterns during past decades)," MSB, Karlstad, Sweden, Research Report MSB1536, March 2020 2020, vol. MSB1536. Accessed: February 2022. [Online]. Available: https://www.msb.se/sv/publikationer/skogsbrander-och-grasbrander-i-sverige--trender-och-monster-under-senare-decennier/

[2] F. Vermina Plathner and J. Sjöström, "Structure survivability in Swedish wildfires," in "WUIVIEW Virtual Essays," RISE Online, TN 7.2, 2021. Accessed: February 2022. [Online]. Available: https://wuiview.org/download/TN72_Sweden_structure_survivability.pdf

[3] C. Pagnon Eriksson and N. Johansson, "Review of wildfire indices. Indices applicable for a Swedish context," Lund University, Lund, 2020, vol. Report 3233. [Online]. Available: https://www.lu.se/lup/publication/404387de-8dd1-4b72-9c45-fe3e4f431048

[4] C. Pagnon Eriksson, N. Johansson, and M. McNamee, "Assessing the performance of wildfire danger indices in Sweden: A comparative study," *Fire Technology (accepted for publication),* 2022.

[5] P. Vacca, D. Caballero, E. Pastor, and E. Planas, "WUI fire risk mitigation in Europe: A performance-based design approach at home-owner level," *Journal of Safety Science and Resilience,* Article vol. 1, no. 2, pp. 97-105, 2020, doi: 10.1016/j.jnlssr.2020.08.001.

[6] S. Gwynne *et al.*, "Modeling and mapping dynamic vulnerability to better assess WUI evacuation performance," *Fire and Materials,* Artikel vol. 43, no. 6, pp. 644-660, 2019, doi: 10.1002/fam.2708.

[7] N. Bénichou *et al.*, "National guide for wildland-urban-interface fires: guidance on hazard and exposure assessment, property protection, community resilience and emergency planning to minimize the impact of wildland-urban interface fires," National Research Council of Canada, 978-0-660-36308-0, 2021.

[8] F. Vermina Plathner and J. Sjöström, "The Wildland-Urban Interface in Sweden," in "WUIVIEW Virtual Essays," RISE Online, TN 7.1, 2021. Accessed: February 2022. [Online]. Available: https://wuiview.org/download/TN71_%20WUI%20in%20Sweden.pdf

[9] J. Wahlqvist *et al.*, "The simulation of wildland-urban interface fire evacuation : The WUI-NITY platform," *Safety Science,* Artikel vol. 136, 01/01/ 2021, doi: 10.1016/j.ssci.2020.105145.

Predicting Char Front Progress in Spruce and Pine Woods Using Oxidative Pyrolysis Model

Aleksi Rinta-Paavola
Department of Civil Engineering
Aalto University
Espoo, Finland
aleksi.rinta-paavola@aalto.fi

Simo Hostikka
Department of Civil Engineering
Aalto University
Espoo, Finland

Keywords: (5 key words)
Char propagation, smoldering, spruce wood, pine wood, pyrolysis modelling.

Abstract

Propagation of char inside timber during a fire is described by a variety of methods. Many of these employed in practice, however, include severe simplifications, such is the case for example with Eurocode 5. As a result, these models are not necessarily applicable in nonstandard fire scenarios.

Our work aims to create a material model to describe charring of spruce and pine timbers, that is suitable for variety of different fire scenarios. The model is estimated and validated using experimental results from cone calorimeter tests. The intended use of our model is to act as a solid phase boundary to a CFD-based fire model, such as FDS.

Materials

Specimens of Norway spruce (*Picea abies*) and Scots pine (*Pinus sylvestris*) are used in the current research. Their average measured dry densities are 408 and 493 kg/m^3, respectively. The specimens are conditioned at 20 °C and 45 % relative humidity, resulting for both into a moisture content of 9 %, wet basis. We assume the chemical compositions of the woods as identical to [1], provided in Table 1.

Table 1. Chemical compositions of spruce and pine woods [1].

Component, weight-%	Spruce	Pine
Extractives	1.7	3.5
Hemicellulose	28.3	28.5
Cellulose	41.7	40.0
Lignin	27.4	27.7
Residual	0.9	0.3

Experimental and numerical

Experimental work in our research is carried out using a cone calorimeter manufactured by Concept Equipment, that could be operated either in accordance with ISO 5660-1, or as a controlled atmosphere cone calorimeter. The latter mode allows for operation in up to near-zero oxygen content, achieved by flushing the specimen chamber with nitrogen.

The pine and spruce specimens are 10 by 10 cm in exposed cross section and 2 cm in thickness, and they were tested for pyrolysis in near-zero oxygen (N_2 atmosphere) conditions, nonflaming combustion but in standard atmosphere (smoldering), and flaming combustion. Part of the tests in near-zero oxygen and in flaming conditions were conducted with K-type thermocouples (TC) in the inside halfway of the specimen (1 cm depth) and on its unexposed side (2 cm depth), to observe temperature in these locations. The flaming tests without installed thermocouples are from our earlier work [2].

Numerical simulations of pyrolysis and oxidation are carried out using Fire Dynamics Simulator (FDS) version 6 [3]. The material properties are estimated by model fitting to cone calorimeter experiments, using the shuffled complex evolution algorithm of the PROPTI software [4].

We continue using the same reaction schemes as in our previous work [2], where we observe individually two different options to describe thermal degradation of wood; either through a single wood component decomposing to form char (single reaction scheme, *a*), or by each of the wood main components (extractives, hemicellulose, cellulose, and lignin) forming char independently (parallel reactions scheme, *b*). Now, when also considering the effect of oxidation, we add a further reaction for oxidation of char (*c*). The kinetic parameters for non-oxidative pyrolysis, that is, all reactions within *a* and *b*, are assumed to hold identical to as determined in [2]. In *b*, extractives are combined to hemicellulose, as it was deemed to have negligible effect in macroscopic experiments (cone calorimeter), even though it was recognized vital in estimating a kinetic model from thermogravimetric experiments in [2].

$$a\ \{wood \rightarrow char + volatiles$$

$$b \begin{cases} hemicellulose \rightarrow char_{hc} + volatiles \\ cellulose \rightarrow char_c + volatiles \\ lignin \rightarrow char_l + volatiles \end{cases}$$

$$c\ \{char \xrightarrow[+O_2]{} CO_2$$

Figure 1. Reaction schemes employed in this work: a: single reaction, b: parallel reactions, c: char oxidation that applies to the residual char from both a and b.

Results

Thermal properties of both woods and their chars were estimated by model fitting to mass loss and temperature measurements from experiments in cone calorimeter under nitrogen atmosphere and a heat flux level of 35 kW/m^2. Table 2 shows the estimated parameters and their values for both species of wood and for both reaction schemes. Char densities are also included in Table 2, being adjusted so that the simulated final thickness of the specimen matches the experiment. Self-measured temperature dependencies of specific heats of woods, and literature-sourced specific heat correlation for char and emissivity of virgin wood of 0.9 are carried over from our earlier work [2]. Char thermal conductivity at 300 °C is assumed as in [5] for each wood and reaction scheme. Figure 2 compares simulated and experimental temperature histories for spruce.

Kinetic parameters for oxidation of char are estimated using the mass loss data from the nonflaming cone calorimeter tests in standard atmosphere, these conditions being achieved by using a sufficiently low heat flux level and an absence of the pilot ignition spark. For spruce and pine, experiments under heat flux levels of 35 kW/m^2 and 30 kW/m^2 were employed for estimation, respectively, since 35 kW/m^2 was already sufficient to spontaneously ignite the pine. The *a* and *b* reaction schemes of a same wood require distinct kinetic parameters for char oxidation, as they produce char differently; *a* produces it in a single relatively narrow reaction step, whereas in *b*, lignin that decomposes over a wide temperature range is mainly responsible for char production. The kinetic parameters for char oxidation are contained within Table 2, the reaction order being assumed as unity. The reaction order with respect to oxygen is assumed as 0.68 [6] and the parameter GAS_DIFFUSION_DEPTH of FDS is set at 0.0001 m, restricting oxidation near the exposed surface.

At the time of writing, simulations in flaming conditions are a work in progress, so they are not considered herein.

Table 2. ***Material parameters. A: frequency factor, E: activation energy, k: thermal conductivity, H_r: heat of pyrolysis, ε: emissivity, ρ: density, hc: hemicellulose, c: cellulose, l: lignin.***

Component, parameter	Reaction scheme *a* Spruce	Reaction scheme *a* Pine	Reaction scheme *b* Spruce	Reaction scheme *b* Pine
Water				
A (1/s)	9.06E17	3.07E6	9.06E17	3.07E6
E (kJ/mol)	160	69.9	160	69.9
Wood				
k (W/(m K))	0.125	0.152	0.116	0.122
H_r (kJ/kg)	167	84.6		
hc			66.8	155
c			357	680
l			-1552	-1552
Char				
k (W/(m K))				
T=300 °C	0.138	0.138	0.138	0.138
T=600 °C	0.245	0.25	0.245	0.286
ε (-)	0.769	0.765	0.769	0.765
ρ (kg/m^3)	52.5	104	20	72
A (1/s)	0.988	1.25	139	11.4
E (kJ/mol)	19.2	9.69	45.4	20.7

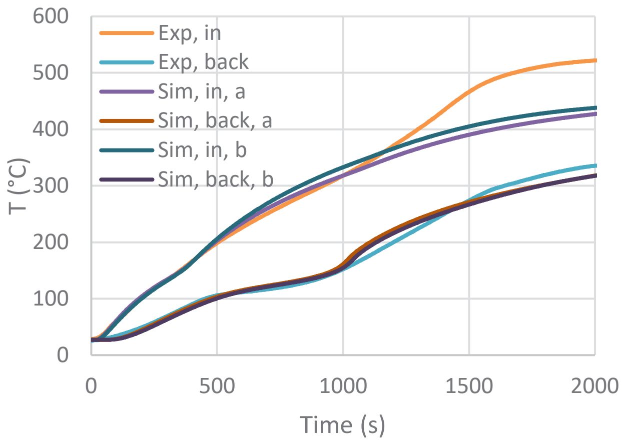


Figure 2. ***Experimental (Exp) and simulated (Sim) temperature histories inside spruce under N_2 atmosphere and 35 kW/m^2. In/back designates the TC location and a/b the reaction scheme.***

Conclusions

Figure 2 shows that both models employing either the single (*a*) or parallel reactions (*b*) schemes, reproduce the experimental temperature measurement in both inside and on the back of the specimen with good accuracy, except for failing to capture the temperature increase within the specimen near the end of the test. We suggest it is caused by cracking of the specimen, which allows further heat transfer, but is not included in the current FDS. The same holds for temperatures measured in pine as well. The simulations of mass loss rates, using schemes *a* and *b*, in nitrogen and in nonflaming conditions agree well with each other and experiments, but are not presented here. This all support the conclusion of our earlier paper [2], that in cone calorimeter scale, a model with multiple reactions offers no advantage over one with a single reaction. Instead, the associated higher number of input parameters adds up into model uncertainty.

As of the time of writing, our analysis tells that virgin wood oxidation competitive to pyrolysis is unnecessary, but this needs more support before a final conclusion.

Acknowledgement

The authors acknowledge the Academy of Finland and the Fire Protection Fund, Finland for funding this work.

References

[1] E. Sjöström, Wood Chemistry: Fundamentals and Applications. New York, NY: Academic Press, 1981.
[2] A. Rinta-Paavola, and S. Hostikka, "A model for the pyrolysis of two Nordic structural timbers", Fire Mater, vol. 46:1, pp. 55-68, February 2021.
[3] K. McGrattan, S. Hostikka, J. Floyd, R. McDermott, and M. Vanella, Fire Dynamics Simulator Technical Reference Guide Volume 1: Mathematical Model. Gaithersburg, MD: National Institute of Standards and Technology, 2021.
[4] L. Arnold, T. Hehnen, P. Lauer, C. Trettin, and A. Vinayak, "Propti – A Generalised Inverse Modelling Framework", J Phys Conf Ser, vol. 1107:3, 032016, November 2018.
[5] S. Alves, and J. Figueiredo, "A model for pyrolysis of wet wood", J Phys Conf Ser, vol. 44:12, pp. 2861-2869, 1989.
[6] A. Anca-Couce, N. Zobel, A. Berger, and F. Behrendt, "Smouldering of pine wood: Kinetics and reaction heats", Combust Flame, vol. 159:4, pp. 1708-1719, April 2012.

Predictive method for fires in CLT and glulam structures

Alastair Temple
Brandforskning
RISE
Lund, Sweden
alastair.temple@ri.se

Daniel Brandon
Brandforskning
RISE
Lund, Sweden
daniel.brandon@ri.se

Johan Sjöström
Brandforskning
RISE
Göteborg, Sweden
johan.sjostrom@ri.se

Keywords:* *CLT, modelling, sturctural, design, timber

Predicting Fires in Mass Timber Buildings

Mass timber is an increasingly popular structural material for large and tall buildings and has been cited for its architectural desirability and low climate impact in comparison with more conventional construction materials.

As mass timber is combustible, implementation of mass timber involves several fire safety challenges. Due to a combination of the limited reach of the fire brigade and increased potential consequences, in some countries it is required to ensure fires in taller buildings decay or extinguish using a performance-based approach. In other countries a prescriptive building code is implemented, which often includes protection requirements for mass timber and limits of exposed surfaces. Some countries allow both prescriptive and performance-based fire safety design approaches.

Predictive modelling of the fire duration, fire temperatures, heat release rates and the structural capacity during building fires can be used to show compliance with performance-based building code requirements. A small number of models [1][2][3][4] have been proposed for engineering use to predict the exposures of flashover fires with exposed surfaces of mass timbers and this presentation describes the SP-TimFire model developed at RISE [5]. Here we present a model focused on the post flashover fire including the decay phase and extinction of flaming combustion for mass timber structures. A priori predictions of five recent compartment fire tests have been set against experimental results and compared. After the tests, the model has been updated, primarily to increase the ease of use and increase accuracy for the decay phase.

Model Description

The model consists of a single-zone model which uses an energy equilibrium approach to obtain gas temperatures and surface temperatures of compartment boundaries. From these temperatures the through-depth temperatures, and therefore the charring rate, of the timber can be calculated to establish the energy contribution of the combustible structure. The basic steps of the model are illustrated in Figure 1 and can be summarised as follows:

1. Calculate the compartment fire temperatures for the full temperature-time history using a single zone model and a heat release rate curve.
2. Use these compartment temperatures to calculate the temperature-time history of any protected and unprotected timber structural element.
3. Calculate the charring rate through time for any timber structural element and calculate the potential heat release rate through time due to the charring
4. Add the CLT combustion contribution to contribution of the moveable fuel load.
5. Iterate (i.e. repeat steps 1 to 4) until convergence.

The calculated through-depth temperatures of mass timber members could also serve to provide information for structural calculations using temperature dependent reduced material properties. However, the structural calculations are out of the scope of this model.

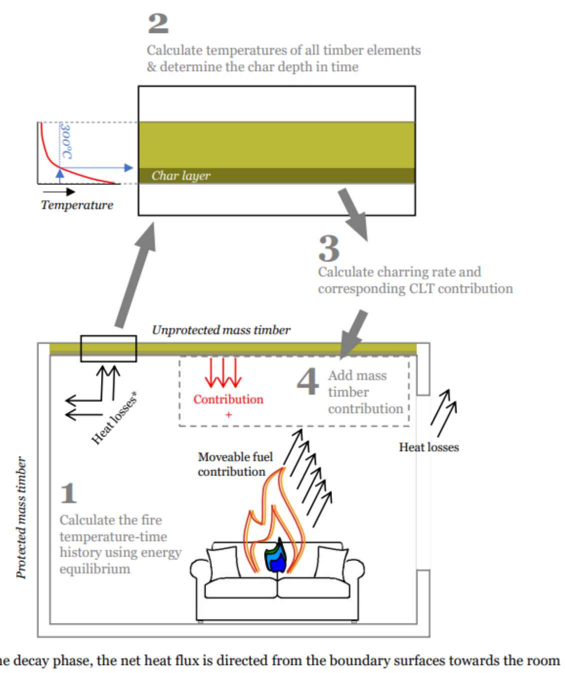


***Figure 1.** The 4 steps of the model which are iterated.*

Prediction Capabilities

The radiation conditions (and total thermal exposure to walls ceilings and floors) predicted by the updated model accurately described the of recent full-scale experiments. The comparisons with experiments showed that the total heat is, however, underestimated in some cases and surface temperatures were underestimated in the decay phase. Local effects caused by a radiative feedback loop between surfaces that show significant char oxidation, which occurred in a part of the test, is not included in the model.

After comparing the predictions with the results from the experimental series [6] the model was updated to include (1) an updated method for the inclusion of char oxidation energy and (2) a simulated shift from radiative interaction between surfaces and gasses to an interaction between surfaces after the disappearance of fire plumes. Comparisons between the experimental results and the model predictions can be seen in figure 2 and figure 3.

The predicted char depths after the full fire corresponded roughly to the average measured in exposed CLT walls of compartments with opening dimensions that correspond to residential occupancy [6] and the char depth of the ceiling was overestimated. The final char depth in the bottom of walls was, however, generally underestimated, see figure 4. This underestimation is most significant at the foot of corners where two exposed CLT walls intersect.

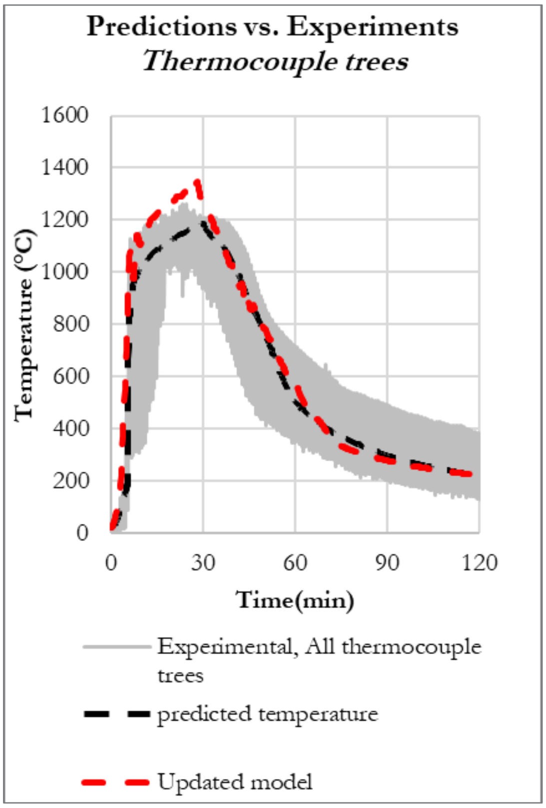


Figure 2. Comparison of model temperature predictions with Test 2 of the experimental series.

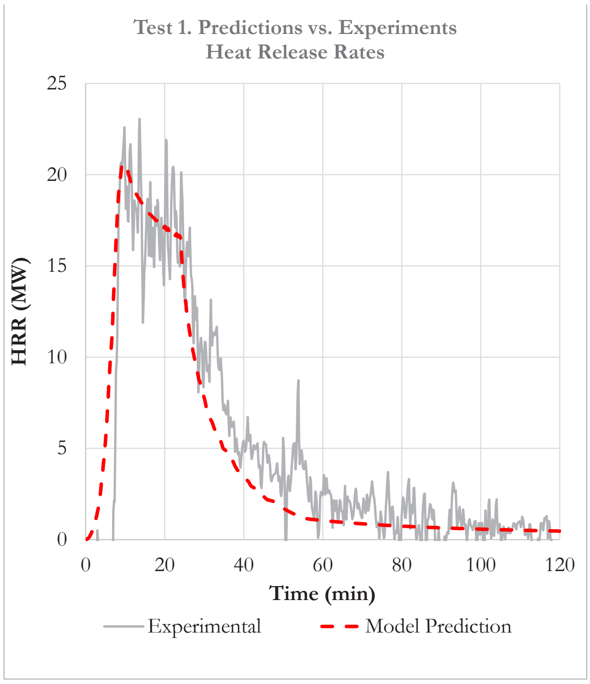


Figure 3. Comparison of the HRR of the updated model with Test 1 of the experimental series.

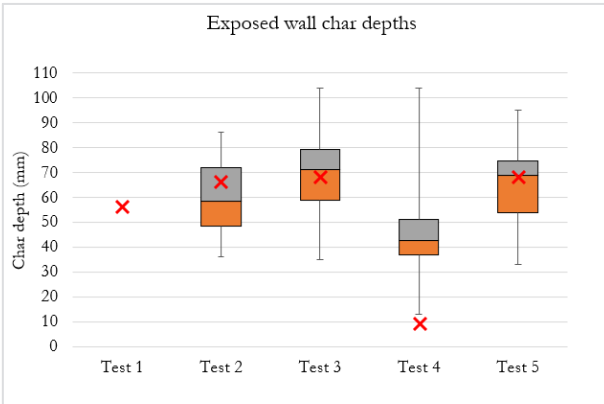


Figure 4. Comparison of predicted and experimental char depths.

References

[1] Brandon, D. (2016). Practical method to determine the contribution of structural timber to the rate of heat release and fire temperature of post-flashover compartment fires.

[2] Barber, D., Crielaard, R., & Li, X. (2016, August). Towards fire safe design of exposed timber in tall timber buildings. In World Conference on Timber Engineering (wcte2016), Wien, Austria.

[3] Brandon, D. (2018). Fire Safety Challenges of Tall Wood Buildings–Phase 2: Task 4-Engineering methods. National Fire Protection Association. NFPA report: FPRF-2018-04.

[4] Hopkin D, Anastasov S, Brandon D (2017) Reviewing the veracity of a zone model based approach for the assessment of enclosures formed of exposed CLT. In Applications of Fire Engineering. CRC Press/Balkema, the Netherlands.

[5] Brandon, D., Temple, A., & Sjöström, J. (2021). Predictive method for fires in CLT and glulam structures – Disseminated predictions versus real scale compartment fire tests, RISE Report 2021:63, RISE Research institutes of Sweden, ISBN: 978-97-89385-53-5.

[6] Brandon, D., Sjöström, J., Hallberg, E., Temple A., Kahl, F. (2021) Fire Safe implementation of visible mass timber in tall buildings – compartment fire testing. RISE Report 2021:40. Research Institutes of Sweden, Borås, Sweden.

Organization

Conference chair:

Anne Dederichs (RISE Research Institutes of Sweden, Technical University of Denmark)

Organizing committee:

Anne Dederichs (RISE Research Institutes of Sweden, Technical University of Denmark)
Linnéa Hemmarö (RISE Research Institutes of Sweden)
Kaisa Kaukoranta (RISE Research Institutes of Sweden)

Scientific committee:

Anne Dederichs (RISE Research Institutes of Sweden, Technical University of Denmark)
Michael Försth (Luleå University)
Tuula Hakkarainen (VTT)
Björn Karlsson (Iceland University)
Simo Hostikka (Aalto University)
Henrik Bjelland (University of Stavanger)
Ove Njå (University Stavanger)
Anne Steen Hansen (NTNU)
Bjarne Christian Hagen (Western Norway University of Applied Sciences)
Nieves Anez (Western Norway University of Applied Sciences)
Margaret McNamee (Lund University)
Henrik Hassel (Lund University)
Lars Schiøtt Sørensen (Technical University of Denmark)
Luisa Giuliani (Technical University of Denmark)
Ragni Fjellgaard Mikalsen (RISE Fire Research, Norway)
Bjarne Husted (DBI, Denmark)

NFSD Partners

Aalto University

Western Norway University of Applied Sciences

DBI

LUND UNIVERSITY

UNIVERSITY OF ICELAND
SCHOOL OF EDUCATION

LULEÅ UNIVERSITY OF TECHNOLOGY

VTT

Universitetet i Stavanger

DTU

DANISH BUILDING RESEARCH INSTITUTE
AALBORG UNIVERSITY COPENHAGEN

NTNU
Norwegian University of Science and Technology

RI. SE

Organised by

RISE Research Institutes of Sweden
2022 | P O Box 857 | SE-501 15 Borås | SWEDEN
E-mail: NFSD@ri.se
https://www.ri.se/en/nfsd