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Assessment of methods for calculating fire resistance of a steel beam

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Preliminary report

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Assessment of methods for calculating fire resistance of a steel beam

Experience shows that the assessment of fire resistance of steel elements based on European standards is conservative, while advanced methods are complex and time consuming. The analysis of existing methods for the tested steel beam exposed to bending and standard ISO fire was conducted in the scope of the international Round Robin study. The comparison of results shows that advanced methods provide non-uniform assessments. Nevertheless, advanced methods are necessary for improving standard methods that overestimate fire resistance of this "trivial" problem.

Key words:
fire resistance, steel beam, calculation methods, round robin study

Prethodno priopćenje

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Procjena metoda proračuna čeličnog nosača izloženog požaru

Prema iskustvu, procjena požarne otpornosti čeličnih elemenata prema europskim normama je konzervativna, a napredne metode proračuna su složene i dugotrajne. U sklopu međunarodne Round Robin studije, procjena postojećih metoda analizirana je za ispitani čelični nosač izložen savijanju i standardnom ISO požaru. Usporedba rezultata pokazuje da napredne metode daju neujednačene procjene. Svejedno, napredne su metode proračuna potrebne za poboljšanje normiranih metoda koje precjenjuju požarnu otpornost ovog "trivijalnog" problema.

Ključne riječi:
požarna otpornost, čelični nosač, metode proračuna, *Round Robin* istraživanje

Vorherige Mitteilung

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Einschätzung der Berechnungsmethoden für Stahlträger, die Feuer ausgesetzt sind

Erfahrungsgemäß ist die Einschätzung der Feuerbeständigkeit von Stahlelementen nach den europäischen Normen konservativ, und fortschrittliche Berechnungsmethoden sind komplex und zeitaufwendig. Im Rahmen der internationalen Round-Robin-Studie wurde die Einschätzung der bestehenden Methoden für den getesteten Stahlträger analysiert, der einer Biegebelastung und einem ISO-Standard-Feuer ausgesetzt wurde. Der Vergleich der Ergebnisse zeigt, dass die fortschrittlichen Methoden eine uneinheitliche Einschätzung ergeben. Jedoch sind die fortschrittlichen Berechnungsmethoden für die Verbesserung der normierten Methoden erforderlich, welche die Feuerbeständigkeit dieses "trivialen" Problems einschätzen.

Schlüsselwörter:
Feuerbeständigkeit, Stahlträger, Berechnungsmethode, *Round-Robin*-Untersuchung

1. Introduction

Fire is an extraordinary action whose destructive effect on structures should be prevented as much as possible, and its effects should be anticipated. For this purpose, fire resistance should be adequately modelled. Sufficient fire resistance of structures should be achieved so that the occurrence of fire does not cause disproportionate property damage or loss of life (Figure 1). The catastrophic World Trade Center collapse, for example, had the effect of increasing global awareness about the importance of structural fire resistance, making it a "hot" topic that has remained in the focus of attention to this day.

Previous experience shows that the analytic fire resistance calculation according to Eurocode, with all its advantages, is still rather inconsistent. Universal control system with standardized calculation has not yet been set up, and so the choice of calculation method is up to the engineer and the reviewer. That is why every effort should be made so that numerical methods and manual calculations can provide robust and reliable results.

Figure 1. Destructive effect of fire on steel structures

Civil engineers prefer reliable and simple fire resistance calculation methods that can readily be used in daily engineering work. To obtain these methods, it is necessary to calibrate standardized calculation rules according to test results that give insight into real structural behaviour. As fire resistance tests are expensive, the use is made of cheaper variants of real behaviour assessment, based on advanced computer simulations and the finite element method. However, the compatibility and reliability of these simulations has to be checked because advanced calculation methods, as well as settings of numerical simulations in different software packages, often give inconsistent results. Specific rules for numerical simulations can be developed by calibrating numerical models with experimental results. Calibrated models can then be reused for simulating the same or similar tests and, in this way, great savings in time and money could in principle be made.

The aim of this paper is to make a qualitative and quantitative assessment of scattered results obtained with various methods for calculating fire resistance of steel structural elements. Specifically, in this paper the comparison is given between experimental behaviour of a free supported element (beam) exposed to fire [1] the theoretical results according to Eurocode (manual calculation and calculation wih Elefir – EN software [2]) and the finite element method (FEM) results (ANSYS [3]). The experimental results obtained during testing conducted by RISE Research Institutes of Sweden (formerly SP Technical Research Institute of Sweden) in the late 2014, along with the results from other international *Round Robin* participants [1, 4], are used to illustrate the inconsistency of results obtained using various approaches for solving the same problem. The Faculty of Civil Engineering - University of Zagreb, one of twelve *Round Robin* participants, prepared the analysis presented in this paper. It should be noted that this *Round Robin* study on calculations was conducted at the same time as a wider *Round Robin* on fire resistance tests organized by EGOLF with 16 participating laboratories [5].

2. Fire calculation methods

The behaviour of structures exposed to fire is very complex even when just one structural element of a simple static system is analysed. The reasons for deviation of experimental resistance of structures to fire, compared to a theoretical model, are a great simplification of steel behaviour in fire as an ideal elastoplastic material, and deviation of material properties used for calculating temperature rise in the element and its fire resistance. In general, design calculations should demonstrate that the overall design effect of actions on a structure in case of fire should be lower than the resistance of the structure in critical cross-sections during a fire event, as shown by the following expression:

$$E_{fi,d} \leq R_{fi,d,t} \tag{1}$$

where:

$E_{fi,d}$ – design effect of actions for the fire design situation

$R_{fi,d,t}$ – corresponding design resistance in the fire situation, at time *t*.

When designing any structural element, the effect of the fire action can be simply obtained by the effect of the actions determined for the normal (room) temperature with the load reduction by reduction factor for the design load level for the fire situation [6]. Fire laboratory tests according to EN 1363-1 [7] are conducted using the standard nominal fire curve (ISO 834). The gas temperature in standard fire rises rapidly and increases infinitely, which is different from what actually happens during a real fire, Figure 2. In a standard fire test, a structural element is exposed to fire in a furnace for a specified period of time to obtain fire resistance, which is expressed as the time in minutes during which the element satisfies certain conditions.

Due to heating, the element loses its ability to transmit load and can fail if sufficiently high temperature is attained. The consequences of such failure depend on the importance of the element for the global behaviour of the structure, and can thus range from negligible to fatal. Failure of one element during fire might not affect the bearing capacity of the entire structure. Therefore, all main structural elements must keep the fire resistance proportional to the assumed risk.

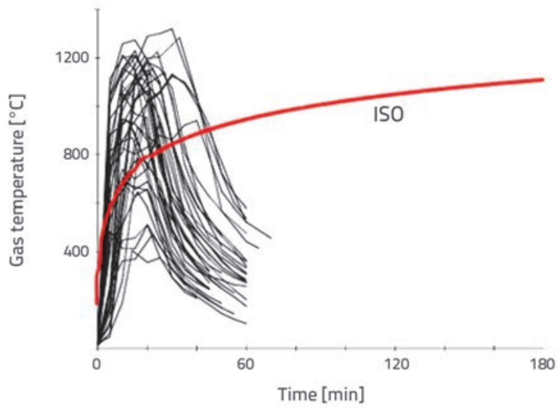

Figure 2. Standard ISO fire curve compared to 50 natural fire tests

EN 1993-1-2 [6] provides a simplified model that includes determination of material properties at elevated temperatures and calculation of elements depending on internal forces they are exposed to. The simplified calculation procedure consists of three steps. The critical steel temperature is determined in the first step, and the temperature development in the steel cross section is defined in the second step. The fire resistance of the steel element is determined in the third step.

Design values for mechanical properties of materials subjected to fire (strength and deformation) are reduced in EN 1993-1-2 [6], by means of a reduction factor dependent on material temperature. An increase in the carbon steel temperature causes degradation of mechanical properties of the material, which is reflected in stress-strain relationships. Therefore, the terms for determining temperature dependent stress-strain relationships are given in EN 1993-1-2 [6].

Calculation of fire resistance of a steel element can also be carried out in the temperature domain. This method for calculating fire resistance is carried out using the following steps:

- selection of appropriate adaptation factors values $\kappa = \kappa_1 \kappa_2$
- calculation of degree of utilization during fire μ_0 at time $t = 0$
- determination of critical temperature for steel member
- definition of cross section factor including shadow effect($A_m / V)_{sh}$ for unprotected steel elements, and A_p / V for protected steel elements, where A_m is the surface area of the member per unit length, V is the volume of a member per unit length, and A_p is the appropriate area of fire protection material per unit length of the member,
- nomogram application in obtaining time of fire resistance using critical temperature.

The Elefir-EN software [2], compliant with EN 1991-1-2 [8] and EN 1993-1-2 [6], can be used for easier calculation of the fire resistance of steel elements. This software automates much of the above process.

Simple thermal and mechanical models are based on some simplified assumptions and are therefore sometimes a limiting factor in structural calculations. For example, in a simple heating model, we assume an equal temperature distribution across the entire element, which is not necessarily the case in real-life situations. These limitations can be overcome by adopting advanced calculation methods, based on fundamental physical behaviour of elements in given conditions. They include separate calculation models for determining development and distribution of temperature in structural elements, and for assessing mechanical behaviour of the structure or any part thereof.

There are presently many software programs that can be used for advanced calculation of structural behaviour in fire. Some of the most known are Abaqus, Ansys, Sofistik, OpenSEES, SAFIR, Infograph and TASEF. The finite element method is presumably the most widely used method for advanced calculation of temperature distribution.

However, some simplifications have to be made even in advanced fire models. In the finite element method, for example, the geometry of the structure is approximated by a series of linear curves or second order curves. In addition, a temperature distribution is assumed in each finite element. The temperature is calculated only at some points of the element, most commonly in nodes, at the location of the element connection, and at certain time intervals. The contact between adjacent materials is considered ideal. A simple heat transfer by conducting is assumed in materials where heat transfer at the local level involves too many complex phenomena.

However, when used correctly, the finite element method provides a good indication of the temperature distribution measured in steel elements during fire tests.

3. International *Round Robin* study

3.1. Introduction

During a recent *Round Robin* study, RISE assembled 12 institutions that individually conducted calculation analysis of a simply supported beam exposed to fire. Participants in the study included universities, testing laboratories and consultancies, whose representatives may be considered experts in the field of fire engineering (section 2. in [1]). Differences in results obtained by advanced methods for calculating fire resistance of steel beams were analysed, and the results were compared with experimental results. The study comprised two stages. The first stage was a preliminary stage in which calculations were made using nominal properties of beam material and temperature exposure. In the second stage, the measured data on steel properties and measured temperatures obtained during furnace testing were made available to the participants. A similar *Round Robin* of laboratory fire tests, which allowed comparison with the *Round Robin* calculations, was conducted by the EGOLF, which is the European Group of Organisations for Fire Testing, Inspection and Certification [5].

The *Round Robin* study is summarised here to provide general guidance to the reader. Full details are provided in references [1, 4].

3.2. First stage

The fire test and calculation specimen was an HEB 300 steel beam made of steel grade S355. The total length of the simple supported beam was 5400 mm, and the span between the supports was 5200 mm, Figure 3. A load of 100 kN was applied at two points, 1400 mm from each support. The total applied load results in a constant 140 kNm moment between the points of load application. 15 mm thick stiffeners were welded to the steel beam over the supports and at the points where concentrated loads were applied. For the fire testing, two beams were tested in a single test, and two identical tests were conducted.

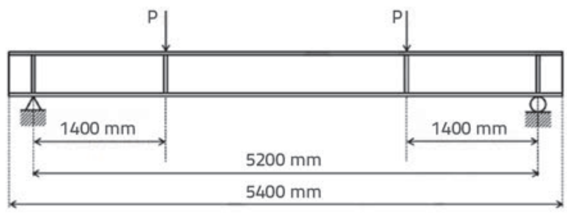

Figure 3. Static system of test specimen, reproduced from [1]

The following measurements were made during the tests:
- the deflection was measured in the middle of the span;
- the beam temperature was measured at eleven locations: in the middle of each of the flanges and in the middle of the web in the centre of the span (five points), and in the middle of the top and bottom flange and in the middle of the web at a distance of 1200 mm from the supports (three points on each side);
- furnace temperature was recorded using 20 plate thermometers.

The beam was unprotected and exposed to fire in the horizontal furnace from three sides - bottom and 2 sides, while the top side was covered with lightweight concrete blocks. The test was performed in accordance with EN 1365-3 [9], and the standard ISO 834 fire was applied to test specimens according to EN 1363-1 [7].

The *Round Robin* participants were asked to provide details about temperature history of the steel beam, deflection history of the steel beam, and a declaration of the steel-beam failure time as obtained in their calculations. When determining thermal exposure of the steel beam, all participants used material properties described in EN 1993-1-2 [6], and heat transfer coefficients and thermal boundaries described in EN 1991-1-2 [8]. All different submissions to the *Round Robin* calculation relied on an uncoupled temperature displacement analysis. The approach to the temperature calculation varied – some participants assumed lumped capacitance; some accounted for the shadow effect; and some accounted for the heat absorbed by lightweight concrete.

The participants reported the temperatures for a range of locations, some provided temperature information at locations which were not recorded in the test. The reported temperature results were grouped according to place where they were reported, and were numbered 1 to 5 according to their location, as shown in Figure 4.

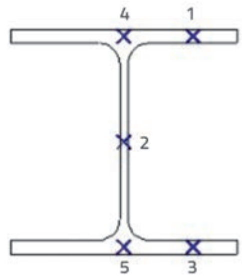

Figure 4. Points at which temperatures were reported, reproduced from [1]

Various assumptions and various approaches resulted in significant differences in calculated temperatures. For example, Figure 5 shows the temperatures reported for point 1, at the middle of the outer part of the beam top flange; and Figure 6 shows temperatures for point 2 in the middle of the web. Curves in Figures 5 and 6 are numbered according to the submission number and location in the section, which means that, for instance, data series 4,1 indicates the temperature submitted by participant number 4, at point 1.

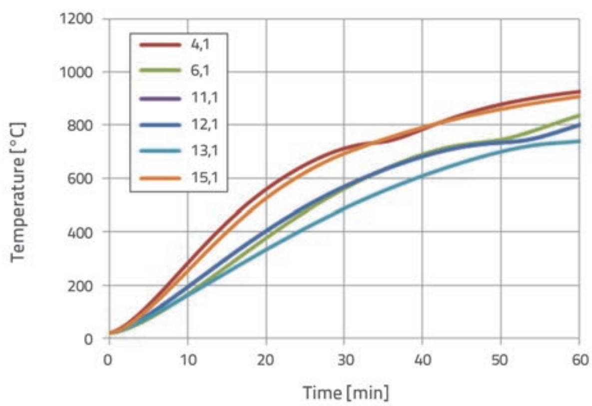

Figure 5. Reported temperatures at point 1, modified from [4]

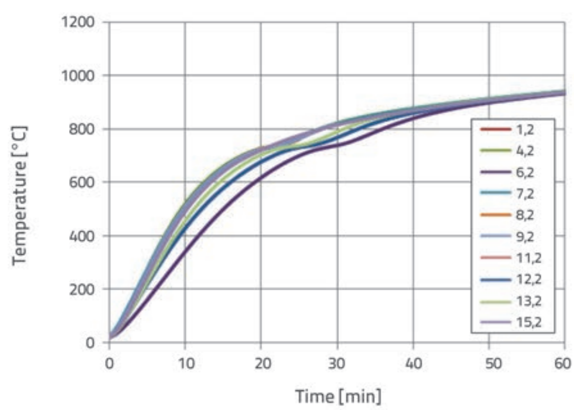

Figure 6. Reported temperatures at point 2, modified from [4]

The deflection histories reported by 16 out of 18 submissions are shown in Figure 7. As can be seen, there is a difference in the time-deflection responses reported. For example, a mid-span deflection of 100 mm ranged between 15 and 28 minutes, and 300 mm between 21 and 37 minutes. This difference is surprising, and could quite possibly be partially accounted for the inconsistency in calculated steel temperatures.

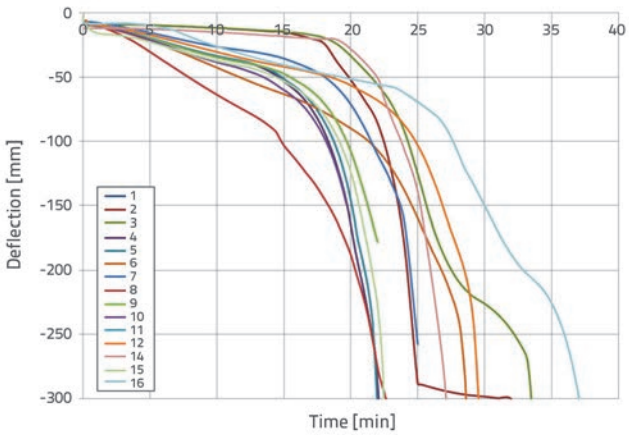

Figure 7. Calculated mid-span deflection histories (1st stage), modified from [4]

Table 1. Failure times in minutes, bold values indicate limiting criteria

Calculation	Time to failure [min]	
	Deflection [mm]	Rate of deflection [mm/min]
1	**21***	-
2	**24**	18
3	**31**	21
4	**21**	16
5	**21**	16
6	**27**	21
7	**24**	19
8	**21**	14
9	**22**	17
10	**20****	16
11	**28**	23
12	**28**	23
13	**28**	22
14	**26**	21
15	**22**	10
16	**34**	26
17	**38*****	-
18	**29*****	-

*Calculation made only to a total deflection of 170 mm, using L/20 as failure criterion,
**Calculation made only to a total deflection of 150 mm, which was used as failure,
***Simplified calculation methods in accordance with Eurocode

All participants used different failure criteria when reporting the time of failure. Therefore the failure times from all submissions, i.e. fire resistance values, are presented in Table 1 based on a reanalysis of deflection histories so as to ensure that all results reflect the same failure criteria. The criteria for failure are as described in EN 13501-2 [10], i.e. failure of loadbearing capacity occurs when both of the following criteria are exceeded:

- deflection $D = L^2 / 400\ d$ [mm],
- 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 fibre of the cold design compression zone to the extreme fibre of the cold design tension zone of the structural section, in mm.

It is clear from the table that there is a significant variation in failure times. In comparison with advanced calculation methods, the use of simplified calculation methods given in the Eurocode (submission 17 and 18) resulted in higher time to failure.

3.3. Second stage

Within the RR study, participants also conducted a second a priori analysis after they were given additional information determined by testing. This information included temperatures measured in furnace, steel temperatures measured at the different locations compared to the first stage, and measured yield strength of the material the beam was made of. The data was given so as to eliminate as many calculation uncertainties as possible, and to improve the correlation between result predictions and real test results.
The test was continued until specimen reached both failure criteria according to EN 13501-2 [10]: criteria for both deflection and rate of deflection. The rate of deflection criteria were exceeded after 26 min, and the deflection criterion was reached after 31 min. Immediately upon reaching both failure criteria, the test was stopped and the specimen was removed from the furnace. The final deflected shape of the specimen is shown in Figure 8.

Figure 8. Photo of specimen after testing, reproduced from [4]

The measured value of the yield strength of steel is 447.5 MPa, which is significantly higher than the nominal value of 355 MPa (S355). The data provided to the participants containing temperature values was extended with assumed values since the test was stopped when the beam failed. In that way, failure time from the test was not revealed to the participants in advance.

Not all participants that participated in the first stage contributed to the second stage. Participants used the provided data in various ways:

- some participants applied the measured temperatures to relevant parts of the beams, with no temperature smoothing at 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);
- one participant applied the measured temperatures across the entire length of the beam;
- another applied the measured temperatures at the midspan with the temperature decreasing linearly to 80% of the midspan temperature at the ends of the beam;
- some participants used the measured furnace temperatures (plate thermometer measurements) as the radiation temperature and gas temperature in the heat transfer calculation;
- some participants adjusted the convective heat transfer coefficient and emissivity to better match their calculated steel temperatures with the reported steel temperatures.

All but one of the participants adjusted the steel stress - strain curve to reflect the higher yield strength of the steel. The deflection histories reported in stage 2 are shown in Figure 9. Series 0 represents one of the test results from 4 beams tested.

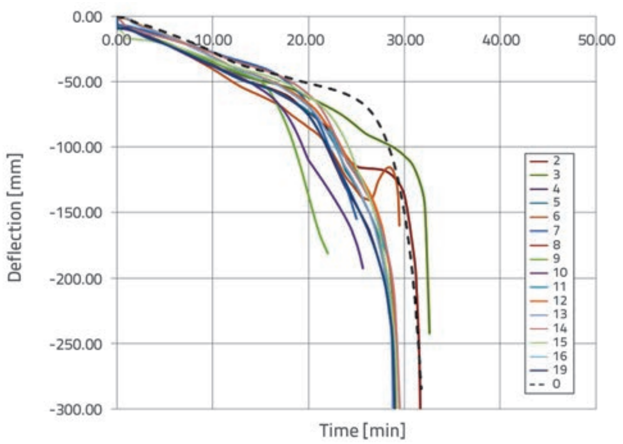

Figure 9. Deflection histories forsecond stage of *Round Robin* study, modified from [4]

The differences in deflection history seem lower for higher deflections for the second stage than in the first stage. There is certainly a cluster of calculations that follow a generally very similar deflection history. Fire resistance times crecalculated to fit failure criteria from EN 13501-2 [10] are given in Table 2.

Table 2. Failure time in minutes, numbers in bold indicate limiting criteria

Calculation	Deflection [mm]	Rate of deflection [mm/min]
1	-	-
2	**31**	29
3	**32**	31
4	**28**	23
5	**28**	21
6	**30**	20
7	**25**	20
8	**25**	23
9	**25**	17
10	**25**	17
11	-	-
12	-	-
13	-	-
14	**29**	21
15	**28**	22
16	**33**	28
17	-	-
18	-	-
19	**28**	21

4. Contribution to the international *Round Robin* study

4.1. General

Fire resistance calculations for a problem similar to the first stage and the second stage of the described beam, based on the simplified (Eurocode) and advanced (ANSYS) methods, are given below. The difference between the first stage *Round Robin* and the analysis presented here is the load applied, which is 150 kN in this case, as opposed to 100 kN. Calculations for the first stage are therefore illustrative of the approach, and allow comparison between the responses of beams exposed to different loads.

4.2. Calculation according to European codes

The fire resistance calculation is conducted by following the steps given in EN 1993-1-2 [6]. The first step involves selection of the adaptation factor $\kappa = \kappa_1 \cdot \kappa_2$. The adaptation factor κ_1 amounts to $\kappa_1 = 0.70$ for the non-uniform temperature in a cross section of an unprotected beam exposed to fire on three sides. For the non-uniform temperature along the beam, the adaptation factor equals to $\kappa_2 = 1.00$ for all cases, except at the supports of the statically indeterminate beam. Thus, $\kappa = \kappa_1 \cdot \kappa_2 = 0.70 \cdot 1.00 = 0.70$.

For the HEB 300 beam made of S355 steel grade (class 1 cross-section), the degree of utilization μ_0 at time $t = 0$ can be obtained as follows:

$$\mu_0 = \frac{E_{fi,d}}{R_{fi,d,0}} = \frac{M_{fi,Ed}}{M_{fi,0,Rd}} = \frac{M_{fi,Ed}}{W_{pl,y} \cdot f_y / (\kappa_1 \cdot \kappa_2 \cdot \gamma_{M,fi})} =$$

$$\frac{21000}{1869 \cdot 35,5/(0,70 \cdot 1,00 \cdot 1,0)} = 0,22$$

where:

E_{fid} - design effect of actions for the fire situation
$R_{fi,0,Rd}$ - corresponding design fire resistance at time $t = 0$
$M_{fi,Ed}$ - design bending moment for the fire situation
$M_{fi,0,Rd}$ - design moment resistance of the beam at time $t = 0$
$W_{pl,y}$ - plastic section modulus about y-y axis
f_y - yield strength at 20 °C
κ_1 - adaption factor for non-uniform temperature across the cross-section
κ_2 - adaption factor for non-uniform temperature along the beam
$\gamma_{M,fi}$ - partial factor for relevant material property, for fire situation.

Except when considering deformation criteria, or when instability phenomena have to be taken into account, the critical temperature of carbon steel $\theta_{a,cr}$ at time t for the uniform temperature distribution in a member may be determined for any degree of utilization μ_0 at time $t = 0$. According to EN 1993-1-2 [6] critical temperature in the beam HEB 300 for the first stage is:

$$\theta_{a,cr} = 39,19 \cdot \ln\left(\frac{1}{0,9674 \cdot \mu_0^{3,833}} - 1\right) + 482 =$$

$$39,19 \cdot \ln\left(\frac{1}{0,9674 \cdot 0,22^{3,833}} - 1\right) + 482 = 711\ °C$$

Temperature development in a steel cross-section depends on the ratio of the exposed surface area A to the volume of steel V. Heat transfer value differs for the unprotected cross-section (A_m) compared to the protected (A_p) cross-section. This ratio is called the section factor (A/V) and it is defined, depending on whether the cross-section is protected or not, for different shapes, radiation exposures, and heat transfer values, as shown in tables 4.2 and 4.3 of the EN 1993-1-2 [6]. For the unprotected steel element with the HEB 300 profile cross-section, the section factor with the shadow effect equals to $(A_m/V)_{sh} = 54\ m^{-1}$.

The last step of fire resistance verification in temperature domain involves determining fire resistance from the nomogram depending on the section factor and the critical temperature of steel.

Given the calculated critical temperature of steel $\theta_{a,cr} = 711\ °C$ and the section factor $(A_m/V)_{sh} = 54\ m^{-1}$, the value of fire resistance time $t_{fi,d}$, determined using the nomogram for the unprotected steel member, amounts to $t_{fi,d} = 30$ min, cf. Figure 10.

$$\mu_0 = \frac{M_{fi,Ed}}{W_{pl,y} \cdot f_y / (\kappa_1 \cdot \kappa_2 \cdot \gamma_{M,fi})} = \frac{14000}{1869 \cdot 44,8/(0,70 \cdot 1,00 \cdot 1,0)} = 0,12$$

$$\theta_{a,cr} = 39,19 \cdot \ln\left(\frac{1}{0,9674 \cdot 0,12^{3,833}} - 1\right) + 482 = 802\ °C$$

$(A_m/V)_{sh} = 54\ m^{-1}$.

Given the calculated critical temperature of steel $\theta_{a,cr} = 802\ °C$ and the section factor $(A_m/V)_{sh} = 54\ m^{-1}$, the fire resistance time $t_{fi,d}$, determined using the nomogram for the unprotected steel member, amounts to $t_{fi,d} = 41$ mm (Figure 10).

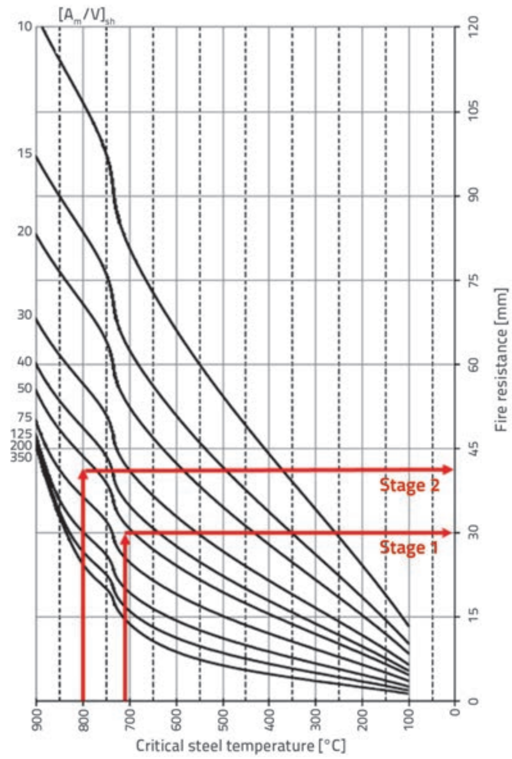

Figure 10. Nomogram for unprotected steel members - first and second stage

4.3. Calculation according to advanced methods (ANSYS)

4.3.1. Stage 1

A steel beam exposed to standard ISO fire is modelled using the ANSYS software [3]. Properties of the cross-section and static system are taken into account with their nominal values. Web stiffeners are included in the model. Changing material properties under high temperatures, reduction factors for stress-strain ratio, specific heat and thermal conductivity, are taken into account according to EN 1993-1-2 [6].

Exposure of steel beam to fire in furnace is modelled according to the approach given in European codes EN 1991-1-2 [8] and EN 1993-1-2 [6]. Temperature distribution in the beam is calculated using the *Steady-State Thermal* modulus in ANSYS. The fact that the upper flange is not exposed to fire is taken into consideration in the analysis. It is therefore assumed that the upper flange temperature is 20 °C and that convection coefficient equals 25 W/m^{2}C. All other sides of the cross section have temperature $Q_{a,t}$ shown in Figure11. Curve Q_{gt} is the gas temperature - ISO curve.

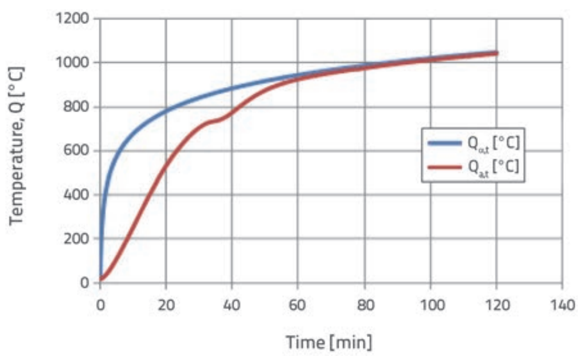

Figure 11. ISO fire gas curve and maximum temperature in steel beam, stage 1

Beam failure during testing is evaluated through bearing criteria – exceeding the limiting values of deflection (D [mm]) and the limiting rate of deflection (dD/dt [mm/min]). Other than criteria given in the code EN 1363-1 [7], it is interesting to use criteria given in British code BS 476-20 [11]. In the following equations, *L* is beam span in millimetres, and *d* is profile height in millimetres.

a) EN 1363-1 [7]:

$$D = \frac{L^2}{400 \cdot d} = \frac{5200^2}{400 \cdot 300} = 225 \text{ mm}$$

$$\frac{dD}{dt} = \frac{L^2}{9000 \cdot d} = \frac{5200^2}{9000 \cdot 300} = 10 \text{ mm/min}$$

b) BS 476, dio 20 [11]:

$$D = \frac{L}{20} = \frac{5200}{20} = 260 \text{ mm}$$

$$\frac{dD}{dt} = \frac{L^2}{9000 \cdot d} = \frac{5200^2}{9000 \cdot 300} = 10 \text{ mm/min, if the limiting}$$

value of deflection L / 30 = 5200/30 = 173 mm is exceeded.

According to EN 1363-1 [7], failure time is 21,7 min, because the limiting value of deflection is reached at that time. At the failure time, the rate of deflection was 10,1 mm/min, central beam deflection was 48 mm (~*L*/110), and maximum temperature of the beam was 571 °C.

According to BS 476-20 [11], failure time is 25,5 min because the limiting value of deflection (*L*/30 = 5200/30 = 173 mm) is reached at that time, and the limiting rate of deflection is exceeded. At that moment, the rate of deflection was 43,1 mm/min, central beam deflection was 173 mm, and maximum temperature of the beam was 636 °C.

4.3.2. Stage 2

In the second stage, the measured average value of yield strength (447,5 MPa) is used instead of the nominal value (355 MPa). Modelling thermal exposure (in furnace) of the steel beam is approximated directly by applying measured temperatures onto the steel profile (top flange, web, and lower flange) (Figure12). The measured furnace temperature is also used.

In this stage, the *Steady-State Thermal* modulus of ANSYS was used once again. It is assumed that the upper flange temperature is 19 °C and that the coefficient of convection equals to 25 W/m^{2}C.

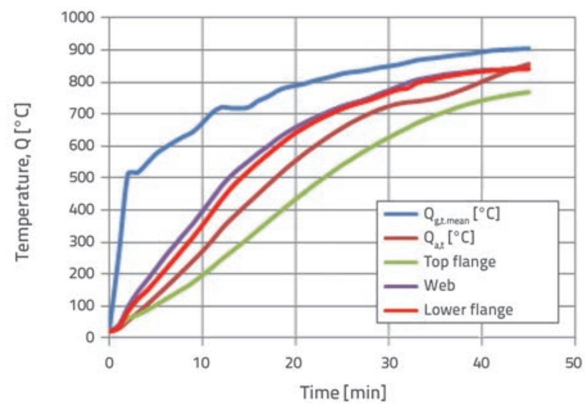

Figure 12. Gas temperature in fire compartment and temperature of steel beam (calculated and measured values)

Figure 13 shows maximum and minimum temperatures developed in steel beam during the fire simulation. Maximum temperature is developed in the web, and minimum in the upper flange.

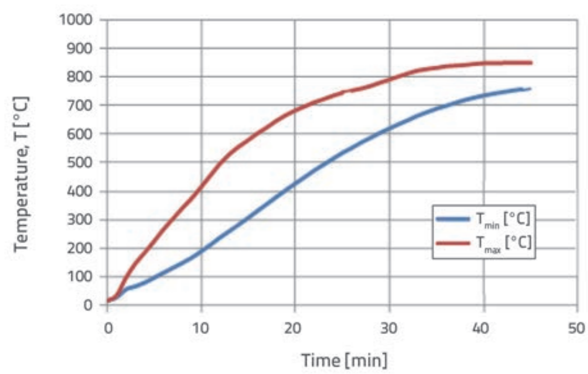

Figure 13. Minimum and maximum temperature of steel beam, stage 2

As already stated, stress-strain curves with 0.2 % yield strain at elevated temperatures, and elastic modulus reduction factors from EN 1993-1-2 [6], were used in numerical simulation. With input from the second stage, a relatively good accordance with experimental behaviour is obtained (see Figure 9, participant 14).

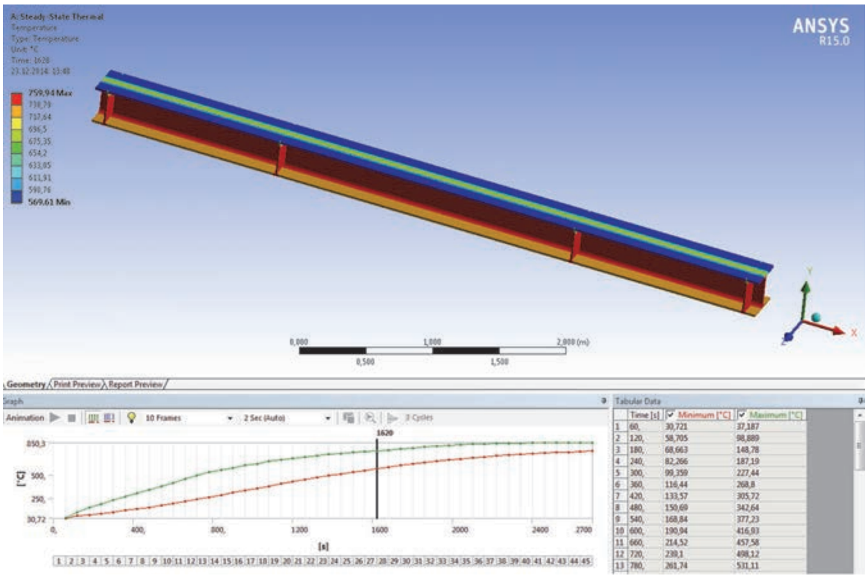

Figure 14. Time distribution of temperature in steel beam at moment just prior to declared failure

Considering all first-stage results, with the exception of the simplified methods, the mean value is 24.9 min, the standard deviation is 4.1 min, and the variation coefficient is 17 %.

The mean value of fire resistance for the second stage (Table 2.) is 28.2 min, the standard deviation is 2.7 min, and the variation coefficient is 9.7 %. For comparison, the frequency of the fire resistance results is shown for both stages in Figure 15. It is visible that dissipation of results for the second stage is narrower than for the first stage. A simple z-score comparison was made of all *Round Robin* results, and the trueness of all analyses, with the exception of the simplified calculation results, was shown to be statistically adequate.

According to EN 1363-1 [7], the failure time is 27 min, because at that moment the limiting value of deflection is reached. That is when the rate of deflection was 10.46 mm/min, central beam deflection was 150 mm, and maximum temperature of the beam was 760 °C. Temperature time distribution in the steel beam at the moment just before the declared failure is obtained in ANSYS, as shown in Figure 14.

According to BS 476-20 [11], the failure time is 28 min because that is when the limiting value of deflection (173 mm) is reached, and when the limiting rate of deflection is exceeded. At that moment, the rate of deflection was 23 mm/min, the central beam deflection was 173 mm, and the maximum temperature of the beam was 769 °C.

5.Comparison of results and discussion

5.1. Discussion of *Round Robin* study results

Fire resistance values sent by participants in the first stage of the *Round Robin* study (Table 1.) differ significantly [1]. It is clear that results obtained by simplified methods from the Eurocode (calculations 17 and 18) give higher fire resistance, as related to the results obtained by advanced methods.

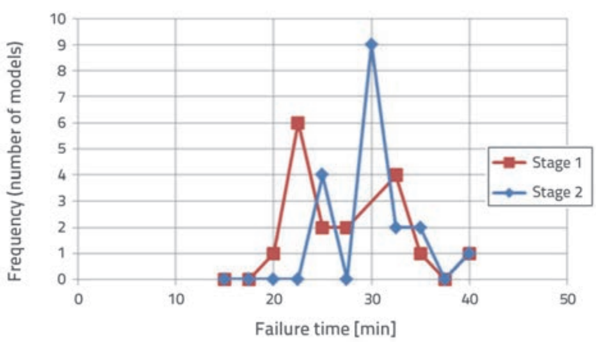

Figure 15. Frequency of corrected results, modified from [4]

5.2. Comparison of results according to different calculation methods

The following is a comparison of the fire resistance values calculated by simplified methods according to European codes in section 4.1, and values calculated by an advanced method using software ANSYS [3], in section 4.2. Results of simple calculation and results obtained by software Elefir-EN [2] are given within the simplified methods. Table 3 contains results of the first stage, and Table 4 results of the second stage.

Table 3. Fire resistance values calculated by Faculty of Civil Engineering, University of Zagreb for the first stage [12]

Method / Criterion		Fire resistance $t_{fi,d}$ [min]
Manual calculation according to EN		30.0
Calculation in software Elefir-EN	f_y = 355 N/mm^2	30.0
	f_y = 345 N/mm^2	29.6
Calculation using advanced method (ANSYS)	EN 1363-1 [7]	21.7
	BS 476-20 [11]	25.5

The mean value of fire resistance calculated for the first stage by different methods is $\overline{t_{fi,d}}$ = 27.4, the standard deviation is σ = 3.69 min, and the coefficient of variation is V = 13.5 %. Comparison of experimental resistance (26 min) and the first stage results (Table 3) shows that member resistance is considerably overestimated by calculation according to the Eurocode [6, 8], by manual calculation, and by calculation using Elefir-EN [2]. By using steel with lower yield strength f_y = 345 N/

mm², for sections thicker than 16 mm, the fire resistance values become slightly more compliant with the experimental value.
On the other side, advanced methods give a bit more conservative results with a higher reliability reserve. The use of failure criteria according to the European code [7] results in more conservative solutions compared to the results based on the British code [11]. The ratios between experimental (test) results and results obtained with different methods are given in Figure 16 for the first stage.

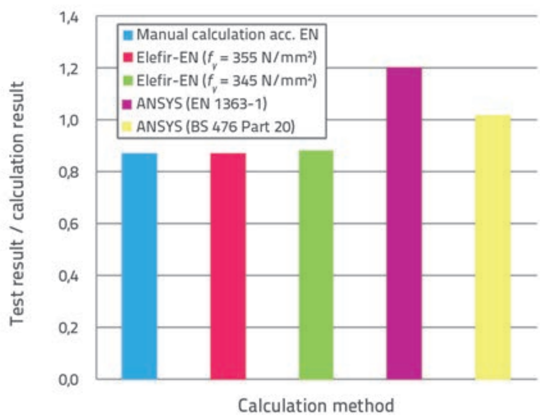

Figure 16. Ratio between the experimental fire resistance result (26 min) and results obtained with different methods for the first stage (from Table 3)

However, any conclusions obtained by comparing laboratory testing and the first stage can not be considered relevant because the input data are not compatible. That is why the second-stage results should be considered relevant.
The mean value of fire resistance calculated for the second stage with different methods is $\overline{t_{fi,d}}$ = 34.1 min, standard deviation is σ = 7.66 min and the variation coefficient amounts to V = 22,5 %.

Table 4. Fire resistance values calculated by Faculty of Civil Engineering, University of Zagreb for the second stage [12]

Method / Criterion		Fire resistance $t_{fi,d}$ [min]
Manual calculation according to EN		41.
Calculation in software Elefir-EN f_y = 447,5 N/mm²		40.5
Calculation using advanced method (ANSYS)	EN 1363-1 [7]	27.0
	BS 476- 20 [11]	28.0

The second stage shows deviations in both simplified and advanced calculation methods. In the second stage, results of the standardized code calculation, for the sake of higher yield strength, give even higher resistance and differ more from the experimental result (26 min). Compared to simplified methods, calculation in ANSYS [3] gives fire resistance that is more similar to the experimental result. However, it is a bit higher than the experimental one. At this stage, failure criteria according to the European code [7] also provide slightly more conservative results when compared to the British code [11]. Even though no calculation method is satisfactory when compared to the experimental result, the solution provided by ANSYS [3], along with the failure criteria from EN 1363-1 [7], provides the best estimate of real behaviour. The ratio between the experimental (test) result (26 min) and the calculation results obtained with various methods is shown in Figure 17.

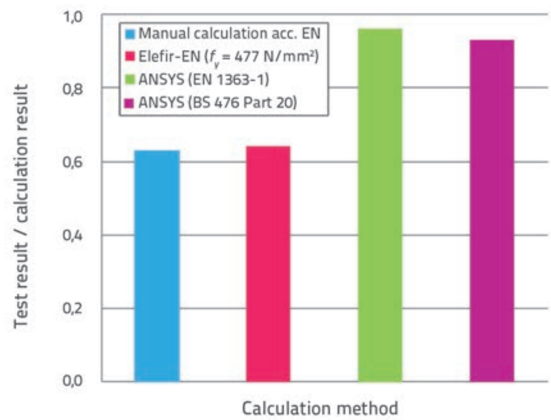

Figure 17. Ratio of the laboratory test result of fire resistance (26 min) to calculation results according to various methods for the second stage (from Table 4)

6. Conclusion

A wide spreading of the *Round Robin* study results is caused by two factors - assumptions made by as well as the general craft of the participant and how the chosen methods are used, and inconsistent failure criteria used by the participants. Some of them used criteria according to European codes, whereas others chose ad-hoc failure criteria. A wide selection of methods, and different failure criteria led to significant spread in the results of the simulation of this seemingly "trivial" problem.
Contrary to expectations, it is shown that the fire resistance calculation of an "ordinary" structural steel element according to simple methods given in the Eurocode does not provide safe results, i.e. the Eurocode overestimates its fire resistance. Deviation between results obtained by the Eurocode and the experimental result is even higher in the second stage of the *Round Robin* study, due to the use of the measured input data. These results clearly point to the fact that fire resistance calculation methods given in the Eurocode should be reviewed.
As expected, advanced methods based on the finite element method are more compliant with experimental results. However, the problem with fire resistance calculation using advanced methods lies in big differences resulting from individual modelling methods, as well as in differences in the failure criteria selection. The problem is also a significant susceptibility

of these methods to the engineer's subjective judgement. A significant first step for reducing variability of results calculated using advanced methods, and for allowing comparison between other effects, is to define and agree on common and consistent failure criteria for calculation that will be reliable and easy to use by the profession.

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