Fire Safety of CLT Buildings with Exposed Wooden Surfaces

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Abstract

An increasing number of tall buildings made of CLT have been built in recent years. Current architectural trends involve having visible timber surfaces in these tall CLT structures. This results in new fire safety challenges, especially because fire service interference is increasingly difficult for increasingly tall buildings.

Recently, a number of research projects involving large scale compartment fire testing studied the development of fires in (1) compartments with a fully encapsulated CLT structure and (2) compartments with exposed CLT surfaces. The studies have shown that sufficient gypsum board protection can avoid the involvement of CLT in a fire. However, fall-off of the base layer of gypsum boards during can result in continuous fires that do not extinguish without fire surface interference, as during fall-off large areas of initially protected timber surfaces start to contribute as fuel to the fire.

If CLT is exposed to a fire, fire induced delamination of CLT (also lamella fall-off or char fall-off) could occur due to weakening of bond lines within the CLT. During fire induced delamination the exposed lamella falls from the CLT and a new relatively cold timber surface becomes exposed to potentially high temperatures, which effectively makes additional fuel suddenly available to a fire.

Very recent studies involved the development of CLT products that are not subject to delamination. The studies indicate that the use of (a) sufficient fire protection, (b) CLT products with thermally resistant adhesives and (c) a limit regarding the surface area of CLT that can be exposed, result in fires that decay and eventually self-extinguish.
This paper reviews the studies and includes a summary of conclusions.

1. Introduction

During the last 5 years the number and the height of tall buildings with CLT members in their structures have increased. CLT has been cited for (among other things) its structural performance, durability and appearance. Due to its aesthetic appeal, architectural designs increasingly often incorporate exposed surfaces of CLT. However, in case of a fire, exposed CLT can contribute to the fuel of a fire, due to the combustibility of timber.

In the last five years a significant amount of studies have increased the knowledge of CLT structures in fires. Additionally, current and very recent studies resulted in the development of CLT products with an increased fire performance. This paper provides a brief review of studies of CLT structures in fires and provides guidelines for the fire safe use of CLT in tall buildings.

2. Standard fire resistance tests versus real fires

High consequence fires in tall timber buildings, such as the recent fire of the Grenfell Tower in London, indicate the difficulty that the fire service can have to extinguish fires in tall buildings. Other fires, such as the fire of the torch tower in Dubai indicate that sprinklers are not always capable of extinguishing fires and limiting fire spread, which is in line with a statistical analysis performed by the National Fire Protection Agency of the USA (NFPA, 2017).

Collapse or partial collapse of buildings due to fires is a high-consequence-event, which is generally avoided using structural fire resistance requirements.

Structural fire resistance requirements indicate a number of minutes a structure should withstand temperatures of a standard fire resistance test without collapse. In a standard fire resistance test, a CLT specimen has to be exposed to temperatures described by a standard time-temperature curve as shown in Figure 1. The required duration of a fire resistance test is dependent on regulatory requirements (i.e. the required fire resistance time). In a (real) compartment fire, the temperatures and the duration of a fire are mainly dependent on the amount of fuel available, ventilation conditions of the compartment, and thermal properties of the compartment linings. Once the combustible content (such as furniture) of a compartment starts to burn out in a compartment fire, the decay phase of the fire starts.

A structural fire resistance requirement of, for example, 90 minutes does not indicate that the building would collapse after 90 minutes in a real fire. It is possible that fulfillment of the fire resistance requirement avoids collapse for the entire duration of a natural fire even if fire service intervention or effective sprinkler activation is absent. Whether collapse is prevented by using fire resistance requirements, is dependent on the temperatures and duration of the compartment fire and the required time of fire resistance. However, it can be stated that collapse can be avoided if continuous compartment fires are avoided and if fire resistance requirements are conservative enough (i.e. if the red line in Figure 1 is located far enough to the right hand side).

If the structure is combustible, it is possible that the fire continues after the combustible room content has completely burned out (see Figure 2). In the case that a fire does not decay, fire resistance requirements are not sufficient to prevent collapse without effective fire service or sprinkler interference.

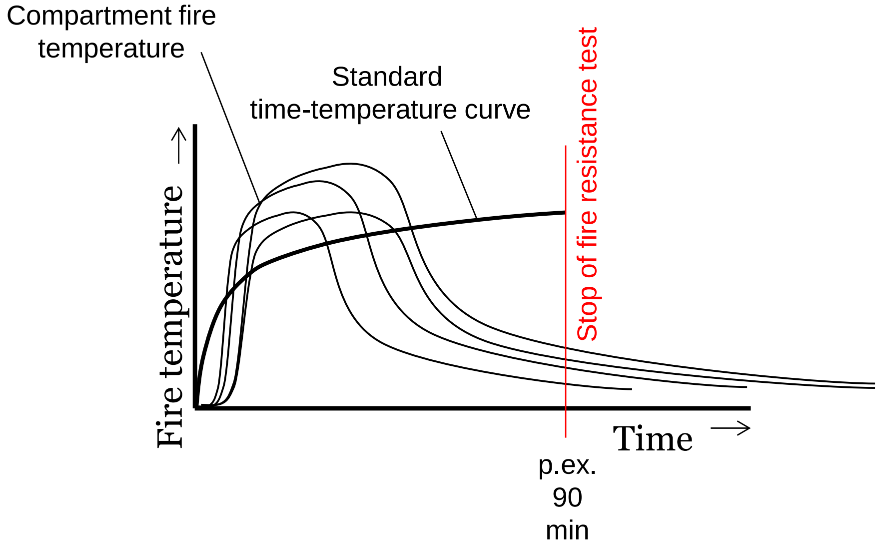

Figure 1: temperatures of a standard fire resistance test versus temperatures of compartment fires (schematic)

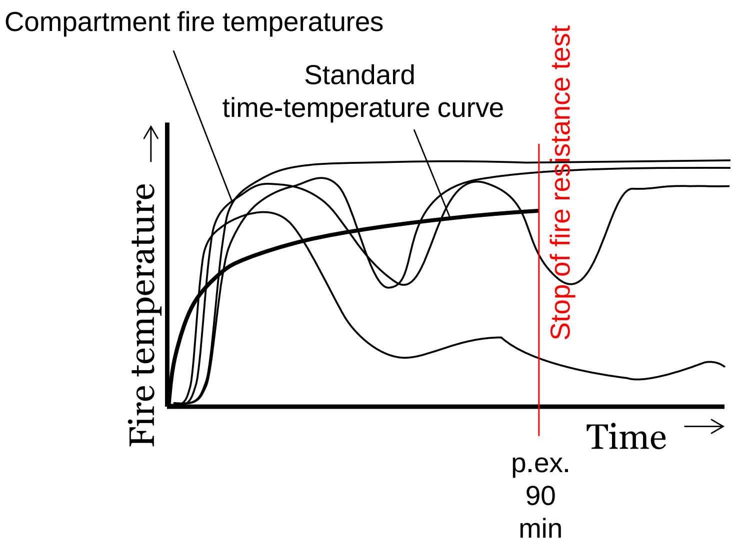

Figure 2: temperatures of a standard fire resistance test versus temperatures of compartment fires (schematic)

3. Studies of encapsulated CLT compartments

Studies involving full-scale fire tests of CLT compartments have been performed by McGregor (2013), Su and Lougheed (2014), Su and Muradori (2015), Janssens (2015), Su et al. (2018), Zelinka et al. (2018). These studies indicated that enough fire protection by gypsum plaster boards (or other fire-rated boards) can prevent involvement of timber in fires. If that is the case, the fire's heat release rate, fire temperature and fire duration correspond to those of fires in non-combustible structures. The amount of gypsum boards required to avoid involvement of the timber in a fire is dependent on the compartment design and the amount of combustible materials in a compartment (Brandon, 2018). In most of the studies mentioned above, two fire-rated (type X) gypsum board layers of either 12.5 to 15.9mm thick were needed to avoid the involvement of CLT in the compartment fire. An early study (Hakkarainen, 2002) showed that fall-off of the base layer of gypsum boards can lead to significant contributions of the timber to a fire, which was in this case evidenced by a significant increase of the fire plume out of the window opening of the compartment.

4. Studies of compartments with exposed CLT

Studies involving full-scale fire tests of compartments with *regular* exposed CLT have been performed by McGregor (2013), Medina Hevia (2014), Hox (2015), Emberley et al. 2017, Hadden et al. (2017), Brandon et al. (2018), Su et al. (2018), Zelinka et al. (2018). Multiple tests of these studies indicated that fire induced delamination of exposed CLT can lead to fire regrowth and continuous fires. Figure 3 shows a photo of a compartment fire tests reported by Su et al. (2018). The photos show fires in two similar compartments with similar contents. The left-hand compartment comprises solely encapsulated CLT and the right-hand compartment has an exposed CLT ceiling and one exposed CLT wall. At 1 hour after ignition the compartment on the left-hand side (test 1-1 by Su et al.) decayed and was nearly self-extinguished. The compartment on the right hand side (test 1-6 by Su et al.), however, had an increase of intensity around 1 hour after ignition, which was caused by delamination. This test was continued until the ceiling collapsed. Figure 4 shows heat release rates of fires in fully encapsulated compartments (test 1-1 and 1-2) and similar compartments with some exposed CLT surfaces. A significant cause of the differences between the curves is due to the occurrence of delamination in compartments with exposed CLT.

Figure 3: Fully encapsulated compartment (left) and compartment with an exposed CLT wall and ceiling (right) 1 hour after ignition (Frame of a video by NIST, USA).

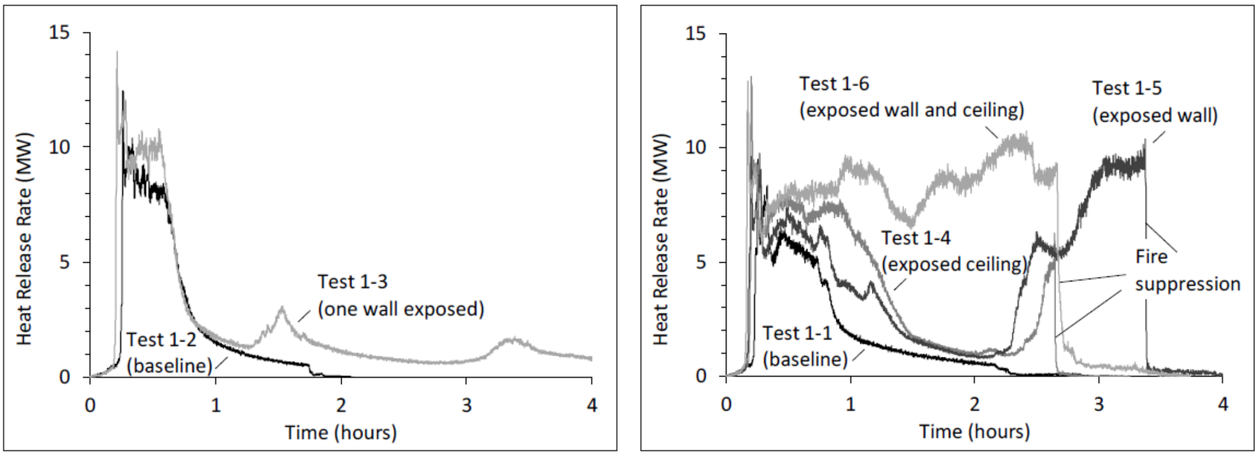

Figure 4: Heat release rates of compartments with a large opening (left) and compartment with a small opening (right), from Su et al. (2018).

Although the majority of reviewed compartment tests with exposed *regular* CLT resulted in continuous fires, studies by Medina Hevia, (2014); Emberley et al. (2017), Hadden et al. (2017) and Zelinka et al. (2018) included fire compartment tests without delamination that self-extinguished, even though a (limited) area of CLT surface was exposed. Additionally, a test by Brandon et al. (2018) and one out of six tests by Su et al. (2018) indicated that fire induced delamination of CLT does not always lead to a fully developed fire.

4. Studies of improved CLT

Fire induced delamination is caused by weakening of the adhesive bond due to increased temperatures. Therefore, the occurrence of delamination is dependent on the type of adhesive used in CLT. Studies by Janssens (2017) and Brandon and Dagenais (2018) proposed methods to identify adhesives that do not lead to delamination. Figure 5 shows box plots of char depth after a fire test reported by Brandon and Dagenais (2018). The tests involved the replication of conditions of a compartment fire in a furnace. Video recordings of the surface and multiple measurements indicated that the adhesives denoted as MF, PRF, EPI and PU2 did not delaminate. The adhesive named PU1 was prone to delamination and had significantly higher char depths after the test.

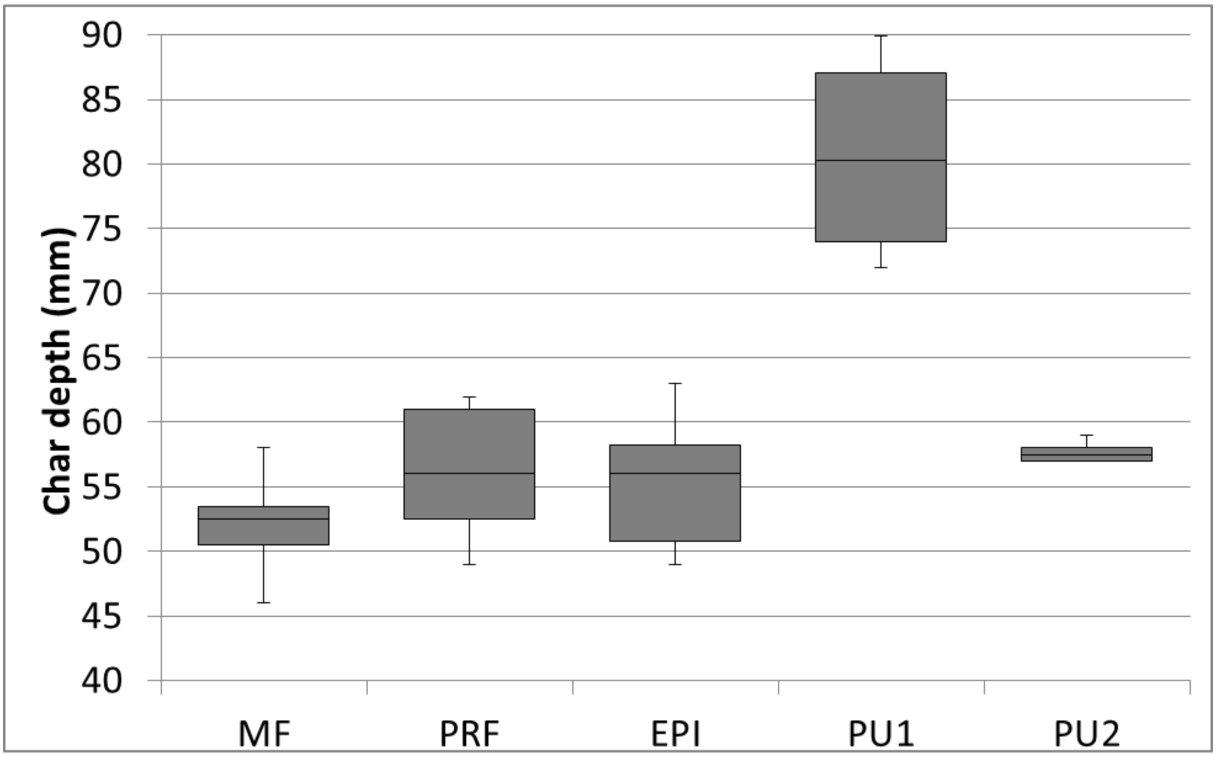

Figure 5:Char depth of CLT with different adhesives, from Brandon and Dagenais (2018).

Su et al (2018,b) performed fire tests of compartments made of CLT with PU2 (of which the brand name is HBX) adhesive. They performed similar, but smaller scale, tests as were presented earlier this year by a group with the same main author (Su et al. 2018). However, as mentioned before they now used the HBX adhesive which was identified to be non-delaminating in fires. Figure 6 shows temperatures of a compartment test with regular CLT on the left and a corresponding compartment test with improved CLT on the right. It can be seen that the implementation of non-delaminating adhesives have led to a decaying fire.

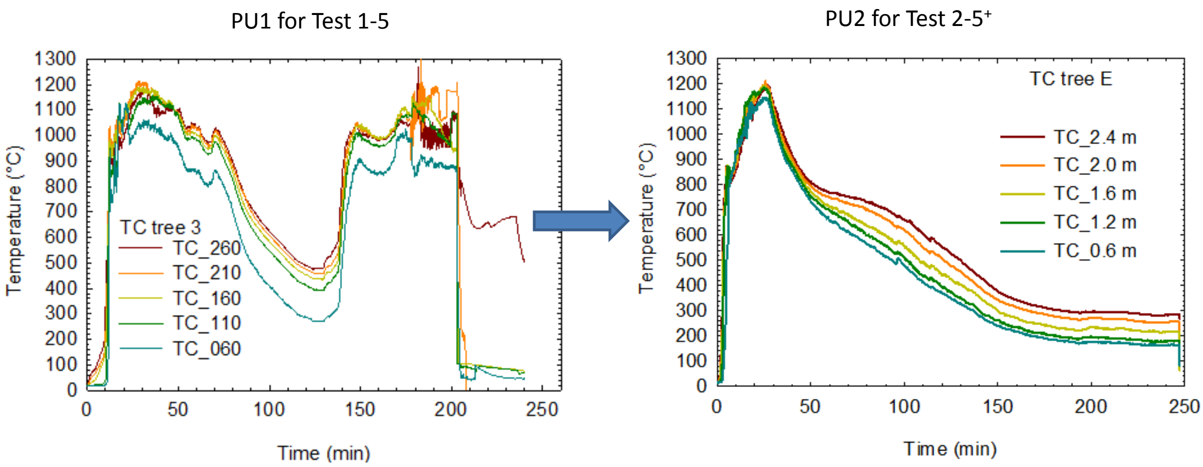

Figure 6:Temperatures of a compartment fire test with regular CLT (left, from Su et al. 2018) and temperatures of a comparmtent fire test with improved CLT (right, from Su et al. 2018b)

4. Calculation method

Calculation methods to determine the amount of CLT that can be exposed and to determine the amount of CLT required have been proposed by Brandon (2018b). Additionally, assessments of structures in conditions of flashover compartment fires are discussed in the same work.

5. Conclusions and guidelines

For increasingly tall buildings, preventing collapse caused by fires becomes increasingly important. In case extinguishment by sprinklers or the fire brigade cannot be assumed (as for example in very tall buildings), it is recommended to design a building so that it withstands a full natural fire without collapse. In order to prevent collapse, it is important to avoid continuous fires caused by:
- Fire induced delamination
- Fall-off of the base layer of fire encapsulation
- Other phenomena that lead to sudden exposure of the timber structure
- Having too large areas of exposed CLT surface.

Fire induced delamination can be avoided by using non-delaminating adhesives. Preventing fall-off of the base layer of fire encapsulation and preventing having too much exposed CLT can be avoided using prescriptive regulations (as is done in North America) or using calculation methods.

References

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.

Brandon D (2018b) Engineering methods for structural fire design of wood buildings – structural integrity during a full natural fire. RISE Report 2018:44.

Brandon D, Just A, Andersson P, Östman B (2018) Mitigation of fire spread in multi-storey timber buildings – statistical analysis and guidelines for design. RISE Report 2018:43.

Brandon D., Dagenais C. (2018) Fire Safety Challenges of Tall Wood Buildings – Phase 2: Task 5 – Experimental Study of Delamination of Cross Laminated Timber (CLT) in Fire. NFPA report: FPRF-2018

Emberley R., Gorska Putynska C., Bolanos A., Lucherini A., Solarte A. , Soriguer D., Gutierrez Gonzalez M., Humphreys K., Hidalgo JP., Maluk C., Law A., and Torero JL. (2017) Description of Small and Large-Scale CLT Fire Tests, Fire Safety Journal, doi:10.1016/j.firesaf.2017.03.024

Hadden RM., Bartlett AI., Hidalgo JP., Santamaria S., Wiesner F., Bisby LA., Deeny S., Lane B. (2017) Effects of exposed cross laminated timber on compartment fire dynamics. Fire Safety Journal (91): 480-489.

Hakkarainen T. (2002) Post-flashover fire in light and heavy timber construction compartments. *Journal of Fire Sciences,* 20 (2002): 133-175.

Hox K. (2015) Branntest av massivtre. SPFR-rapport SPFR A15101. SP Fire Research, Trondheim, Norway *(unpublished). (in Norwegian)*

Janssens M. (2015) *CLT compartment fire test results*. Video presentation. http://www.awc.org/Code-Officials/2015-IBC-Code-Changes (accessed on 2015/10/26)

Janssens (2017) Development of a fire performance assessment methodology for qualifying cross-laminated timber adhesives. South West Research Institute

Kolaitis D.I., Asimakopoulou E.K., Founti M.A. (2014) Fire protection of light and massive timber elements using gypsum plasterboards and wood based panels: A large-scale compartment fire test. *Construction and Building Materials,* 73 (2014): 163-170.

Li X., Zhang X., Hadjisophocleus G., McGregor C. (2014) Experimental study of combustible and non-combustible construction in a natural fire. *Fire Technology,* 2014.

McGregor, C.J. (2014) *Contribution of cross-laminated timber panels to room fires*. Master thesis. Department of Civil and Environmental Engineering Carleton University. Ottawa-Carleton Institute of Civil and Environmental Engineering, Ottawa, Ontario, Canada.

Medina Hevia A.R. (2014) *Fire resistance of partially protected cross-laminated timber rooms*. Master thesis. Department of Civil and Environmental Engineering Carleton University. Ottawa-Carleton Institute of Civil and Environmental Engineering, Ottawa, Ontario, Canada.

NFPA (2017) Fact Sheet – Research - Sprinklers in Reported U.S. Fires during 2010 to 2014. National Fire Protection Association, USA.

Su J.Z. and Lougheed G.D. (2014) *Report to research consortium for wood and wood hybrid mid-rise buildings – Fire safety summary – Fire research conducted for the project on mid-rise wood construction*. National Research Council Canada, Client report: A1-004377.1, Ottawa, Ontario, Canada.

Su J.Z. and Muradori S. (2015) *Fire demonstration – Cross-laminated timber stair/elevator shaft*. National Research Council Canada, Client report: A1-004377.1, Ottawa, Ontario, Canada.

Su J., Lafrance P-S., Hoehler M., Bundy M. (2018) Cross Laminated Timber Compartment Fire Tests for Research on Fire Safety Challenges of Tall Wood Buildings – Phase 2.

Su J., Leroux P., Lafrance P-S., Berzins R., Gibbs E., Weinfurter M. (2018b) Fire testing of rooms with exposed wood surfaces in encapsulated mass timber construction. NRC CNRC Report A1-012710.1.