Round robin on calculations:
Steel beam with standard fire exposure

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SP Technical Research Institute of Sweden

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Abstract

This report details a round robin study of the calculated response of structures in fire. In this instance, the study is based on a fire test which was conducted on two steel beams in a horizontal fire resistance furnace at SP's fire resistance laboratory in Sweden. The two specimens in the test were identical having come from the same cast flow. The tests were conducted according to EN 1365-3 and the steel beams had a total length 5.4 m, spanning 5.2 m.

The calculations were conducted by round robin participants both 'a priori' and 'a posteriori' to the test itself. In the first instance a prediction of the response was made without knowledge of the measured temperatures of the steel beam and with only the grade of steel and details of the test setup. In the second instance the participants were also given the measured elastic limit of the steel, which differed significantly from the elastic limit implied by the grade, as well as measured temperatures from the steel beam and the plate thermometers from the furnace and asked to refine their model.

Statistical analysis of the round robin results are presented to illustrate the variation which arises in the results of calculations The results of the round robin study serve to illustrate the fire research and testing community's capability for modelling this simple case as well as the uncertainty in the calculation results.

In the a-priori study there is a wide spread both in predicted temperatures and the predicted deflection history of the beam. When the participants were provided with the measured temperatures to use in their models there was a slightly smaller spread in the predicted deflection histories. However there was still a significant spread. Both a-priori and a posteriori deflection histories were generally on the conservative side, however the source of this conservativeness is not immediately apparent and certainly in the a-priori results the majority of the conservativeness may arise as a result of the steel being of higher grade than specified. Other sources of conservativeness may be from the models or from the modellers themselves. This requires further investigation.

Not all of the participants used the same failure criteria when reporting the failure time, and the authors of this report corrected the failure times to allow for a comparison between the submissions to the study. If modelling is to continue to be used in the future for design and / or certification then some kind of consensus as to failure criteria may be beneficial.

Key words: Round robin, calculation, steel beam

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1 Introduction

1.1 Background

Structural fire design has taken a huge step forward in the past two decades. Enabled by the results of large scale testing and the lessons learned from the analysis of, for example, the Cardington tests [1] amongst others, fire engineers now employ sophisticated analysis tools in order to evaluate the structural response of a building to fire. This has led to significant cost savings, as well as the contribution of a building structure to the performance based design of a building for life safety in the event of fire.

The Cardington tests were designed to represent a typical type of construction which was used in the UK in the 1990's – a braced composite steel framed building [2]. The beams were designed as simply supported, acting in composite with a 130 mm concrete slab. Connection details were one of either of two types (beam to beam connections were comprised of fin-plates and beam to column connections were comprised of flexible end plates) and no other connection type was studied. Subsequent work included the modelling of these tests in order to further understand the underlying mechanisms which governed their behaviour in fire.

Based on the analysis of these and a few other tests researchers identified some of the fundamental mechanisms which govern the response of structures to fire and the fire engineering industry now confidently applies complex tools to determine the impact of fires on structures.

Calculations or simulations are often used as a more cost effective evaluation of elements and structures compared with testing. For building elements and structures the Eurocodes are the basis for design. For certification of certain building products calculations have the same credibility as testing. However while for testing there are requirements on accreditation of the test laboratory as well as follow up inspections, this is not the case for calculations. In other words, when evaluating building products for certification based on testing there is a formal control system that must be followed. This type of control does not exist when doing the same job based on calculations. Therefore it is important that the calculation methods and software used are robust and reliable, and that the results from calculations are both conservative and importantly consistent.

1.2 Round robins in fire science

A round robin study is a study conducted by a group of experts commencing from a common starting point, for example a collection of data, who proceed to predict independently the response of a system; or performing and comparing actual experiments. The purpose behind round robin studies is to evaluate the scatter of results across a discipline or between different laboratories.

Over the past decade there has been some renewed interest in round robin studies in fire science and modelling in particular. In fire dynamics, the round robin studies of the Dalmarnock tests which were coordinated by the University of Edinburgh [3] highlighted the considerable dependency of modelling results on the underlying assumptions and approach taken. Further, while the tools which were used have been successfully validated against existing test results their use in prediction is extremely dependent upon the way that the model is set up.

In structural fire engineering, a small round robin study was undertaken to predict the temperature exposure of a single steel beam exposed to a pool fire. This was also coordinated by the University of Edinburgh [4]. The principal conclusion from this study was that design tools for estimating temperatures of elements of structure in pool fires are very conservative and that they are very dependent on the scenario.

In the report from the Dalmarnock tests, the lack of historical round robins was highlighted. It is stated that relatively few examples exist, for example one unpublished round robin conducted by the CIB and one carried out by Emmons [5]. Emmons's work highlighted the discrepancy between different fire testing laboratories throughout the world – something which the European Group of Laboratories for Fire testing (EGOLF) has made significant movements to address.

Round robin studies in fire engineering serve to highlight issues within the discipline, however very few of them are undertaken. They pool the collective knowledge of experts in the field and help to focus directions for future research. A need for more round robins within the field was one of the conclusions of the recent international R&D roadmap for fire resistance of structures compiled by NIST [6].

1.3 Overview

This report details a two stage round robin study on calculations which has been performed along with a benchmarking test on the same object for study. The scope of the reported round robin is to determine the reproducibility of calculations on a fire exposed, unprotected, simply supported steel beam.

The test which the round robin study is based upon was carried out as part of an experimental round robin carried out by EGOLF on an unprotected simply supported steel beam [7]. This is one of the most simple fire resistance tests on load bearing elements. This round robin will give a good estimation of the load bearing capacity of this element type, and thus a comparison between the calculated load bearing capacity can be compared with the "true" behaviour.

This report details first an a-priori modelling stage, to which 18 different submissions were received. For this stage of the round robin the participants were only given a description of the test setup and the specimen. We then describe the results of the test which was to serve as the benchmark for the round robin before describing the a-posteriori round robin results, where the participants were given additional information made available from the tests in order to refine their calculation results.

2 Selection of participants

An invitation (Appendix A) to this round robin was sent out to numerous institutes, laboratories, universities, consultants and other possible participants. There was no cost for the participants more than their own time to perform the calculations and send the results to SP Fire Research.

The participants comprised universities, research institutes, testing laboratories and consultancies. They represent a cross section of the fire engineering community who are involved in research, certification, and consultancy and may be considered to be among experts in the field. Of 22 invited, in total 12 participants agreed to contribute to the study, with some of them submitting more than one solution to the problem using different calculation tools. These additional solutions are treated as further participants in the overview of the data. In total 19 submissions were made to the first stage. One of the participants, however, contributed with only the thermal analysis to the first stage.

One of the participants declined to contribute to the second stage, however one of the participants contributed with an additional submission, meaning that in total we received at least one submission from 10 different groups and in total 18 different submissions to the second stage.

The submissions were all assigned an identification number known only to the authors and their identities have been kept secret from one another. This information will not be published.

3 Stage 1 round robin

3.1 Information provided to the participants

All of the participants were provided with the same initial information (Appendix B).

The test object was an HEB 300 steel beam, grade S355. In the test which was performed the beam had a total length of 5400 mm, and a span of 5200 mm between the supports. Loading is applied at two points, 1400 mm from either support. At both the supports and the points of loading application web stiffeners were welded to the steel beam. The stiffeners had a thickness of 15 mm.

The configuration of the beam is shown in Figure 1.

The applied loads, P, created a uniform bending moment of 140 kNm between the loading points.

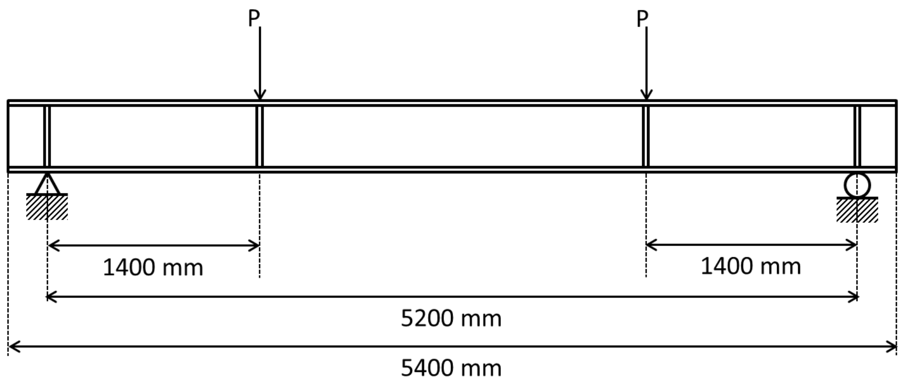


Figure 1. Geometry of the test specimen

During the testing the deflection was measured at mid span, as well as 700 mm from either of the supports, and the temperature of the beam at 11 locations: in the middle of each of the flanges and in the middle of the web at the mid-span of the beam; and in the middle of one each of the top and bottom flanges and the web at 1200 mm from the supports.

The beam was unprotected and exposed to fire in a horizontal fire resistance furnace on 3 sides (bottom and the two sides – the top was not exposed to fire and continuity of the top of the furnace was ensured by covering the top of the beam with light weight concrete blocks). The test was carried out in accordance with EN 1365-3 [8] and the fire was an EN 1363-1 (ISO 834) standard fire [9].

3.2 Information requested from the participants

Prior to the fire test being carried out, all participants were asked to carry out an a-priori prediction of the response of the steel beam using any software tool or calculation technique which they deemed to be applicable. The participants were asked to report the following:

1. A short description of the modelling approach taken, including the following:
    a. details of any assumptions which were made in the preparation of the model

   b. details of the material model used in the calculation
   c. a short description of the approach taken for modelling the thermal exposure from the furnace to the steel beam
2. A summary of the temperature in the steel beam (participants were free to choose how they conduct the heat transfer analysis)
3. The deflection history of the beam during the standard fire exposure
4. A declaration of the failure time of the beam during standard fire exposure
5. A description of the failure criteria which they used in determining the failure time

3.3 Modelling approach

All of the participants followed slightly different approaches to calculate the information requested in stage 1 of the round robin. The differences ranged from differences in the software used to the assumptions made when carrying out the analysis and the different means of carrying out the heat transfer analysis.

Beginning with the heat transfer analysis, 5 of the 19 solutions presented for the heat transfer analysis assumed lumped capacitance for the temperature distribution. This was either calculated using the method presented in EN 1993-1-2 [10] or using special software packages. These included Abaqus, Ansys, Sofistik, OpenSEES, SAFIR, Infograph and TASEF. 4 of the submissions accounted for the shadow effect, and 3 accounted for the heat absorbed by the light weight concrete when determining the temperatures of the beam. Regardless of the assumptions with regards to the temperature distribution, all of the different approaches relied on an uncoupled temperature displacement analysis. In all cases the coefficient of convective heat transfer; as well as the emissivity of the steel was taken from the Eurocode.

The approach used for the structural analysis either relied on the simplified methods presented in EN 1993-1-2 or finite element (FE) software packages. FE solvers used included Abaqus, Ansys, Sofistik, OpenSEES, SAFIR and Infograph (Note that one of the participants did not contribute to the mechanical analysis so the number of solutions presented for this stage was 18). Even comparing the solutions which relied on finite element analysis, different approaches were taken when developing the solutions, including using beam elements, shell elements and solid elements. Some of the solutions relied on symmetry, including quarter symmetry in one case. The solutions which used beam elements necessarily ignored the stiffeners.

All of the submissions relied on the material properties which are given in EN 1993-1-2.

3.4 Steel temperatures

Since not all of the participants reported steel temperatures at the points where the temperature was measured, it is hard to compare the results. Some participants reported the temperature at the centre of the web as well as the middle of the flanges, whereas others reported the temperature at the top, centre, and bottom of the web. In order to compare the temperatures provided, these have been grouped according to where they were reported and numbered 1 to 5 according to their location; see Figure 2. Others still reported a temperature which was calculated using an assumption of lumped capacitance, with the whole section temperature being number 6 in the reporting of the results.

Figure 2 also indicates the locations where the measurement of temperature were taken from the beam section during the test, with series 1a and 1b, and 3a and 3b, indicating measurements taken for the opposite side of the upper and lower flanges respectively.

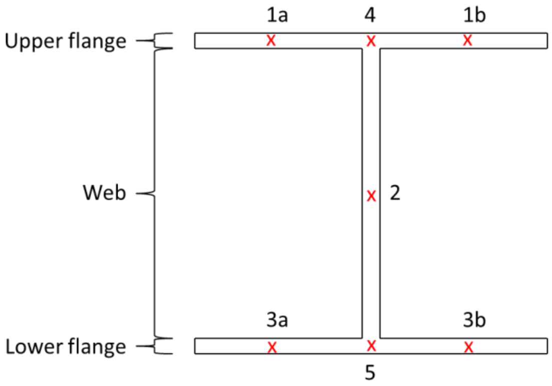


Figure 2. Points at which temperatures are reported

The results are truncated after 60 minutes, meaning that there is no comparison between results after this time although some did include data after this time.

All of the participants used material properties described in EN 1993-1-2 [10] and heat transfer coefficients and thermal boundaries described in EN 1991-1-2 [11] when determining the temperature of the steel beam. The different assumptions which were made and the different approaches taken nevertheless resulted in a significant difference in the calculated temperatures.

Figure 3 shows the temperatures reported for point 1, at the middle of one of the top flanges of the beam. The series in the figure are numbered according to submission and location in the section; i.e. 4,1 is from submission 4 and is the temperature reported at point 1. Figures 4, 5, 6 and 7 show the temperatures at points 2, 3, 4 and 5 respectively. Figure 3 shows only results from submissions 4, 5, 11, 12, 14 and 20 since those are the submissions which reported the temperatures at point 1. Results from the same submissions are also reported below for points 2 and 3 in Figures 4 and 5, and the results from the remaining submissions are shown for points 4, 5 and for lumped capacitance in Figures 6, 7 and 8.

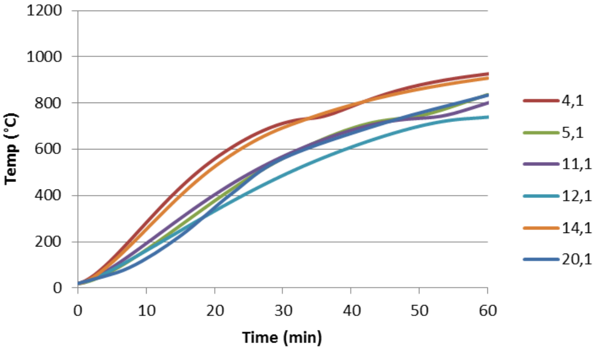


Figure 3. Reported temperatures at point 1

The largest variation in the reported temperatures occurs at points 1 and 4, which are at the top of the beam. The reason for this is that the different participants accounted for the insulation provided by the concrete on top of the steel beam in different ways. Some assumed an adiabatic boundary, whereas others made assumptions with regards to the thermal properties of the light weight concrete which was used to seal the top of the furnace.

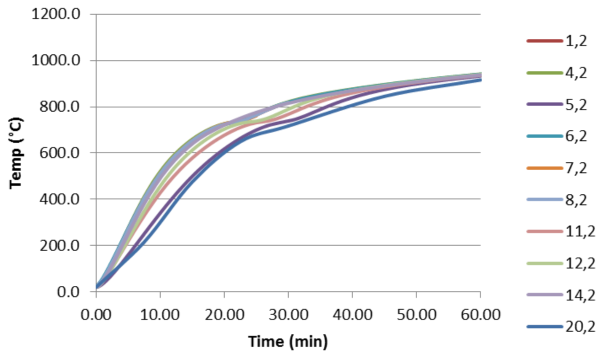


Figure 4. Reported temperatures at point 2

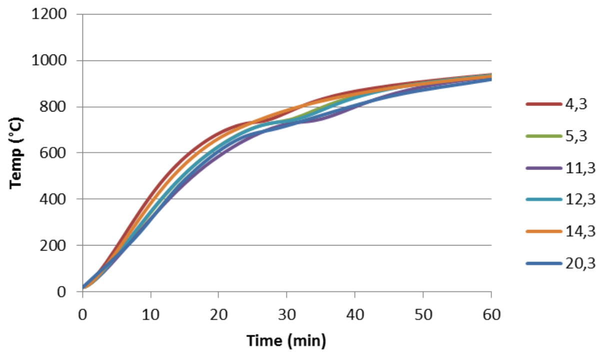


Figure 5. Reported temperatures at point 3

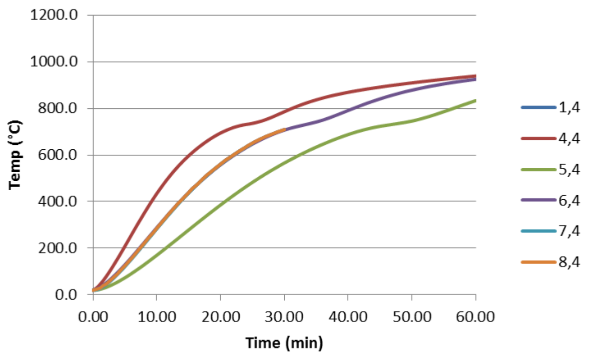


Figure 6. Reported temperatures at point 4

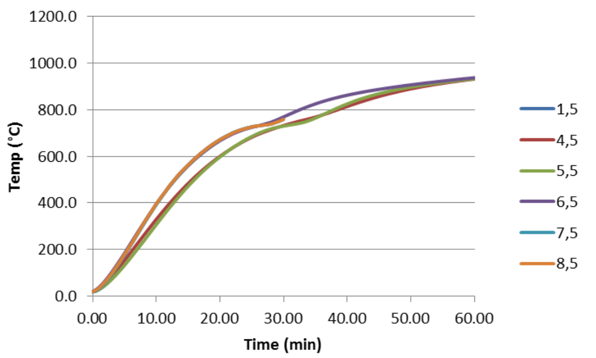


Figure 7. Reported temperatures at point 5

Figure 8 shows the reported temperatures by the participants where lumped capacitance was assumed. It should be noted that participant 3 reported two different temperatures, 3,6a and 3,6b, where the latter result was obtained assuming that the temperature at the ends of the beams tested was 20% lower than the temperature in the middle of the span. The temperature of the beam in the mechanical analysis (discussed later) was then varied linearly between these two temperatures. Participant 10 carried out two thermal calculations accounting for the shadow effect in different ways; and participant 13 in fact reported only the maximum and the minimum temperature in the beam. The results of participant 13 are included in this figure for comparison with the lumped capacitance calculations since it is not clear from the supplied description where the maximum or minimum temperatures occurred.

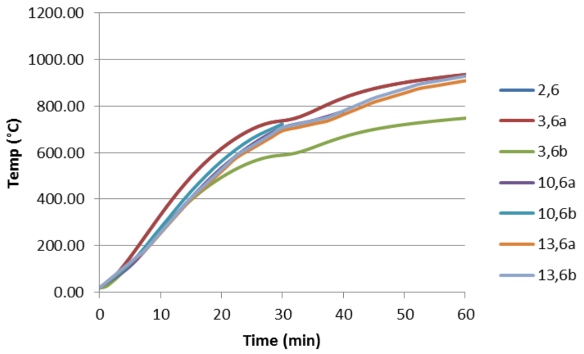


Figure 8. Reported temperatures assuming lumped capacitance

3.5 Deflection history

In most of the submissions (15 out of 19) to the round robin study at this stage the time-deflection response was reported. This, and its first derivative, is typically used as the failure criteria in the evaluation of the analyses by the participants. The complete collection of mid span time-deflection histories is presented in Figure 9. One of the participants withdrew one of their submissions (number 13) from the data set after the first stage was completed as a result of finding an error in their model. There is however a corresponding submission in the second stage.

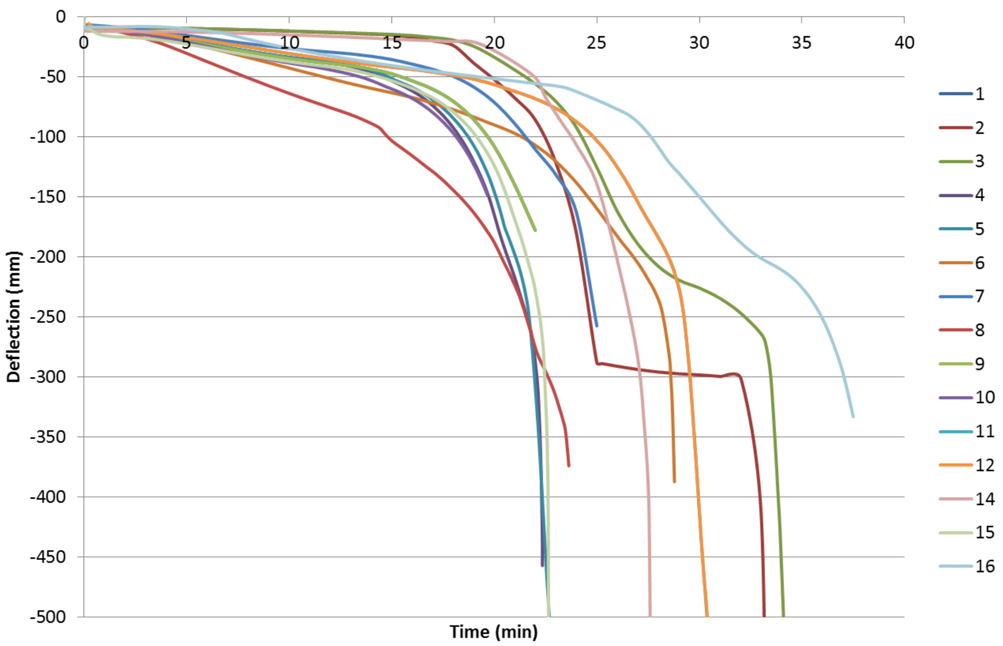


Figure 9. Calculated midspan deflection histories.

It can be seen that there is a huge span within the time-deflection responses reported, with the analyses reaching a mid-span deflection, e.g., of 100 mm at between 15 and 28 minutes, and a mid-span deflection of 300 mm at between 21 and 37 minutes. This represents a difference in time of 13 and 16 minutes respectively when comparing the deflection responses. This difference is surprising since the models used have all been validated a posteriori in comparison with experimental results in the past. The spread is not easily accounted for by comparing any one of the differences in the modelling approach; although clearly the difference in the steel temperatures will have some influence on this.

3.6 Failure time and failure criteria

The failure times and failure criteria from the calculations are reported in Table 1, which shows both the reported time to failure and the corrected time to failure. The declared failure times from all of the submissions are based on either a rate of deflection or a deflection criteria, varying by participant. The table indicates the time when both criteria are exceeded where both are given, with the limiting criteria stated in bold. All failure times presented in the table are given as full minutes where the element still fulfilled the requirements.

In order to better compare the results from the different participants, the results were 'corrected' according to the failure criteria described in EN 13501-2 [12].

These criteria are:

Failure of loadbearing capacity shall be deemed to have occurred when both of the following criteria have been exceeded:

a) deflection $D = L^2/400\ d$ *(mm) and*

b) rate of deflection $dD/dt = L^2/9000\ d$ *(mm/min)*

where L is the clear span of the test specimen in mm and d is the distance from the extreme fiber of the cold design compression zone to the extreme fiber of the cold design tension zone of the structural section, in mm.

The corrected failure times are also reported in Table 1 taking the result as the full minute before which the criteria was reached. Again, the failure time using both criteria described is shown and the limiting criteria is indicated in bold.

Table 1. Time to failure in stage 1 for the two failure criteria. The bold numbers in the column "Reported time to failure" indicates the failure time given in the participants report. The corrected time to failure is based on the criteria of EN 13501-2

Calculation	Reported time to failure		Corrected time to failure	
	Deflection	Rate of deflection	Deflection	Rate of deflection
1	**21***	<21	**21***	-
2	25	**19**	**24**	18
3	31	**21**	**31**	21
4	**21**	16	**21**	16
5	**21**	16	**21**	16
6	22	**27**	**27**	21
7	**24**	<24	**24**	19
8	**21**	<21	**21**	14
9	**22**	<22	**22**	17
10	**19****	-	**20****	16
11	28	**23**	**28**	23
12	28	**23**	**28**	23
14	26	**21**	**26**	21
15	**22**	10	**22**	10
16	34	**26**	**34**	26
17	**38*****	-	**38*****	-
18	**29*****	-	**29*****	-

* Calculation made only to a total deflection of 178 mm, and used L/20 as failure criterion as opposed to the rate of deflection criteria given in EN 13501-2 [12]
** Calculation made only to a total deflection of 150 mm which was used as failure
*** Simple calculation methods in accordance with Eurocode 3, no displacement history is reported and so no rate of deflection is given

One participant also proposed an alternative failure criterion – not represented in the table – of lateral deflection of the end of the beam. i.e. the failure criteria proposed was when the rate of lateral displacement changed sign and the net-expansion of the beam was overcome by the retraction at the free end caused by increasing curvature from both the applied load and the thermal curvature. This participant was responsible for two submissions, and the failure times for these submissions based on this criteria were both 20 minutes.

It is clear from the table that there is a significant variation in both reported and corrected failure times. The use of the simple calculation methods in the Eurocodes results (perhaps counterintuitively) in a longer time to failure than when the advanced calculation methods are used. The mean time to failure in the reported results is 22.7 minutes, and the standard deviation is 6 minutes. The coefficient of variance is 25 %. Neglecting the results based on the simple calculation methods gives a smaller variation: this results in a mean time to failure of 21.3 minutes, a standard deviation of 3.8 minutes, and a coefficient of variance of 18 %.

Figure 10 shows the frequency and the cumulative percentage of the different reported failure times from each submission.

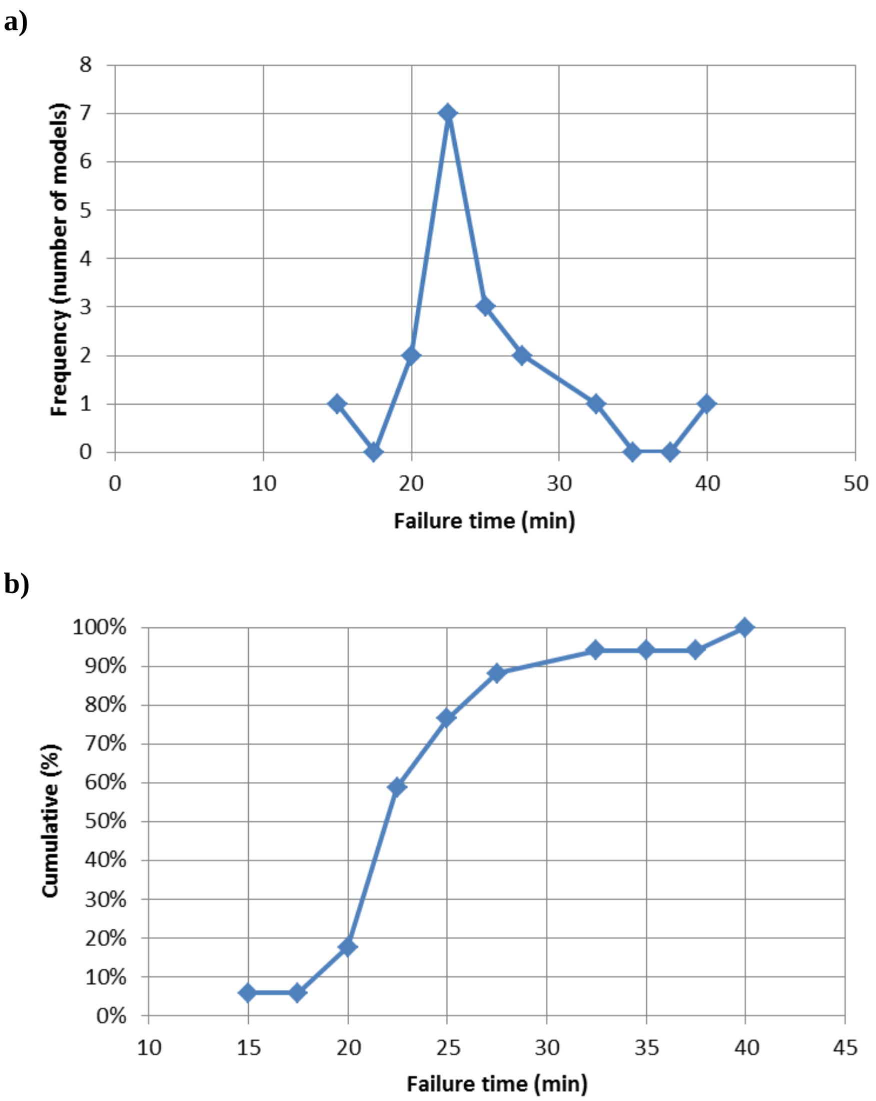
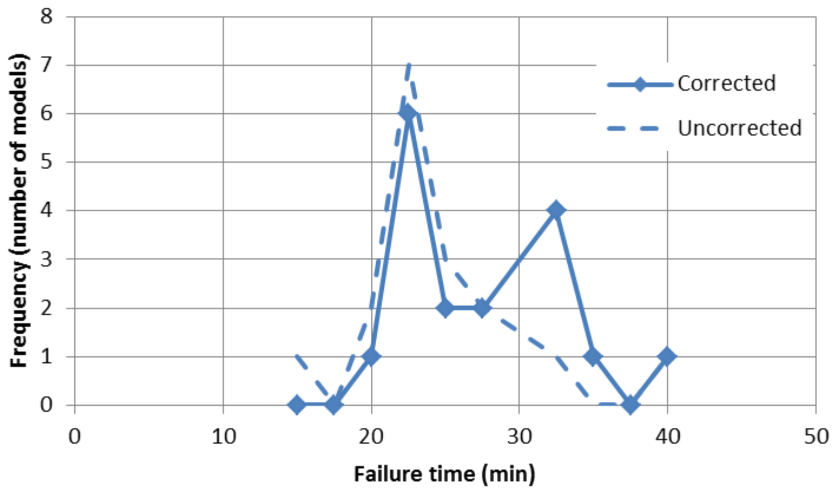


Figure 10. a) frequency and b) cumulative percentage of the reported failure times

Considering the corrected results gives a mean time to failure of 25.7 minutes, a standard deviation of 5 minutes and a coefficient of variation of 20 %. Again, neglecting the results which relied on the simple calculation methods in the Eurocode as opposed to FE analysis these result in a mean time to failure of 24.7 minutes, a standard deviation of 4.2 minutes and a coefficient of variation of 17 %.

Figure 11 shows the frequency of the results and the cumulative percentage respectively from the corrected results from round 1. These are overlaid with the uncorrected results.

a)



b)

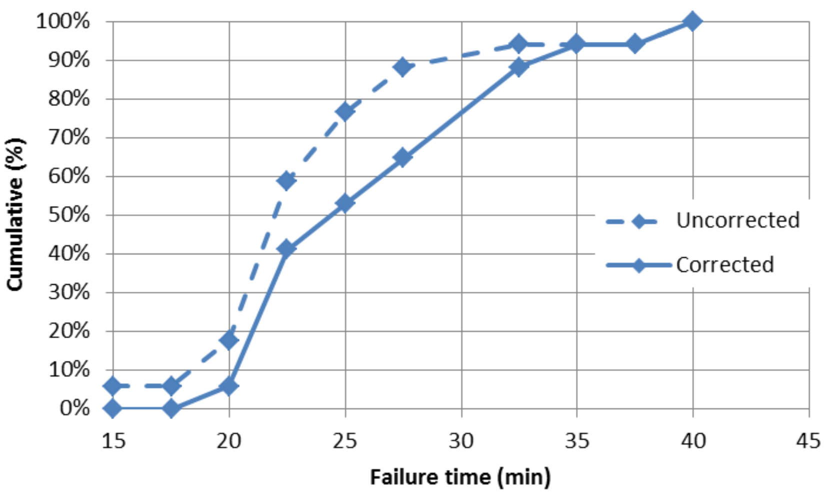


Figure 11. a) frequency and b) cumulative percentage of the corrected failure times, including a comparison with the reported failure times

The bias and thus the trueness of each calculation are here expressed as a z-score, which is defined as:

$$z_i = \frac{y_i - m}{s}$$

Where y_i is the result from the actual calculation, m is the mean value of all results and s is the standard deviation for all results. The z-score indicates how many standard deviations away from the mean result each of the data points is; and can be used to identify likely outliers.

The z-score for each calculation based on the corrected failure criteria is presented in Figure 12. The interpretation of the z-score is based on the following criteria:

- $|z_i| \leq 2$: the trueness performance of the calculation is satisfactory
- $2 < |z_i| \leq 3$: warning signal, the trueness performance of the calculation is questionable
- $3 < |z_i|$: action signal, the trueness performance of the calculation is unsatisfactory

Only one of the results has an unsatisfactory trueness. This calculation is based on one of the simple methods.

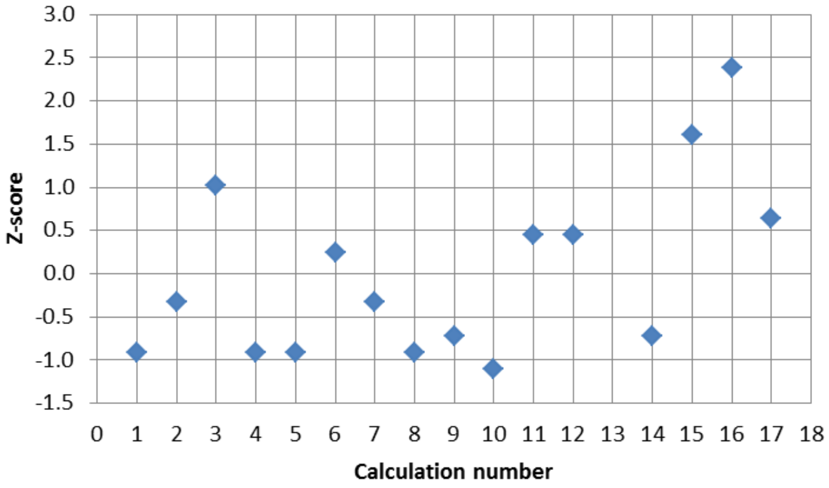


Figure 12. Z-score for each calculation.

Table 2 summarises the mean and standard deviation from the corrected and uncorrected failure times, including and not including the simple calculation results.

Table 2. Summary of the mean, standard deviation, and coefficient of variance of the failure times

	Uncorrected failure times			Corrected failure times		
Including simple methods	Mean value	22.7	minutes	Mean value	25.7	minutes
	Std dev	5.7	minutes	Std dev	5.2	minutes
	CoV	24.9	%	CoV	20.1	%
Omitting simple methods	Mean value	21.3	minutes	Mean value	24.7	minutes
	Std dev	3.8	minutes	Std dev	4.2	minutes
	CoV	18.1	%	CoV	17.0	%

3.7 Stage 1 round robin summary and conclusions

Eleven different participants have performed calculations to try to predict the result for the same experiment. A total of 18 calculations have been performed. There were no two submissions which used the same calculation approach and different assumptions or approaches were taken with regards to the thermal exposure and the mechanical modelling.

Approaches taken included using the simple calculation models in the Eurocode and advanced calculation models using material properties and boundary conditions taken from the Eurocode. The simple calculation methods when used gave a longer fire resistance than the advanced calculation methods, although it would be expected that the simple methods should be more conservative. The z-score of the failure times from the simple calculation methods was also amongst the highest from the total set. Omitting these results from the data set reduces the spread in the results slightly.

Nevertheless, there is quite considerable scatter in the results with a coefficient of variation of 17 % when the results were corrected and the simple calculation results omitted.

4 Fire test results

4.1 Test setup

As described in the previous section, the test was carried out in accordance with EN1363-1, the test object was an HEB 300 steel beam of total length 5400 mm, spanning 5200 mm, as shown earlier in Figure 1. The beam had web stiffeners located 1400 mm from both of the supports and at the supports. The beam was simply supported. Load was applied via hydraulic cylinders positioned above the stiffeners. The total applied load resulted in a moment of 140 kNm between the points of load application.

In preparing the specimen, thermocouples were peened to the steel at the locations 1, 2, 3, 4 and 5 shown in Figure 2 at the midspan of the beam. In addition to this, thermocouples were peened to the surface of the beam 700 mm from the supports at locations 1, 3 and 4.

Furnace temperature was measured using 20 plate thermometers. The specimen positioned in the furnace is shown in Figure 13. The top of the specimen is covered with light weight concrete blocks with dimensions 150 mm x 200 mm x 580 mm and a density of 535 kg/m^3. On either side of the concrete blocks the furnace was sealed with reinforced concrete slabs. To prevent interaction between the lightweight concrete and the concrete slabs a layer of insulation material was attached to the adjacent side of the light weight concrete.

Figure 13. photo of the test setup

4.2 Measured temperatures

The average plate thermometer measurement from the fire test is shown in Figure 14. Also shown in Figure 13 is the ISO 834 fire curve.

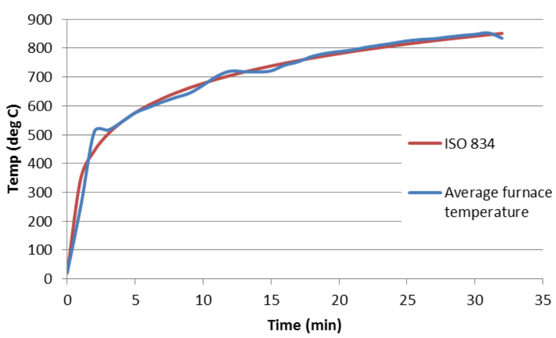


Figure 14. Furnace temperatures during the test

The temperatures recorded from the measurement locations shown in Figure 2 during the test are shown in Figure 15. Series marked without an asterisk are taken from the midspan of the steel beam, the series denoted 1a and 1b, and 3a and 3b, come from the opposite sides of the upper and lower flanges respectively. The series marked with the asterisk are from the stations at the north end of the furnace. The series marked with two asterisks are from the south end of the furnace.

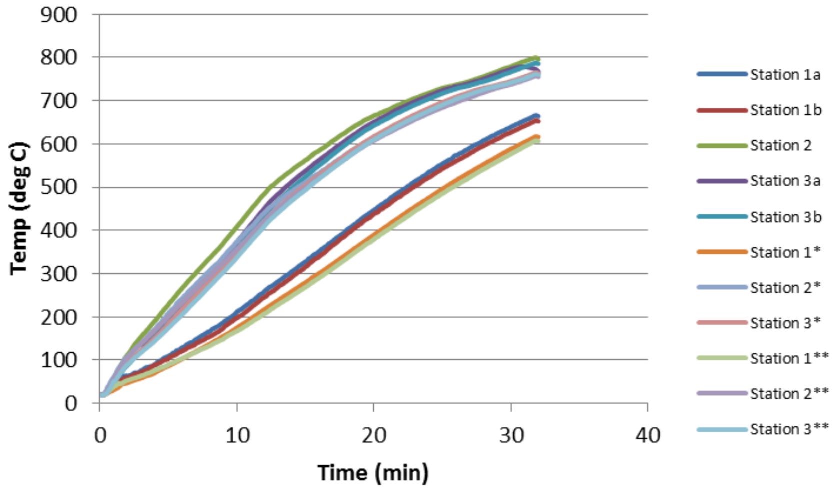


Figure 15. Measured steel temperatures during the test

4.3 Measured deflections

Measurement of deflection at the midspan and at 700 mm from the north and the south supports of the beam was measured using a linear displacement transducer throughout the test. The total deflection history is shown in Figure 16. The test was continued until the specimen reached both failure criteria in EN13501-2: criteria for both deflection and rate of deflection. Rate of deflection criteria was exceeded after 26 minutes; deflection criteria was reached after 31 minutes. The results for deflection measured 700 mm from the north and south supports coincide with one another and the results from the measurement at the north are hidden below those from the south in the figure.

Immediately upon both failure criteria being reached the test was stopped and the specimen was removed from the furnace. The final deflected shape of the specimen can be seen in Figure 17.

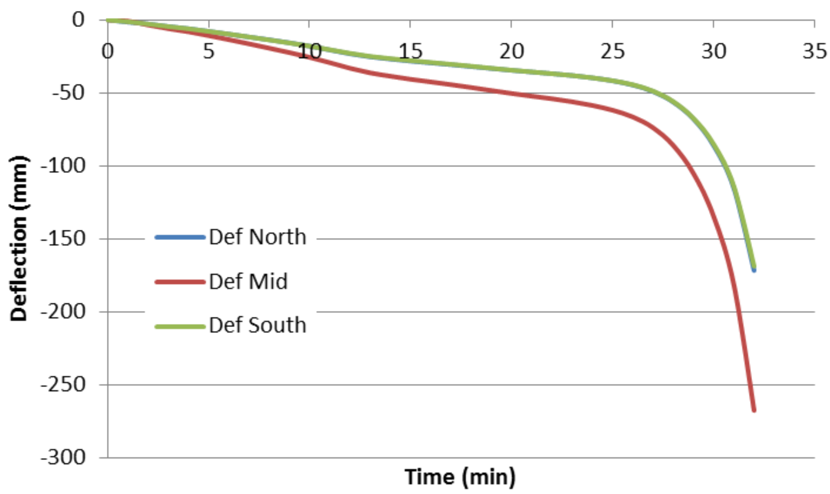


Figure 16. Measured deflection during the test

Figure 17. Photo of the specimen after the test

4.4 Comparison with stage 1 results

A comparison of the temperatures predicted during stage 1 of the round robin with the measured temperatures from stations 1, 2 and 3 in the test are shown in Figures 18, 19 and 20. Measured results at stations 1 and 3 are based on the average temperatures measured at these points at the midspan. These show remarkably good between the different analyses and the temperatures measured in the experiments, with the exception of the temperatures at location 1, where there is a wider spread associated with the approach which different participants used to account for the lightweight concrete cover on the top of the beam.

The measured deflections and the calculated deflections are compared in Figure 21. The calculated deflections are in most cases larger than the measured deflections at any given time, suggesting that the calculated results from the stage 1 round robin are conservative in comparison with the test.

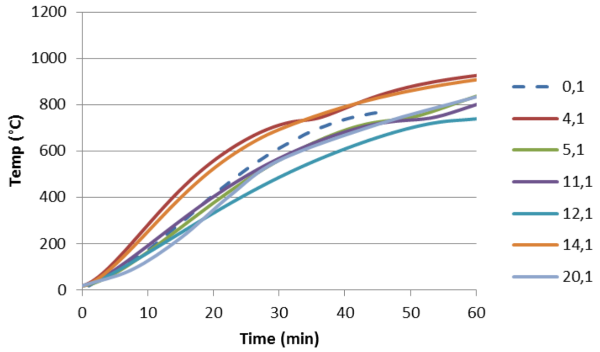


Figure 18. Comparison of the a-priori predicted temperatures at point 1 with the measured temperatures. The 0,1 graph corresponds to the experimental data.

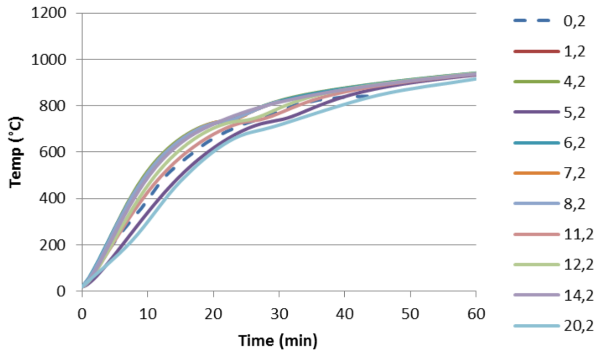


Figure 19. Comparison of the a-priori predicted temperatures at point 2 with the measured temperatures. The 0,2 graph corresponds to the experimental data.

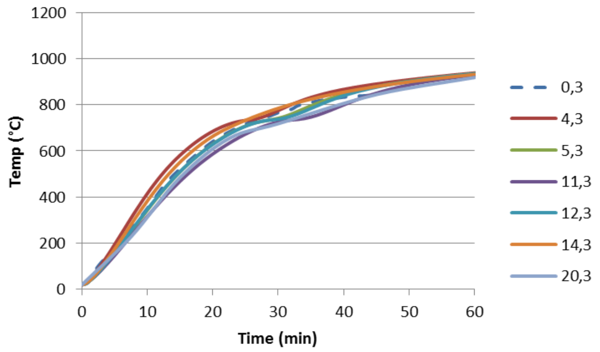


Figure 20. Comparison of the a-priori predicted temperatures at point 3 with the measured temperatures. The 0,3 graph corresponds to the experimental data.

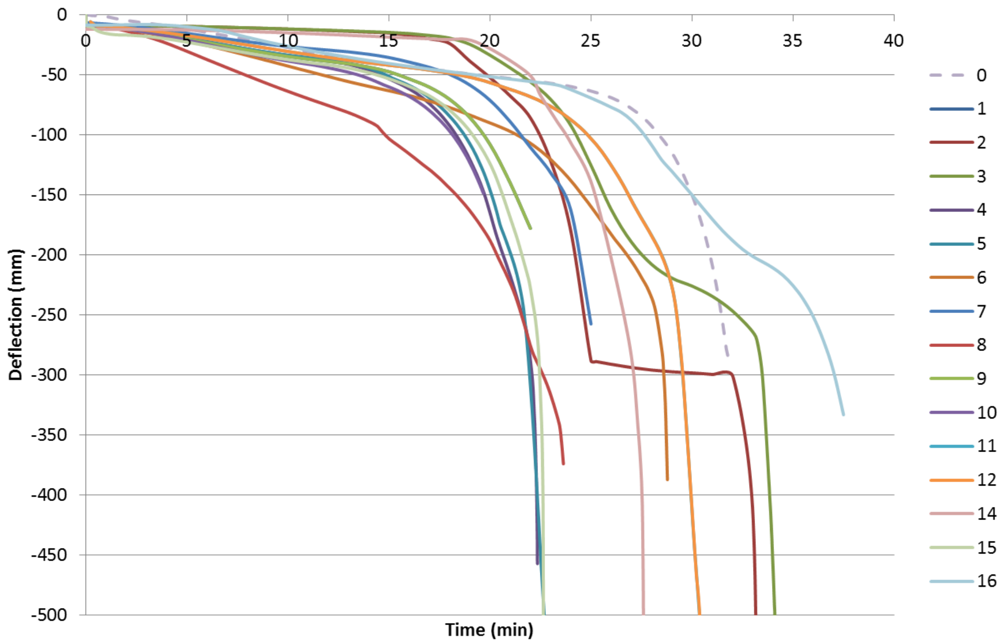


Figure 21. Calculated midspan deflection histories compared with the test performed.

5 Stage 2 round robin

5.1 Additional information provided to the participants

In the instructions for the second stage of the study the participants were furnished with additional information (Appendix C) which would allow them to improve their estimation of the fire resistance of the steel beam. This information included the tensile strength of the steel; as well as the measured temperatures from the furnace plate thermometers and the measured temperatures at the midspan of the steel beam during the test.

By means of tensile testing of the steel, the elastic limit was determined to be 447.5 MPa, based on 6 samples tested according to ISO 6892-1[12]. The standard deviation was below 2 %. This is notably higher than the elastic limit implied by the steel gradeof 355 MPa.

The temperatures which were provided were extended with estimated temperature values since the test was terminated when the beam failed, and by only giving the measured temperatures we would be informing the participants of the actual failure time. Therefore the temperatures from the failure time to the end of the table are estimated values.

Average plate thermometer temperature measurements are provided in Table 3. Measured temperatures in the steel at the different measuring locations shown in Figure 2 are provided in Table 4.

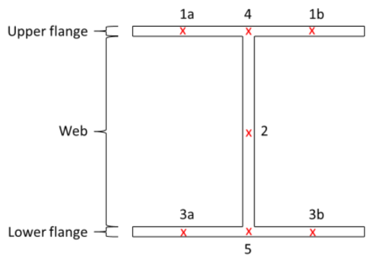
Table 3. Average plate thermometer measurements provided to the participants

Time (min)	ISO 834 Temperature time curve	Furnace plate thermometer measurements
0	20	22
1	349	252
2	444	511
3	502	516
4	544	544
5	576	575
6	603	595
7	625	613
8	645	629
9	662	644
10	678	671
11	692	702
12	705	720
13	717	718
14	728	717
15	738	721
16	748	741
17	757	753
18	765	771
19	773	782
20	781	788
21	788	794
22	795	803
23	802	810
24	808	817
25	814	825
26	820	830
27	826	833
28	831	838
29	836	844
30	841	848

Time (min)	ISO 834 Temperature time curve	Furnace plate thermometer measurements
31	846	853
32	851	860
33	856	867
34	860	871
35	864	874
36	869	878
37	873	882
38	877	885
39	881	888
40	884	893
41	888	897
42	892	899
43	895	900
44	899	902
45	902	903

Table 4. Steel temperatures from the mid span provided to the participants

Time (min)	Location 1a	Location 1b	Location 2	Location 3a	Location 3b
0	19	19	19	19	19
1	38	34	37	30	32
2	63	56	95	86	75
3	71	69	141	125	111
4	85	83	177	149	141
5	104	99	215	181	173
6	123	115	254	216	206
7	141	132	289	251	239
8	160	148	324	286	273
9	179	166	357	322	306
10	201	189	395	359	343
11	226	212	434	399	381
12	251	237	473	438	421
13	274	260	505	473	457
14	297	283	531	503	487
15	320	307	554	529	515
16	344	333	578	554	542
17	368	357	599	578	567
18	391	383	622	601	592
19	415	407	642	624	615
20	440	429	659	645	636
21	462	451	674	662	653
22	485	475	689	679	671
23	506	495	701	693	686
24	526	517	714	706	700
25	548	536	725	720	712
26	565	554	734	729	724
27	585	572	742	738	733
28	601	590	752	746	742
29	619	606	764	758	751
30	634	622	775	769	763
31	650	637	787	778	774
32	664	652	798	774	786
33	677	670	808	798	795
34	689	683	814	805	803
35	701	695	819	811	809
36	711	705	825	817	816
37	721	717	828	822	820
38	730	727	831	826	825
39	738	736	835	830	829
40	745	744	838	833	833
41	751	751	839	835	835
42	756	757	840	837	838
43	761	763	841	839	839
44	766	767	842	840	841
45	770	771	842	841	841



5.2 Information requested from the participants

For the second stage, the participants were asked to repeat their analyses accounting for the new information which was provided to them and to provide the following information:

1. A description of any changes which were made to the model between the initial modelling stage and this stage

2. A description of if and how the measured temperatures were accounted for in the model
3. The revised deflection history of the beam during the standard fire exposure
4. A declaration of the revised failure time of the beam during standard fire exposure

5.3 Participation in stage 2

Participation in stage 2 compared with that in stage 1 changed slightly, with one submission (number 1) not being repeated and an additional submission (19) made using a slightly different modelling approach. The numbering of the submissions is kept the same between the first and the second stage in order to allow comparison between the stages.

5.4 Changes to the heat transfer modelling

Participants responsible for submissions 2, 3, 6, 8, 11, 12, 13 and 14 applied the measured temperatures to the relevant parts of the beams, with no smoothing of the temperatures at the transitions between web and flange (i.e. three temperature histories were applied, one to the upper flange; one to the web; and one to the bottom flange). In submission 2 the temperatures were applied across the entire length of the beam, whereas in submission 3 the measured temperatures were applied at the midpsan and the temperature (in °C) was decreased linearly to 80% of the midspan temperature at the ends of the beam. In both submissions 2 and 3 the average of the reported temperature was applied to the stiffeners. Submission 6 applied the temperature of the web to the stiffeners.

The participant responsible for submission 7 changed the convective heat transfer coefficient from 25 kW/m^{2}K in stage 1 to 35 kW/m^{2}K. They also changed the surface emissivity of the steel to 0.6 from 0.7. The measured furnace temperatures (plate thermometer measurements) were then used as the radiation temperature and the gas temperature in the heat transfer calculation. The use of the measured furnace temperatures in this way was also the case for submission 9.

Submission 10 did not account for the additional information provided regarding the temperatures.

For submission 15, the participant adjusted the convective heat transfer coefficient and the surface emissivity of the steel in order to make the temperatures in the simulation better fit the measured temperatures. In this case they used a convective heat transfer coefficient of 12 kW/m^{2}K on the upper flange and 15 kW/m^{2}K everywhere else; the emissivity was changed to 0.5 throughout.

Submission 16 used the reported temperature data to recalculate the emissivity of the element, using the following equation:

$$\varepsilon_m = \frac{\frac{c_a}{k_{sh}{}^{A_m}/_V}\frac{\Delta\theta_{a,test}}{\Delta t} - \alpha_c(\theta_g - \theta_m)}{\Phi\varepsilon_f\sigma(\theta_r^4 - \theta_m^4)} \qquad 0.20 \leq \varepsilon_m \leq 0.99$$

where ε_m is the emissivity of the member, c_a is the specific heat of the member, k_{sh} is a correction factor for the shadow effect, A_m/V is the section factor for the section, $\Delta\theta_{a,test}$ is the change in temperature of the element in the test, Δt is the time increment, α_c is the convective heat transfer coefficient, θ_g is the gas temperature in K, θ_m is the steel temperature in K, Φ is a view factor, ε_f is a flame emissivity, θ_r is a radiation temperature.

Submission 16 also used the reported furnace temperature (plate thermometer temperature) as the radiation and gas temperature for the heat transfer calculation.

Participants responsible for submissions 4, 5 and 19 applied the measured temperatures to the steel directly. The top flange temperature was the average of the measured temperature at both stations in the upper flange and the bottom flange temperature the average of both stations on the bottom flange.

5.5 Changes to the mechanical modelling

Participants responsible for submissions 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15 and 19 adjusted the temperature dependent stress-strain curve to reflect the measured value of the elastic limit which was reported to the participants.

The participant responsible for submission16 did not adjust the stress-strain curve to reflect the measured value of yield strength of the steel reported.

5.6 Deflection history

The deflection histories reported in stage 2 are shown in Figure 20. As said, the submission number was kept the same in this stage as in the 1st stage; so that the numbers are comparable with the first stage bearing in mind the changes detailed above to the models taking into account the additional information supplied. In Figure 20 series 0 represents the test results.

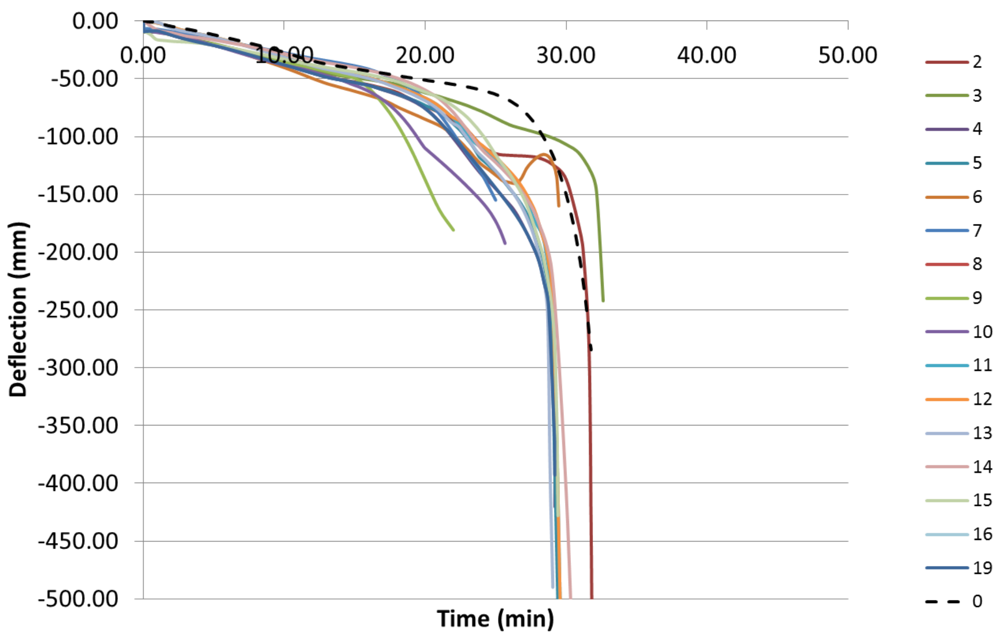


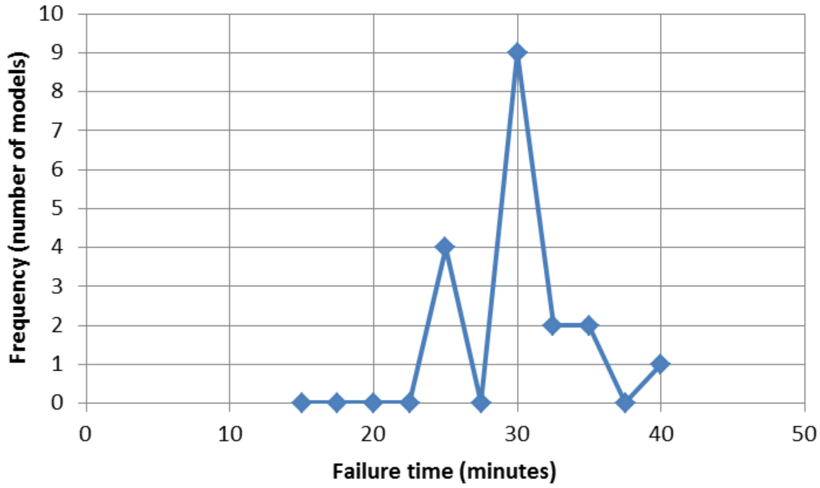
Figure 20. Deflection histories reported following the stage 2 analyses

Comparing the spread in times to reach 100 mm deflection in Figure 20 which is between 18 – 32 minutes, with the time to reach 100 mm in the first stage, figure 9, which is between 15 – 28 minutes the spread in the two stages is actually comparable.

5.7 Failure time and failure criteria

As with the first stage of the round robin, the participants were asked to report the failure times of the their different models. The different participants relied on different failure criteria. The scatter of the different results are shown in figure 21.

a)



b)

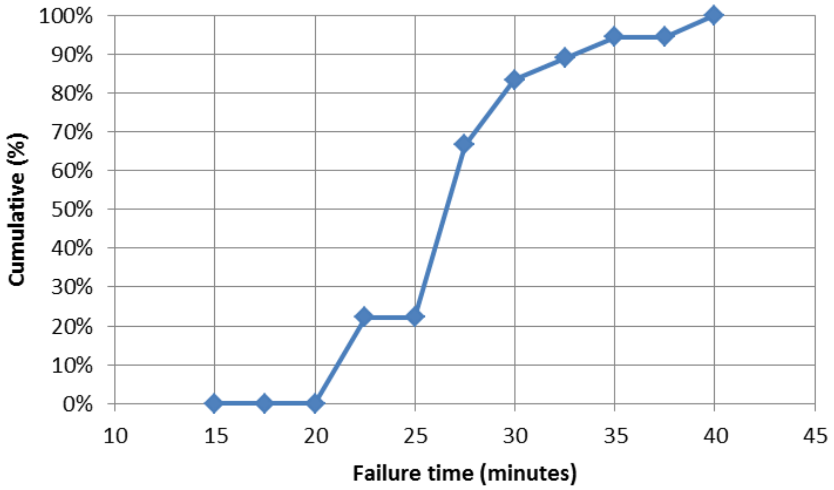


Figure 21. a) frequency and b) cumulative percentage of the reported failure times in the second stage

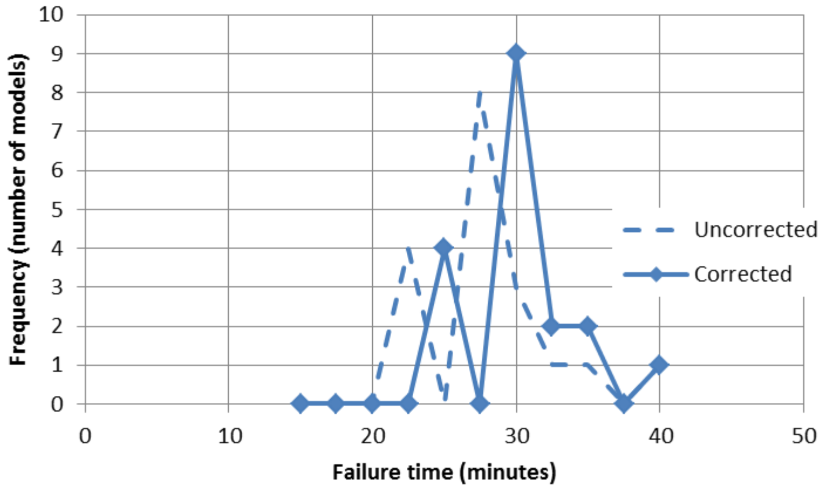
The reported failure times are summarised in Table 5. Again, this includes corrected failure times based on the failure criteria in EN 13501-2. The failure time for the limiting criteria reported is again indicated in bold, with the failure time based on the other criteria also included where this was provided. The limiting criteria in the corrected results is also indicated in bold.

Table 5. Time to failure in stage 2 for the two failure criteria. The bold numbers in the column "Reported time to failure" indicates the failure time given in the participants report. The corrected time to failure is based on the criteria of EN 13501-2

Calculation	Reported time to failure		Corrected time to failure	
	Deflection	Rate of deflection	Deflection	Rate of deflection
0 (test)	**-**	-	**31**	26
1	**-**	-	-	-
2	31	**29**	**31**	29
3	32	**31**	**32**	32
4	**26**	-	**28**	23
5	**27**	-	**28**	21
6	29	**21**	**30**	22
7	**26**	26	**25**	20
8	**26**	-	**24**	18
9	**27**	-	**25**	16
10	**26**	-	**25**	17
11	**22**	**-**	**29**	22
12	**22**	**-**	**29**	22
13	**22**	**-**	**28**	21
14	**28**	**-**	**29**	21
15	**28**	-	**28**	22
16	33	**27**	**33**	28
17	40	-	**40**	-
18	33	-	**33**	-
19	26	-	**28**	21

The frequency and cumulative frequency of the corrected failure times in stage 2 is shown in figure 22 along with the uncorrected data for comparison. Generally there is a trend for the corrected failure times to be slightly longer than the uncorrected.

a)



b)

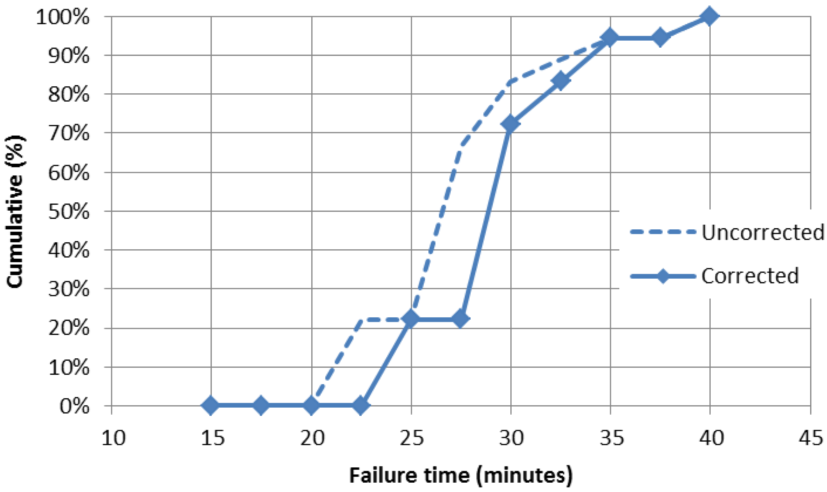
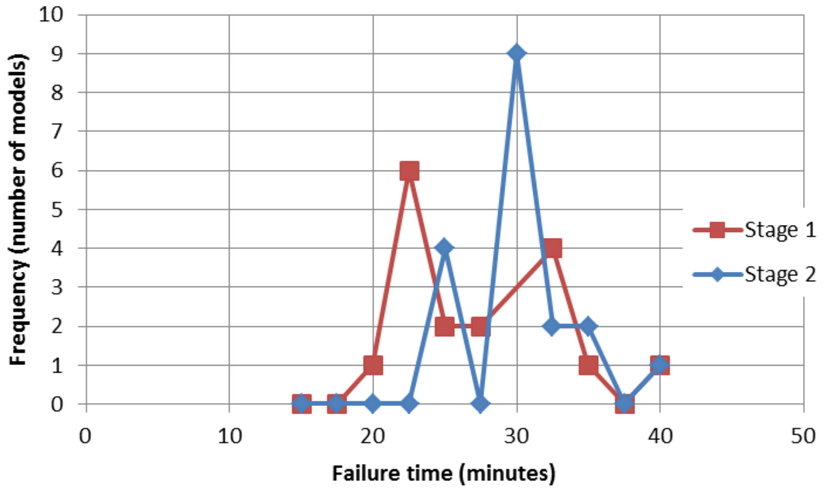


Figure 22. a) frequency and b) cumulative percentage of the corrected failure times in the second stage round robin including the uncorrected times for comparison

A comparison of the frequency and the cumulative frequency of the corrected failure times in stage 1 and stage 2 is shown in figure 23. There is a narrower spread in failure times in stage 2 in comparison with those in stage 1.

a)



b)

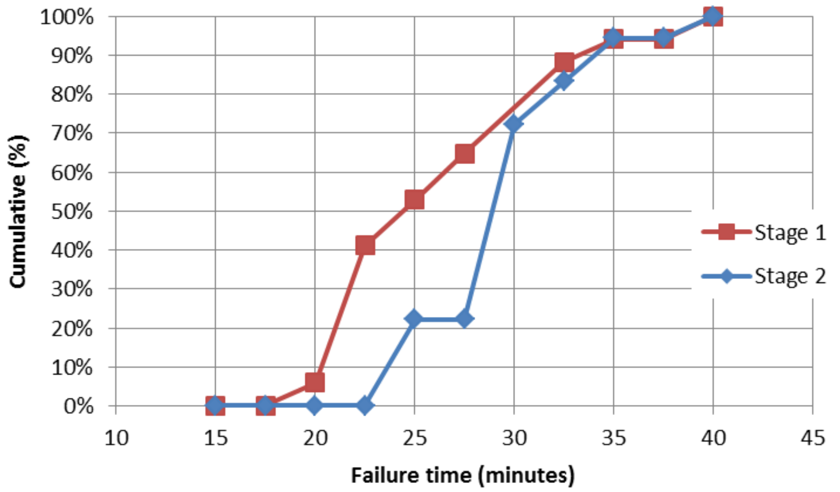


Figure 23. a) frequency and b) cumulative percentage of the corrected failure times in both stages of the round robin

As with stage 1, the z-score is once more calculated for the corrected failure times in stage 2, see figure 24. Generally the z-score of the submissions is satisfactory, however as with stage 1, the simple calculation method used in submission 17 in stage 2 results in the worst z-score.

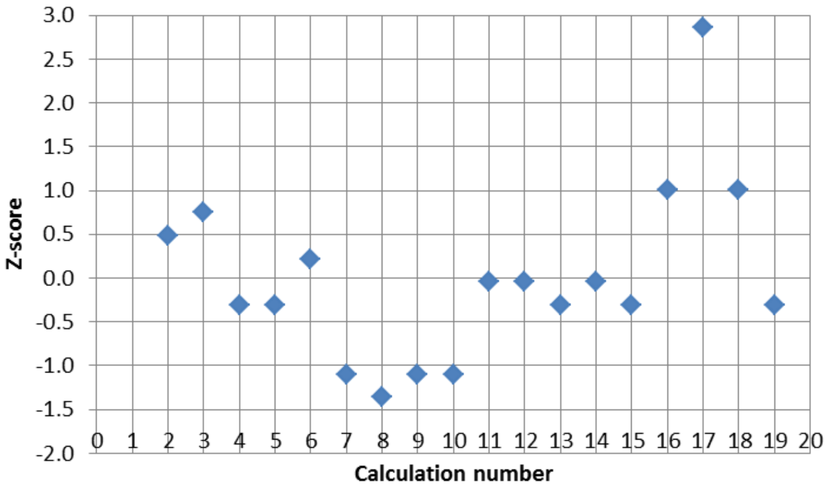


Figure 24. z-score of the calculations in stage 2.

A summary of the mean failure time and the standard deviation of failure time in stage 2 is shown in Table 5. This summary includes the failure time reported as well as the corrected failure time. As with stage 1, the values are also reported including and omitting the simple calculation methods.

Table 5 Summary of the mean, standard deviation, and coefficient of variance from the corrected and uncorrected failure times in stage 2, including and not including the simple calculation results from.

	Uncorrected failure times			Corrected failure times		
Including simple methods	Mean value	27.0	minutes	Mean value	29.2	minutes
	Std dev	4.5	minutes	Std dev	3.8	minutes
	CoV	16.7	%	CoV	13.0	%
Omitting simple methods	Mean value	25.9	minutes	Mean value	28.3	minutes
	Std dev	2.8	minutes	Std dev	2.6	minutes
	CoV	11.0	%	CoV	9.1	%

5.8 Stage 2 round robin summary and conclusions

A comparison between the second stage round robin results and the first stage round robin results suggests that the additional information which was given to the participants reduced the variation between the different solutions to the problem posed. Nevertheless there remains a standard deviation between the different solutions which is between 16.7 % of the mean result using the uncorrected failure times and including the simple methods, and 9.1 % of the mean result once the failure times are corrected and omitting the solutions which relied on the simple methods, suggesting a relatively high variation arising from either the methods used or the assumptions or approach taken by the different users.

6 Summary and conclusions

This report described the results of a round robin study carried out to evaluate the scatter in predictions of the response of a steel beam loaded in 4 point bending under standard fire exposure. The round robin was based on calculations rather than actual testing, although it was designed to mimic a round robin as it would be carried out as part of the certification process which fire testing laboratories in Europe have to go through. The example used in this case is one of the simplest examples of a fire resistance calculation which could be undertaken, with a single element and well defined mechanical and thermal boundary conditions.

The participants were provided with information about the testing method and the standard which would be followed and were requested to provide details about the response taken in performing the calculation as well as to declare the failure time of the beam. The participants were allowed to make any assumptions, follow any methods and to adhere to any standards which they deemed to be appropriate. In the majority of cases, the participants employed numerical codes, basing the thermal exposure on EN 1991-1-2 and the material behaviour on EN 1993-1-2. Different numerical codes were used and different assumptions were made with regards to the approach which was taken. Some participants did use simpler or hand calculation methods. Some participants provided more than one submission to the round robin using either variants on an analysis method or using different analysis methods. These multiple submissions from the same partner were treated as different submissions to the round robin.

Two separate stages were carried out in the study. The first stage was an a-priori round robin and the second stage was an a posteriori round robin where the participants were given additional information about the measured temperatures in the furnace and the actual yield strength of the steel.

The failure criterion used by the participants was different. According to the European classification standard EN 13501-2 the failure of a fire exposed beam element occurs when both the criteria on limiting deflection and limiting rate of deflection has been reached. Some participants used the time when the first of the two criteria has been reached. Some participants used other criteria such as a limiting deflection of L/20 or L/30. Some participants proposed an alternative failure criterion.

In the a-priori round robin, using the different declared failure times based on these different criteria the coefficient of variation in failure times was around 25 %. Omitting the simple calculation methods from the set of results this reduced to 18 %. Once the failure criterion were corrected so that they follow the criteria in EN 13501-2 there was a small reduction in the variation in failure times to 20 % and 17 % respectively including and omitting the simple calculation methods.

In the a-posteriori round robin the coefficient of variation was around 17 % including the simple calculation methods and 11 % omitting the simple calculation methods. Correcting the failure times in this case reduced the variation to 13 % and 9 % respectively.

In the first stage round robin the scatter in the deflection histories is quite large. This was reduced partially in the second stage by providing the participants with the measured temperatures from the steel beam and the plate thermometers in the furnace. However there remained a quite large scatter in the second stage. The measured yield strength of the steel was larger than the steel grade suggested and there was a corresponding increase in the predicted fire resistance time when this was taken into account. Nevertheless this made no contribution to the scatter in the results since all participants relied on the information which was given to them at all stages and the biggest impact this information would have had would have been to increase the mean of the corrected failure times.

A comparison of the temperatures reported in the first stage is very difficult since not all of the participants reported steel temperatures at the points where the temperature were measured or even at equivalent points on the steel section. Better control over the results which are reported is a necessary requirement for future round robins in order to ensure that the most possible information can be gained from them.

Considering the impact of using the measured temperatures in the furnace, this made a noticeable difference to the scatter in the deflection histories and the failure times. The second stage failure times are less varied, especially when corrected for consistent failure criteria. The temperatures reported in the first stage by the different participants were quite variable, however the use of the measured temperatures by the participants (in various ways) removed this variation. Any variation in the furnace temperatures from the standard fire or inhomogeneity in the furnace temperatures would not have affected the spread in the calculations since the participants were given average furnace temperatures only and only one set of the recorded steel temperature measurements.

Comparing the second stage round robin results with the actual test, it is clear that the average response is conservative. However, at this stage of analysis there is no conservativeness resulting from the strength of the steel in these models or in the thermal exposure, meaning that the conservativeness is inherent in the models themselves or the different approaches made in developing them. Given that the use of FE modelling as an advanced method in the Eurocode has supposedly been validated based on the results of testing it is unclear why this conservativeness would be present.

There are two issues highlighted by the results of the study, the first relating to the spread in the calculated deflection histories and the calculated times to failure; the second relating to the failure criteria used by the participants.

This type of modelling is routinely used in structural fire design. Being a relatively simple example of the calculation of the fire resistance of an element of structure the authors did not anticipate such a large scatter. Yet the scatter in results suggests that the relative performance of the design tools or of the designers has some inherent variation which should perhaps be taken account of in design, such as the interpretation of the results, or the selection of different solvers and solver dependent parameters. Not all of the calculations were conservative either a-priori or a-posteriori, although the majority were. The conservativeness of the a-priori calculations in comparison with the test response is largely a result of the higher yield strength than the grade of steel suggests. The source of the remaining conservativeness inherent in the calculation methods is unclear: whether this is a factor arising from the user or the methods employed or a combination of the two requires further investigation.

A lack of consistency in failure criteria used by the participants also highlights a potential issue when calculations are relied upon for certification or design purposes. As mentioned earlier, there are controls implemented to ensure that fire testing laboratories follow the same procedure when determining the fire resistance of different structural elements. There is however no common consensus or approach to determining the point or time of failure in equivalent calculations.

In summary, the results of the study highlight the fire research and testing community’s capability for modelling this simple case as well as the uncertainty in the calculation results. The variation in response was larger than expected, as was the variation in failure times. The results were conservative, however it is not clear where this conservativeness arises from.

7 References

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[9] EN 1363-1: 999 Fire resistance tests. General requirements
[10] EN 1993-1-2: 2005 Eurocode 3: Design of steel structures -Part 1-2: General rules - Structural fire design
[11] EN 1991-1-2:2002 Eurocode 1: Actions on structures - Part 1-2: General actions - Actions on structures exposed to fire
[12] EN 13501-2:2007 Fire classification of construction products and building elements. Classification using data from fire resistance tests, excluding ventilation

Appendix A: invitation to the round robin

Contact person	Date	Reference	Page
David Lange Fire Research +46 10 516 58 61 David.Lange@sp.se	2014-09-03		1 (3)

Invitation to participate in a round robin calculation of a loaded steel beam exposed to fire

Dear prospective participant,

We write to invite you to participate in a structural fire engineering calculation round robin. The objective of the project is summarised below as well as the project timeline. This proposed round robin is similar to another calculation round robin which we intend to run in 2015 of a much larger test and which we will also be seeking participants for.

The available time for the a priori modelling is short and therefore we request expressions of interest as soon as possible, at the latest by the end of September. Following receipt of expressions of interest we will distribute details of the requested measurements to all participating groups.

Because of the simplicity of the test specimen we do not anticipate the modelling to take a significant amount of time. However, we will require some time to process the results of the round robin and to carry out the analyses required.

No financial contribution is requested for participating in the round robin, and no financial support can be given to the round robin participants.

Please register expressions of interest by the *end of September* with either of the undersigned. These people can also be contacted if you have any questions.

Yours sincerely,

SP Technical Research Institute of Sweden
Fire Research - Fire Resistance

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Summary and Objective

The objective of the project is to evaluate the capability of different commercial groups including testing laboratories, consultancies and universities in modelling what is supposedly a simple test specimen in a furnace test. The round robin study will highlight either: the fire research and testing community's capability in this area, or that further development is required.

Two fire tests will be conducted on steel beams at SP's fire resistance laboratory in Sweden on identical test specimens which are to come from the same cast flow from steel foundries. The tests will be conducted according to EN 1365-3 and will comprise a loaded, unprotected steel beam with web stiffeners of total length 5.4 m, spanning 5m, which will be exposed to a standard fire on the horizontal furnace. Additional tokens from the same cast flow have been retained for material testing. The tests are scheduled for week 44 of 2014, beginning the 27th of October.

Project timeline

The proposed project follows the general methodology which is outlined below:

1. Invitation for expressions of interest

   Participants from fire resistance laboratories, universities and consultancies will be invited to attempt to model the response of the steel beam.

   Expressions of interest are sought by the end of September 2014

2. Preparation of documentation and distribution of structural configuration including details of requested output ; a priori structural modelling and evaluation of results

   Once the round robin group has been assembled, the participants will be asked to predict 'a priori', i.e. before the test, aspects of thermal response and structural behaviour including, e.g. temperatures and mid-span deflections. The exact details of the requested output will be determined and distributed to the participants in the first week of October.

   Results are requested by the 27th of October.

3. Distribution of thermal field measurements from the tests

   Results of the temperatures measured on the steel will be distributed to project participants and they will be asked to repeat their modelling using the measured temperature data.

   A second round of modelling will then be undertaken using the measured data from the thermal field. Again the results will be collected and evaluated.

   Results are requested by the 30th of November.

4. Summary of results and reporting
   Once all results have been received, reporting will take the form initially of an SP work report. This is an open access un peer- reviewed publication which is available on the SP website freely for download. Future presentation of the results at a suitable conference will

also be carried out. Participants will be allocated a number during the process which will remain known only to them and to the project team at SP. In all discussion of the results participants will remain anonymous.

Expected output

The test specimen that is proposed for the round robin is almost as simple a case of structural response to fire as could be envisioned. The unprotected steel beam will be simply supported and loaded in four point bending. No additional restraint or insulation will be provided. Web stiffeners will help to reduce the potential for lateral torsional buckling or other global stability problems during the test. Given the simplicity of this case it should be relatively straightforward to model the response of the element in fire, using either finite element analysis or simple calculation methods. The test therefore provides a good benchmark for both of these methods.

The analysis using the finite element method conducted by multiple research groups and potentially using different finite element codes will provide valuable information as to the variability in the results of such analyses and the 'user factor'; i.e. the variation in the results of the analyses which arises as a result of assumptions made by and approaches taken by different users.

The results of the project will give an indication as to the potential suitability in the future for replacing or supplementing test results with finite element analysis or the results of other calculation methods. If there is good agreement between the results from the different laboratories this has potential future impact for, e.g. extended application of test results if 'a priori' modelling is found to have a good agreement with the results of the individual fire tests.

Appendix B: information provided to the participants in the first stage

Contact person
David Lange
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Date
2014-09-07

Reference

Page
1 (3)

Round robin calculation of loaded steel beam exposed to fire: Stage 1

Dear participant,

Thank you for agreeing to participate in our round robin of the calculation of the response of a loaded steel beam exposed to fire. Enclosed with this letter, you will find details of the different stages of the round robin as well as a detailed schedule of the analyses and testing.

With the testing scheduled for the end of October, time is short for completing the first analyses. However we hope that the time available is enough, since the required time for calculation should be relatively short – of the order of only a few hours.

In addition to the first and final stages which we proposed in our letter of invitation, several of the invitees came back with proposals for additional intermediate stages. We have therefore included these as optional stages in the round robin. We can't expect anyone to carry out these stages, but if you do intend to please let us know and we will pass you the required information as an intermediary step.

If you have any questions regarding the problem stated or the information provided please do contact us.

Once again thank you, we are very grateful for your willingness to participate in this exercise!

Yours sincerely,

SP Technical Research Institute of Sweden
Fire Research - Fire Resistance

David Lange
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The test object

The test object is an HEB 300 steel beam, grade S355. In the test which we will be performing the beam has a total length of 5400 mm, and a span of 5200 mm between the supports. Loading is applied at two points, 1400 mm from either support. At both the supports and the points of loading application web stiffeners will be welded to the steel beam. The stiffeners will have a thickness of 15 mm.

The configuration of the beam is shown in Figure 1.

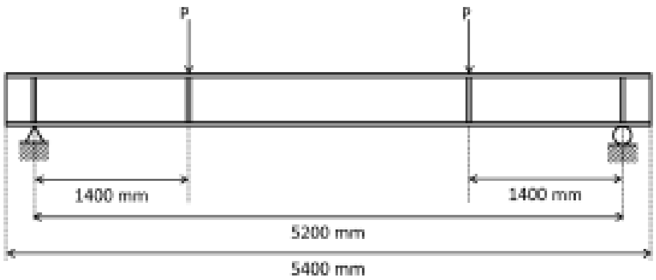

Figure 1 - geometry of the test specimen

The applied loads, P, are to create a bending moment of 140kNm which is uniform between the loading points.

During the testing we will measure deflection at mid span and the temperature of the beam at 5 locations: in the middle of each of the flanges and in the middle of the web. All temperature measurements will be made at mid-span.

Fire exposure

The beam will be unprotected and will be exposed to fire in a horizontal furnace on 3 sides (bottom and the two sides – the top will not be exposed to fire). The test will be carried out in accordance with EN 1363-1 and the fire exposure will be an ISO 834 standard fire.

First stage round robin

Prior to the fire test being carried out, we would ask all participants to carry out an a-priori prediction of the response of the steel beam. Please use any software tool or calculation technique which you deem to be applicable. Required output from the participants at this stage is the following:

1. A short description of the modelling approach taken, including the following:
    a. details of any assumptions which have been made in the preparation of the model
    b. details of the material model which you used in the calculation
    c. a short description of the approach which you took to modelling the thermal exposure from the furnace to the steel beam
2. A summary of the temperature in the steel beam (participants are free to choose how they conduct the heat transfer analysis)
3. The deflection history of the beam during the standard fire exposure
4. A declaration of the failure time of the beam during standard fire exposure

5. A description of the failure criteria which you have used in determining the failure time

Please provide all written results in a word file. Please provide the deflection history and the temperature history of the beam in tabular format in either an excel file or CSV format to aid in analysing the results of the round robin.

We hope to have completed this first stage in the round robin on or around the date of the test. Please therefore **return your responses before the end of October** (the test is scheduled for the 28th of October).

Second stage round robin

Following completion of the test, we will distribute information about ambient material testing which is to be carried out on the steel of the beams as well as the measured temperature field in the steel beam. We will ask project participants to repeat their analysis using this new information.

We will ask you to return the following results from this modelling stage:

1. A description of any other changes which you have made to the model between the initial modelling stage and this stage
2. A description of how you applied the measured temperatures to the model
3. The deflection history of the beam during the standard fire exposure
4. A declaration of the failure time of the beam during standard fire exposure

Once more, we request written results in a word file and the deflection history of the beam in tabular format in either an excel file or CSV format.

We would ask that this stage in the round robin is completed and results returned by the **end of November**.

Optional intermediate stage

For any interested parties, the following intermediate stage round robin has been proposed.

Once we have performed the test, we will distribute the plate thermometer measurements. Parties will be asked to use these measurements as input to the heat transfer analysis and to repeat the analysis in stage 1.

Appendix C: information provided to the participants in the second stage

Contact person
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Date
2014-11-20

Reference

Page
1 (5)

Round robin calculation of loaded steel beam exposed to fire: Stage 2

Dear participant,

Thank you for your contribution to the firsts stage of our round robin of the calculation of the response of a loaded steel beam exposed to fire. We've received quite a few submissions from the first stage, but not quite everything yet. Sadly, I can't share the results with you just yet but, in any case, I can say that they are not what we expected!

All testing is now completed, and enclosed with this letter you will find details required to undertake the second stage of the round robin. Hopefully it shouldn't take very long to make the changes!

If you have any questions regarding the problem stated or the information provided please do contact us.

Once again thank you, we are very grateful for your willingness to participate in this exercise!

Yours sincerely,

SP Technical Research Institute of Sweden
Fire Research - Fire Resistance

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The test object

The test object was an HEB 300 steel beam, with a stated grade of S355. In the test which we performed the beam had a total length of 5400 mm, and a span of 5200 mm between the supports. Loading was applied at two points, 1400 mm from either support. At both the supports and the points of loading application web stiffeners were welded to the steel beam. The stiffeners had a thickness of 15 mm.

The configuration of the beam is shown in Figure 1.

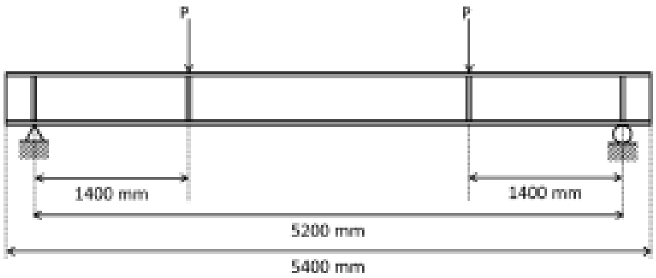


Figure 1 - geometry of the test specimen

The applied loads, P, created a bending moment of 140kNm uniform between the loading points.

During the testing we measured deflection at mid span and the temperature of the beam at 5 locations: in the middle of each of the flanges and in the middle of the web. All temperature measurements were made at mid-span (although some duplicates were made between the loading points and the supports).

Fire exposure

The beam was unprotected and exposed to fire in a horizontal furnace on 3 sides (bottom and the two sides – the top was not exposed to fire). The test was carried out in accordance with EN 1363-1 and the fire exposure was an ISO 834 standard fire. In table 1, below, we have included the plate thermometer measurements.

First stage round robin

The first stage round robin is complete. Results will be distributed to the partners once we have received submissions from the second stage.

Second stage round robin

Following completion of the tensile testing of the steel, we can advise that the elastic limit was 447.5 MPa. This is notably higher than the elastic limit implied by the steel grade.

Provided below, at the end of these instructions, are details of the temperature measurement from the steel section. Temperatures were measured on the upper and lower flanges on both sides, and in the middle of the web, as shown in Figure 2. The numbers correspond with the data provided in Table 2 at the end of these instructions.

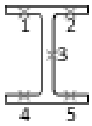


Figure 2 – temperature measurement positions on the steel section

> **Note:** *Table 2 has been extended with estimated temperature values since the test was terminated when the beam failed, and by only giving the measured temperatures the table would tell the actual failure time. Therefore the temperatures from the failure time to the end of the table are estimated values.*

We now would like to ask you to repeat your analysis using this new information and to return the following results from this modelling stage:

1. A description of any other changes which you have made to the model between the initial modelling stage and this stage
2. A description of if and how you accounted for the measured temperatures in your model
3. The revised deflection history of the beam during the standard fire exposure
4. A declaration of the revised failure time of the beam during standard fire exposure

Once more, we request written results in a word file and the deflection history of the beam in tabular format in either an excel file or CSV format.

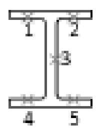
We would ask that this stage in the round robin is completed and results returned as soon as possible so that we can complete our report and distribute the results of the round robin to the participants.

Table 1 – average furnace plate thermometer measurements

Time (min)	ISO 834 Temperature time curve	Furnace plate thermometer measurements
0	20	22
1	349	252
2	444	511
3	502	516
4	544	544
5	576	575
6	603	595
7	625	613
8	645	629
9	662	644
10	678	671
11	692	702
12	705	720
13	717	718
14	728	717
15	738	721
16	748	741
17	757	753
18	765	771
19	773	782
20	781	788
21	788	794
22	795	803
23	802	810
24	808	817
25	814	825
26	820	830
27	826	833
28	831	838
29	836	844
30	841	848
31	846	853
32	851	860
33	856	867
34	860	871
35	864	874
36	869	878
37	873	882
38	877	885
39	881	888
40	884	893
41	888	897
42	892	899
43	895	900
44	899	902
45	902	903

Table 2 – measured and estimated steel temperatures

Time (min)	Station 1	Station 2	Station 3	Station 4	Station 5
0	19	19	19	19	19
1	38	34	37	30	32
2	63	56	95	86	75
3	71	69	141	125	111
4	85	83	177	149	141
5	104	99	215	181	173
6	123	115	254	216	206
7	141	132	289	251	239
8	160	148	324	286	273
9	179	166	357	322	306
10	201	189	395	359	343
11	226	212	434	399	381
12	251	237	473	438	421
13	274	260	505	473	457
14	297	283	531	503	487
15	320	307	554	529	515
16	344	333	578	554	542
17	368	357	599	578	567
18	391	383	622	601	592
19	415	407	642	624	615
20	440	429	659	645	636
21	462	451	674	662	653
22	485	475	689	679	671
23	506	495	701	693	686
24	526	517	714	706	700
25	548	536	725	720	712
26	565	554	734	729	724
27	585	572	742	738	733
28	601	590	752	746	742
29	619	606	764	758	751
30	634	622	775	769	763
31	650	637	787	778	774
32	664	652	798	774	786
33	677	670	808	798	795
34	689	683	814	805	803
35	701	695	819	811	809
36	711	705	825	817	816
37	721	717	828	822	820
38	730	727	831	826	825
39	738	736	835	830	829
40	745	744	838	833	833
41	751	751	839	835	835
42	756	757	840	837	838
43	761	763	841	839	839
44	766	767	842	840	841
45	770	771	842	841	841



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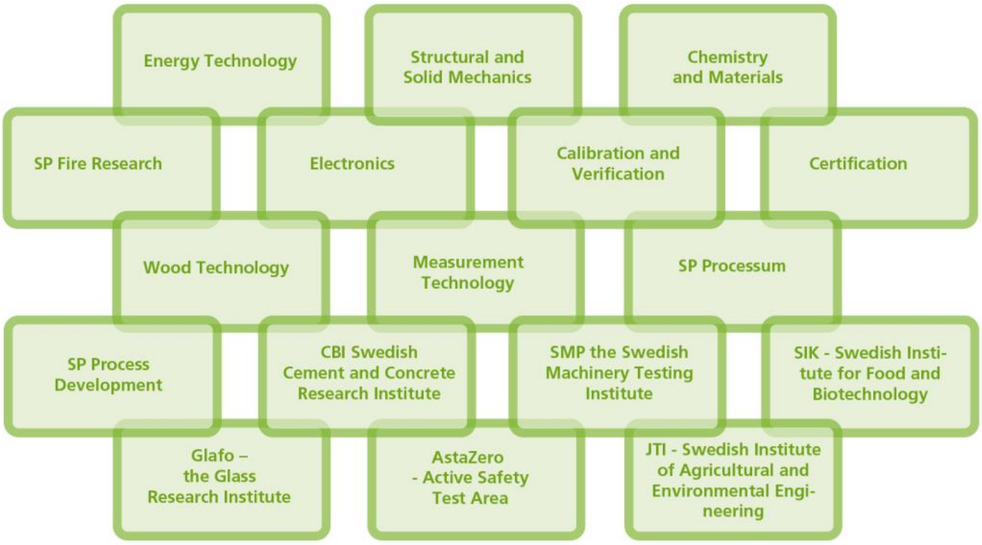

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