Calculation method for structural fire resistance. Calculation method validation

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Abstract—The paper concisely presents the calculation methods of structural fire resistance for buildings, the conditions that an advanced calculation method should accomplish in order to be used for calculation, and also the additional validation of numeric analysis programme SAFIR for fire stressed structures. The validation is achieved using the results of a fire test relevant for numeric calculation validation of fire resistance for structural pillars of Bucharest Tower Center, and that is the fire test of the octagonal pillar with cross steel profiles, with concrete between the visible blooms of steel profiles, tested by ARBED – RECHERCHES Luxembourg.

Keywords—fire resistance, temperature, thermal response, structural element.

1. Introduction

The principle that generates the resistance definition of a structural element made of steel, concrete or concrete-steel mixture to fire is that the high temperatures produced during a fire reduce the resistance and rigidity of those materials. When the temperatures on the cross section of a structural element have led to the element resistance decrease under the level of calculation effort established by loadings in fire situations, it is considered that the element has depleted its carrying capacity under fire action.

SR EN1991-1-2 describes the thermal and mechanic actions that must be taken into consideration for a structure under fire action, offering normalized fire models, parametrical fire model, and natural fire model respectively. The standard normalized fire curb ISO, although it is internationally acknowledged and very useful for experiments, represents a poor model for reality, because it does not respect any physical parameter, considering the same temperature evolution for any building and more, the temperature rises continuously in time. In reality, the temperature evolution within a compartment is directly bound to a series of parameters as openings, thermal loading and fire conduction speed. However, standards curb ISO is very frequently used in calculations.

The standard curb temperature – time is determined by (1):

$$\theta_{g,t} = 20 + 345\log_{10}(8t+1) \qquad [^{o}C] \qquad (1)$$

where: $\theta_{g,t}$ is the temperature of hot gases within the fire test oven, near the fire exposed element, at time t, in $[^{o}C]$; t – the fire exposure time, in minutes.

The fire is considered an exceptional action, and as the seismic test situation, there are considered reduced calculation coefficients of actions, in comparison with calculation at limited state in fundamental combination. In order to achieve a calculation test, relevant for fire action, with its help achieving the calculation effort in a limit fire state, the following accidental combination (2) is used:

$$\sum \gamma_{GA} G_k + \psi_{1,1} Q_{k,1} + \sum \psi_{2,i} + Q_{k,i} \qquad (2)$$

where: G_k is the characteristic values of permanent test; $Q_{k,1}$ - the characteristic value of the dominant variable test; $Q_{k,i}$ - the characteristic values of the others variable tests; γ_{GA} - the partial safe coefficient for permanent tests at limit fire state, ,

$\gamma_{GA} = 1{,}0$; $\psi_{1,1}$ - is the combination coefficient for the dominant variable loading; $\psi_{2,i}$ - combination coefficient for the other variable tests. Basically, there are three possibilities to verify the carrying capacity of a structural element under fire action:

Verification in time field: - it is verified that the time corresponding the element ruin t_f is superior to the time requested for fire resistance t_{req} (3):

$$t_f > t_{req}: \tag{3}$$

the time corresponding the element ruin is the time for which the element resistance under high temperature action reaches the appropriate calculation effort produced by loadings in fire situations.

Verification in loading field – it is verified that at the requested fire resistance time t_{req} the element resistance $R_{d,fi}$ is superior to the calculation effort produced by tests in fire situation (4):

$$R_{d,fi} > E_{d,fi} \quad \text{for } t = t_{req} \tag{4}$$

Verification in temperature field: - it is verified that at the requested fire resistance time t_{req} , the temperature on the elements section θ is less than the critical temperature (5):

$$\theta < \theta_{cr} \qquad \text{for } t = t_{req} \tag{5}$$

The last type of verification is designed exclusively for steel elements. The critical temperature for a structural steel element is the reached temperature in the cross section for which the diminished resistance appropriate for this temperature equalizes the uniform demand effort, resulted from the fire exceptional combination.

This verification is available for elements that do not need deformation criteria or stability loss phenomena. It is highlighted that the thermal protection of a structural steel element, that must be chosen so that on the period required by the fire resistance, the temperature within the section does not reach the temperature appropriate to the element subsidence, it is subsequently determined the massiveness function of the cross section, and the demand level of that element.

An alternative to the thermal protection use for metal elements is the use of constructive solutions with elements with steel – concrete mixture section. This solution has a double advantage because the steel - concrete increases the carrying capacity of the elements, not only to normal temperature but also during fire situations and due to the concrete the section heats slowly, with direct advantages in fire cases.

The European norms offer, generally, three calculation methods for fire resistance:

Tabular method - it has as a base the observations made during the experiments. It is very simple to use, but the applicability field is limited, due to a geometrical conditions assembly required to sections. This method is usually applied for concrete or steel- concrete mixed elements, but it is not present within the normative EN 1993 – 1-2- for steel elements under fire action.

Simplified calculation methods - allow the calculation of the last carrying capacity based on some formulas (mainly for steel elements) or calculation monograms (for concrete or steel-concrete mixture elements), calibrated based on numerous experimental tests.

The general calculation method - implies the numeric analysis with the help of some advanced calculation models – specialized calculation programs, designed for thermal and mechanical analysis of structures under high temperatures action. The advanced calculation methods are applicable for any type of temperature evolution curb within the fire compartment, inclusively for natural fire models and may be used for the analysis of the whole structure. The advanced calculation models must deliver an analysis closer as possible to the structure reality under fire. These must rely on the fundamental physical behavior so that they lead to a conclusive approximation of the due behavior of the relevant structural elements in fire conditions. In comparison with the table values or simple calculation models, the advanced calculation models deliver an improved approximation of the real structural behavior in fire conditions.

2. Model of calculs

Advanced models of calculus (calculus programs) must fulfil the following conditions:

1) To contain separate models of calculus to determine:

- the evolution and distribution of temperature in the structure’s elements (thermal response model);
- the mechanical behaviour of the structure or of a random part of the structure (mechanical response model);
- the ability to be utilised in association with any temperature-time evolution curve provided that the properties of the material are known to the targeted temperature domain;
- the reliability on the acknowledged principles and hypotheses of the thermal transfer theory.

2) The thermal response model must consider:

- the proper thermal actions specified in SR EN 1991-1-2;
- the variations of the material properties with temperature;
- to rely on the acknowledged principles and hypotheses of the structural mechanics theory considering the changing of the mechanical properties along with the evolution of the temperature.

3) The mechanical response model must consider:
- the combined effect of the mechanical actions, geometrical imperfections and thermal actions;
- the temperature dependent on mechanical properties;
- the geometric nonlinear effects and nonlinear effects of the materials' properties, including the effect of discharge upon the structural rigidness.

Models of advanced calculus can be utilised for any shape of transversal section. The SAFIR program used to verify by numeric calculus the pillars of Bucharest Tower Center structure fulfils all these conditions. The SAFIR program allows a nonlinear structural analysis in time phases corresponding to temperature increase in transversal section under the action of constant static loads or variables in time.

The calculus of resistance time of a structural element under the action of fire has two stages:
- at the first stage the evolution of temperature in transversal section of the elements is determined, thus considering the degradation of the mechanical characteristics of the materials that make the section;
- at the second stage the response of the structural element under the thermal loads and the highest static loads obtained from the combinations corresponding to special fire grouping is determined.

3. Relevant test to validate the model of calculus

The experimental test relevant for the validation of the advanced model of calculus SAFIR in case of testing the pillars of the structure of Bucharest Tower Cenetr by numeric calculus was taken from the experimental research report REFAO-EUR10828EN [1] of the European Commission from year 1987 where we can find the fire tests conducted by ARBED RECHERCHES on pillars and beams with composite section of steel-concrete, made of steel profiles with concrete between the visible soles.

The fire test for the octagonal pillar with steel profiles with cross disposition, with concrete between the visible soles of the steel profiles was conducted at the fire tests laboratory of the University of Gent, Belgium. The test was used in the current report to additionally validate the SAFIR advanced model of calculus. The transversal section of this pillar that has similar construction to those of the Bucharest Tower Center is shown in Fig. 1 together with the pillar disposition in the experimental setting. Fig. 1 also shows the disposition of the thermo-elements (termocuple) for experimental determining of the temperatures in transversal section.

The test was conducted under the action of the standardized temperature-time curve ISO-834 with a temperature evolution in accordance to article 3.2.1 (1) of SR EN1991-1-2 (also used for the verification by numeric calculus of the fire resistance of structural elements of Bucharest Tower Center).

The material characteristics for concrete were determined on cubes of 200 mm tested at dates close to the fire test date.

On the surfaces exposed to fire, the net heat flow is determined considering the heat transfer by convection and radiation in accordance to paragraph 3.1 of SR EN1991-1-2 "Eurocode 1: Actions upon structures. Part 1-2: General actions-Actions upon fire exposed structures" [2]. This depends on the resulting emittance as a product between the fire emittance and the surface of the element emittance.

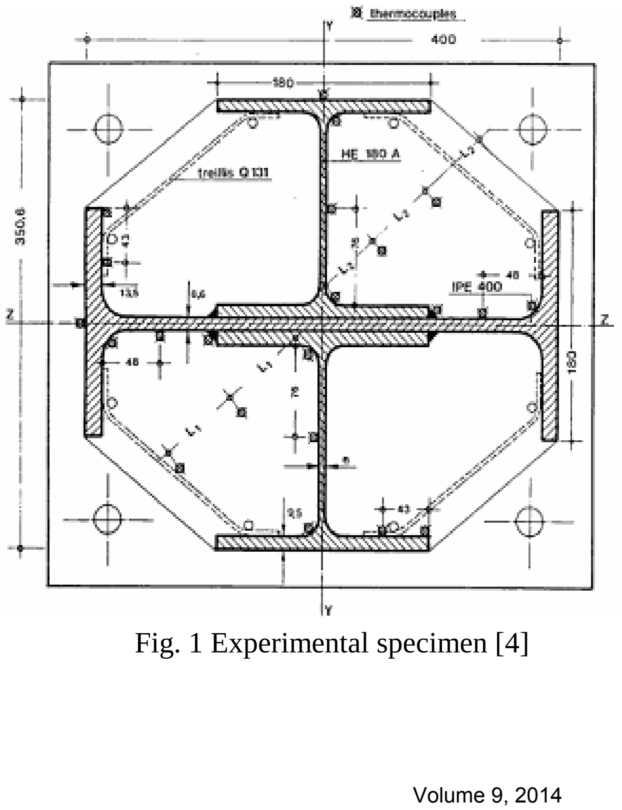


Fig. 1 Experimental specimen [4]

The resulting emittance in case of a fire test depends on the position of the burners in respect with the experimental specimen, furnace size, fuel used and characteristics of furnace walls. Fig. 2 shows the values of the resulting emittances considered for the visible steel surfaces (0.3 and 0.5) and concrete surfaces (0.45) for the octagonal pillar tested in specific conditions of the fire test furnace of the University of Gent as they were given in the ARBED report (fig. 32 of the report). These values were also considered in the SAFIR program numeric calculus.

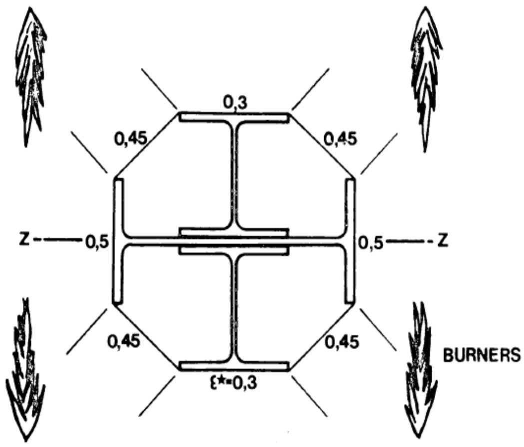


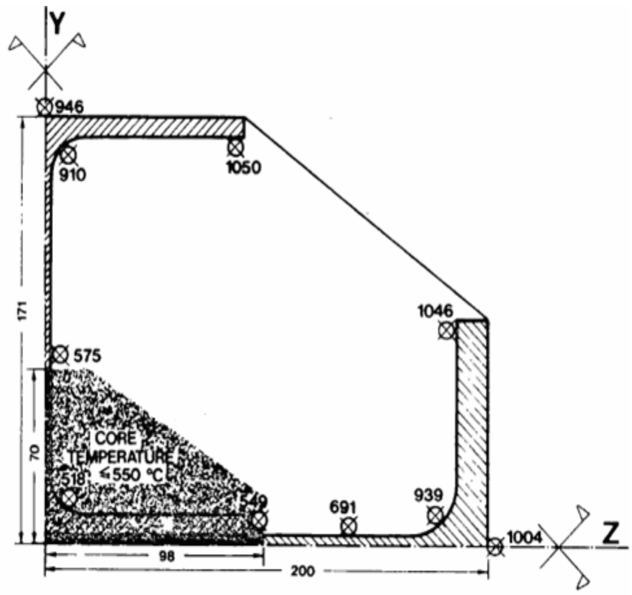
Fig. 2 Resulting emittances for the steel soles and concrete surfaces of the pillar tested in the furnace of the University of Gent [3]

EN 1991-1-2 states that for fire emittance, a value of 1.00 can generally be considered. The emittance of regular steel surface (thus being the case of the profiles used for the octagonal pillar tested for fire) and the emittance of the concrete surface have a value of 0.7. As a consequence, the resulting emittance for steel and concrete in accordance with SR EN1991-1-2 would have a value of 0.7 on the whole perimeter of the tested pillar, a superior value to those of the emittances calculated for the octagonal pillar tested in the furnace of the University of Gent laboratory.

The pillar with octagonal section considered to validate the SAFIR advanced calculus model behaved extremely well at fire test showing a fire resistance of 172 minutes in terms of unprotected exposure of the soles of the steel profiles. The conclusions of the report were that this type of pillar made of steel profiles with a cross disposition, with concrete between the visible soles of the profiles, unprotected, without additional reinforcements, represent an efficient structural solution from fire resistance point of view, capable of enduring the combined action of axis compression with bend along both main directions and attractive not only from architectural point of view. Moreover, the fact that the soles of steel profiles are visible on all four sides of the pillar allows uncomplicated realization of the joints usually used in steel structures. The pillar wasn't additionally reinforced with longitudinal resistance reinforcements as it was in the case of the Bucharest Tower Center structure pillars. Shackles, same as in the case of Bucharest Tower Center structure, were welded on the soles of the metallic profiles together with a constructive longitudinal reinforcement as shown in Fig. 1.

4. Validation of calculus model

Fig. 3 shows the comparison between experimentally measured temperatures at thermo-elements level [3] and the numeric calculated temperatures at yield time of the experimental specimen of 172 minutes (10,320 seconds) at the same thermo-element level. As one can observe, the SAFIR program gives good results, with close values, covering (higher temperatures), for temperatures calculated at the level of the thermo-element used in fire test. In the numeric calculus, were used for steel and concrete, the values of the emittances determined for the octagonal pillar placed in fire test furnace of the University of Gent, shown above.



Temperature field of column 1.4 measured just before buckling (172 minutes).

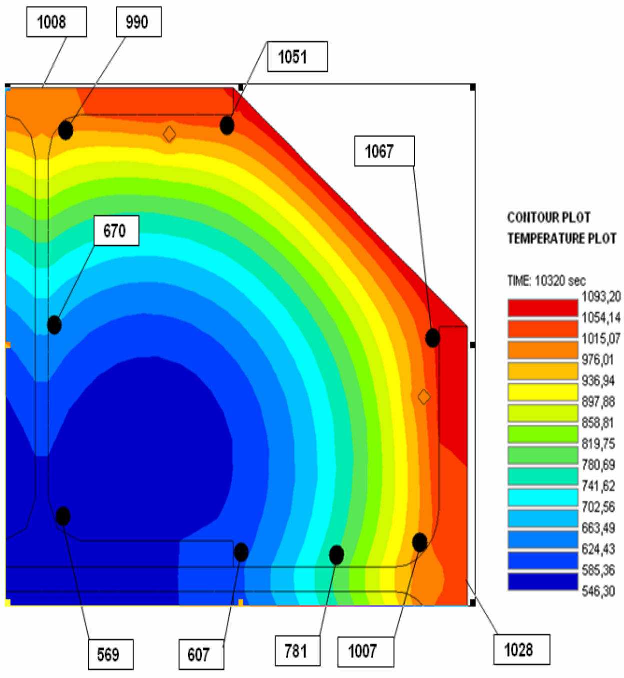


Fig. 3 Distribution of temperature in transversal section and at the thermo-elements level by numeric calculus with the SAFIR program for a period of 172 minutes (10,320 seconds) in comparison with the experimental results [3]

In case of considering a buckling length of 70% of the pillar's length (intermediate situation of articulate-embedded propping of the pillar, between the case of the pillar with perfect articulated propping, perfectly embedded at both ends) the yield time obtained by numeric calculus is of 164 minutes, conservative result but closer to the yield time experimentally determined. This might suggest that in reality, for the experimental specimen, perfect articulations for propping couldn't be realised and that there was a certain degree of embedding at the ends of the experimental specimen. It is worth mentioning the fact that the pillar is leaner (considering its length and characteristics of the transversal section) and thus its behaviour can be affected in cases where propping provides a certain degree of embedding at ends. It is obvious that it is impossible to know for certain the level of embedding at ends realised by the grips of the experimental specimen. Further on, in the sensibility analysis of the calculus model at other critical parameters' level, one would consider as reference the intermediate case of the articulate-embedded bar that is closer to the real situation of experimental trial.

In case of considering a buckling length corresponding to the double embedded bar situation (50% of the pillar's length) the yield time obtained by numeric calculus is 188 minutes. It is noticed that the yield time is superior to the time experimentally obtained, which is obvious because in the experimental sett-up a perfect embedding couldn't (and wouldn't) be obtained, no matter how large the real embedding degree at the ends of the specimen had been, considering the gripping details that were made (Fig. 1).

In conclusion, following the sensibility analysis carried out at the level of initial imperfections amplitude (critical parameter for the determination of fire resistance for a structural element) was demonstrated the fact that the SAFIR advanced calculus model gives results in accordance to the principles of engineering: yield time obtained as a result of numeric calculus decreases with the increase of initial imperfections amplitude of the pillar. The yield time decreases from 164 minutes for an imperfection with an amplitude of 1 mm (considering that the experimentally measured imperfections were 0), to 156 minutes for an imperfection with a higher amplitude, of 1/1000 of the pillar length and to 140 minutes for an imperfection with the highest considered amplitude of 1/200 of pillar lengths. It may be highlighted the fact that, as the sensibility analysis shows, the initial imperfections with the amplitude of 1/200 of the pillar length, considered in the fire resistance verification by numeric calculus of the Bucharest Tower Center structure pillars were covering for the results of the calculus.

As shown, the resulting emittances of steel and concrete, in accordance to SR EN1991-1-2 have the value of 0.7 (considering that for fire emittance one can generally consider the value 1.00), a superior (covering) value opposed to the emittances determined for the octagonal pillar tested in the furnace of the University of Gent laboratory. Fig. 4 shows the distribution of temperatures in transversal section for the yield time of the experimental specimen of 172 minutes (10,320 seconds) in case of considering a resulting emittance of value 0.7 for the whole pillar perimeter. It may be noticed that the temperature values are higher, so covering, compared to the temperatures resulted of numeric calculus for emittance values determined in the Gent laboratory, of 0.45 for the concrete surface, of 0.3 and 0.5 for the surfaces of the steel soles (Fig. 3).

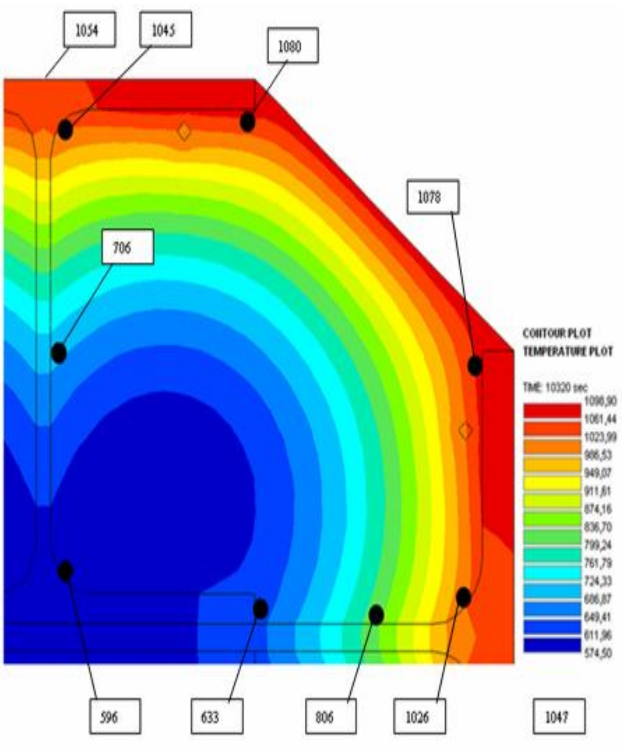


Fig. 4 Distribution of temperature in transversal section corresponding to the yield time of the experimental specimen of 172 minutes (10,320 seconds) considering resulting emittances of 0.70 for exposed surfaces of concrete and steel

The yield time resulted from numeric calculus (buckling length corresponding to the case of articulate-embedded bar, with an amplitude of global imperfection of 1 mm), considering for the resulting emittaces values of 0.70 for exposed surfaces of concrete and steel, is of 152 minutes.

In conclusion, following the sensibility analysis carried out at the level of resulting emittances for steel and concrete surfaces, was proved that the SAFIR advanced calculus model gives results in accordance to the principles of engineering: yield time resulted by numeric calculus decreases with the increase of the values of resulting emittances. The yield time decreases from 164 minutes for resulting emittances of 0.45 for concrete, 0.3 and 0.5 for steel (determined for the fire test furnace of the University of Gent), to 152 minutes for resulting emittances of 0.70 for steel and concrete as foreseen in SR EN 1991-1-2. Higher values for emittances imply a radiation increased component of the net thermal heat flow over unit of surface that, as demonstrated also by numeric calculus, leads to higher temperatures in transversal section and to a lower yield time of the element. It is highlighted the fact that, as the sensibility analysis also shows, the values of the resulting emittances considered in accordance to the SR EN 1991-1-2 for verification by numeric calculus of the fire resistance of Bucharest Tower Center structure pillars, were covering for the results of the calculus.

5. Conclusions

The program for numeric analysis of structures under the action of fire SAFIR is a program renowned and used at international level, follows the principles stated by the Eurocodes, in order to be considered a model of advanced calculus for this type of analysis. In accordance to the conditions stated by Eurocodes for validating models of advanced calculus, the SAFIR program was validated through numerous comparisons both to fire tests and other acknowledged programs.

For the case of verification by numeric calculus of the structure pillars of Bucharest Tower Center, an additional validation of the advanced calculus model was considered, by comparing the results offered by the SAFIR program to a relevant trial, for a pillar experimentally tested for fire at the University of Gent, Belgium, pillar of similar type to those of the Bucharest Tower Center structure (I profile with cross disposition, with concrete between the visible, unprotected soles of the steel profiles).

As expected, the SAFIR program offered, by comparison to the experimental trial, good results with covering values, for temperatures calculated at the level of the thermo-elements used for experimental determining of temperature in transversal section as well as for the fire resistance time. Following the sensibility analysis, necessary for validating a model of advanced calculus, but can also be done for a particular situation, was shown that the SAFIR program gives results in accordance to the principles of engineering. The sensibility analysis was carried out considering various critical parameters to determine the fire resistance of a structural element: buckling lengths, equivalent geometrical imperfections and resulting emittances.

In fire testing the pillars of the Bucharest Tower Center structure, all critical parameters previously enumerated were considered with values to lead to covering results in terms of fire resistance time. Thus, in numeric calculus, the buckling lengths of the pillars were considered equal to the lengths of the elements (the hypothesis of bi-articulate grip of the pillars), the amplitude of equivalent geometrical imperfections was considered of 1/200 of the elements' length and the values of the resulting emittances were considered those indicated by the Eurocodes. All these hypotheses were proved to be covering following the shown numeric calculus and also following the sensibility analysis as well as in comparison to the experimental trial.

In conclusion, the SAFIR advanced numeric calculus model can be considered validated also for the particular situation of the pillars of Bucharest Tower Center structure, where, for their verification, were chosen all the calculus hypotheses that lead to covering results from the fire resistance time point of view.

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