Endrit HOXHA[1]

INFLUENCE OF DESIGN PARAMETER IN FIRE SAFETY OF STRUCTURAL STEEL BEAMS

Abstract: This paper focuses on the identification of the main design parameters influencing fire safety of steel beams. In order to do so, a set of case studies was created, with design parameters for steel beams, that vary within an acceptable range. Load resistance, critical temperature and time resistance for 35 cases of simple supported simple beams were analyzed. Finally, the four design parameters of span, self-weight of slab, combination coefficient and section factor were ranked according to their influence on time resistance of steel beams. This paper's findings can be useful for architects and structural engineers during the early design phase of a building project.

Key words: Fire analysis, contribution analysis, steel beams.

[1] PhD, EPOKA University, Autostrada Tiranë-Rinas, km. 12, 1000 Tirana, Albania, ehoxha@epoka.edu.al

1. INTRODUCTION

A large number of dramatic fires have been the reason of the evolution of structural fire engineering within the construction industry. In 1967 around 300 people died as a result of a fire at the Innovation supermarket in Brussels. In Vienna, Austria in 1979, at the Augarten Hotel, 25 people were killed by the smoke of the fire. In 1980, at the psychiatric hospital in Górna, Poland 55 in-patients died, while one year later, 14 people died at the gastronomic complex in Szczecin. Another dramatic fire occurred in 1994, at the show hall in GdaMsk Shipyard, where seven people lost their lives [1]. In addition to the lives lost, there was also an estimated material damage counting up to millions of euros in losses. These consequences and the high risk of fire accruement have led to the development of regulations and codes.

Historically, the issues of fire have been within the remit of the architects, but nowadays with the development of codes and regulations, structural engineers are responsible for fire safety analysis [2]. In Europe, methods of evaluation of structures for fire are given in Eurocodes. Respectively, methods and rules for fire safety analysis for reinforced concrete structures, steel, composite, timber, masonry and aluminum structures are described in part 1.2 of Eurocode EC-2, EC-3, EC-3, EC-4, EC-5, EC-6 and EC-9 [3-8]. Within building structural typology, that of steel is the weakest to resist in case of fire. For this reason, several researches are published regarding the properties analysis of steel in high temperature [9-11] and proposed active and passive strategies for increasing fire resistance [12-13]. However, based on a literature review and current knowledge, none of the studies have tried to identify and then rank the design parameters influencing these structures' fire resistance. For this reason, the aim of this paper is to analyze the influence of design parameters in fire resistance of steel beams.

2. METHOD

Influences of design parameters in structural fire resistance of steel beams are evaluated with the help of the critical temperature approach [14] and sensitivity analysis [15]. Firstly, the fire resistance of a set of scenarios is evaluated, created by randomly changing the design parameters of the building, one at a time, while keeping all other parameters constant. Then, the relative influences of design parameters (span, combination coefficients, self weight and section factor) are repeatedly calculated until the steel beams' critical temperature is reached.

2.1. Fire resistance assessment of steel beam

Critical temperature methodology is used for the evaluation of the fire resistance of steel beams in terms of resistance capacity, critical temperature and time duration. Inspired mainly from [14, 16], the methodology includes seven steps and follows the equation recommended by Eurocodes [4].

Step 1: Initially, the permanent and imposed loads applied to the structural element of the building are evaluated. Imposed loads for different categories of use and permanent actions which are calculated by nominal values of materials' densities and their dimensions, are taken from EC-1-1-1.

Step 2:Since the loads do not act at the same time on the structural elements, their most probable combination for ultimate limit state and accidental design situations for the fire case are evaluated.

For the ultimate limit state, the combination of the action is calculated by the formula:

$$\sum_{j\geq 1}\gamma_{G,j}\cdot G_{k,j}+\gamma_P\cdot P+\gamma_{Q,1}\cdot Q_{k,1}+\sum_{i\geq 1}\gamma_{Q,i}\cdot\psi_{0,i}\cdot Q_{k,i} \tag{1}$$

And for the accidental design situation:

$$\sum_{j\geq 1}\gamma_{G,j}\cdot G_{k,j}+\gamma_P\cdot P+\gamma_{Q,1}\cdot Q_{k,1}+\sum_{i\geq 1}\gamma_{Q,i}\cdot\psi_{0,i}\cdot Q_{k,i} \tag{2}$$

Where:

$G_{k,j}$ - present characteristic permanent action,

$\gamma_{G,j}$ - partial factor for permanent action j,

P - relevant representative value of a prestressing action,

γ_P - partial factor for prestressing actions,

$Q_{k,1}$ - leading variable action,

$\gamma_{Q,1}$ - partial factor for leading variable action,

$Q_{k,i}$ - characteristic variable action,

$\gamma_{Q,i}$ - partial factor for variable action i,

$\psi_{0,i}$ - factor for combination values of a variable action,

$\psi_{1,1}$ or $\psi_{1,1}$ - combination values should be related to the relevant accidental design situation.

Step 3: A pre-dimensions of the thickness of the composite slab is evaluated based in the internal loads for ultimate limit state design combination. Approximately [17] is calculated with the help of the equation:

$$\mathrm{h}\geq\frac{\mathrm{M_{Rd}}}{\mathrm{A_{pl}}\cdot\mathrm{f_{yP,d}}}+\mathrm{e}+0.5\cdot\frac{\mathrm{A_{pl}}\cdot\mathrm{f_{yP,d}}}{0.85\cdot\mathrm{f_{cd}}\cdot\mathrm{b}} \tag{3}$$

Where:

A_{pl} - effective cross-sectional area of the profiled steel sheeting,

$f_{yP,d}$ - design value of the yield strength of the profiled steel sheeting,

f_{cd} - design value of the cylinder compressive strength of concrete,

b - width of the element,

e - distance of centroidal axis of the profiled steel sheeting from lower sheet,

M_{Rd} - design value of the resistance moment of a composite section or joint.

In additional, EC-4-1-1recommends that the minimal overall depth of the slab should not be lower than 90mm and the minimal thickness of the concrete 50mm.Thickness of the profiled steel sheeting must also admit fire resistance criterion. A simplified procedure for the evaluation of this thickness is described in [14].

While the dimensions of double-Tee steel beam are approximately evaluated with the following equation:

$$W_{pl} \geq \frac{M_{pl,Rd} \cdot \gamma_{M0}}{f_y} \tag{4}$$

Based in the moment of resistance calculated with equation (4) the properties of the most adequate cross section are found in tables given by ().

Step 4: Critical temperature that the steel beam can reach in order to respect also the resistance criteria is evaluated with the equation:

$$\theta_{cr} = 39.19 \ln\left(\frac{1}{0.9674 \cdot \mu_0^{3.833}} - 1\right) + 48 \tag{5}$$

Where:

$\mu_{0,M}$ - present the degree of utilization of steel beam and is evaluated:

$$\mu_{0,M} = \frac{M_{fi,d,t}}{M_{Rd}} \cdot \frac{\gamma_{M0}}{\gamma_{M,fi}} \tag{6}$$

Step 5: Finally the temperature-time curve for the steel beam is found from:

$$\Delta T_s = \frac{0.9 \cdot (F/V)_b}{\rho_s \cdot c_s}\left[h_c \cdot (T_g - T_s) + \sigma \cdot \varepsilon \cdot \left((T_g + 273)^4 - (T_s + 273)^4\right)\right] \tag{7}$$

Where:

T_s - temperature of the steel beam (at $t = 0s$ the value of $T_s = 20℃$),

ρ_s - density of the steel (7850 kg/m^3),

σ - Stefan-Boltzmann constant (56.7x10^{-12}kW/m^{2}K),

ε - emissivity (0.7 for the steel),

h_c - convective heat transfer coefficient (25W/m^{2}K of standard fire),

$(F/V)_b$ - box value of the section factor,

T_g - temperature of the fire.

According ISO-834 standard (4) the temperature-time fire curve is calculated:

$$T_g = 20 + 345 \cdot \log(8 \cdot t + 1) \tag{8}$$

Where:

c_s - specific of the steel calculated by the following equation:

$$\begin{aligned} c_s &= 425 + 0.773T - 1.69x10^{-3}T^2 + 2.22x10^{-6}T^3 20℃ \le T < 600℃ \\ &= 666 + 13002/(738 - T) 600℃ \le T < 735℃ \\ &= 545 + 17820/(T - 731) 735℃ \le T < 900℃ \\ &= 650 900℃ \le T \le 1200℃ \end{aligned} \tag{9}$$

At the end, based in temperature-time curve is found the time that the steel beam can last in order to not pass the critical temperature and consequently to respect the resistance capacity.

2.2. Fire resistance assessment of steel beam

Equation used for the assessment of the contribution of design parameters to the fire safety resistance has the form:

$$R_C = \frac{R_{time\ resistance}}{R_{design\ parameter}} = \frac{\dfrac{T_{\max} - T_{\min}}{T_{\max}}}{\dfrac{D_{\max} - D_{\min}}{D_{\max}}} \tag{10}$$

where:

$D_{\max}$ - maximal value of design parameter,

D_{min} - minimal value of design parameter,

T_{max} - maximal time resistance corresponding to the maximal value of design parameter

T_{min} - minimal time resistance corresponding to minimal value of design parameter.

3. CASE STUDY

The methodology described in the previous section is applied to a simple support beam of the compartment presented in Figure 1. For this study a double-T cross section with yield strength of 275N/mm^2 is considered. The floor is designed as composite slab of type Cofrastra-70 from Arcelor Mittal producer [19]. Steel sheeting has a height of 7.3mm and yield strength of 350 N/mm², while the concrete poured above the sheet is of the type C25/30. The overall height of the slab and the dimensions of the steel beam are calculated based on the ultimate limit state and accidental load combination (fire safety resistance).

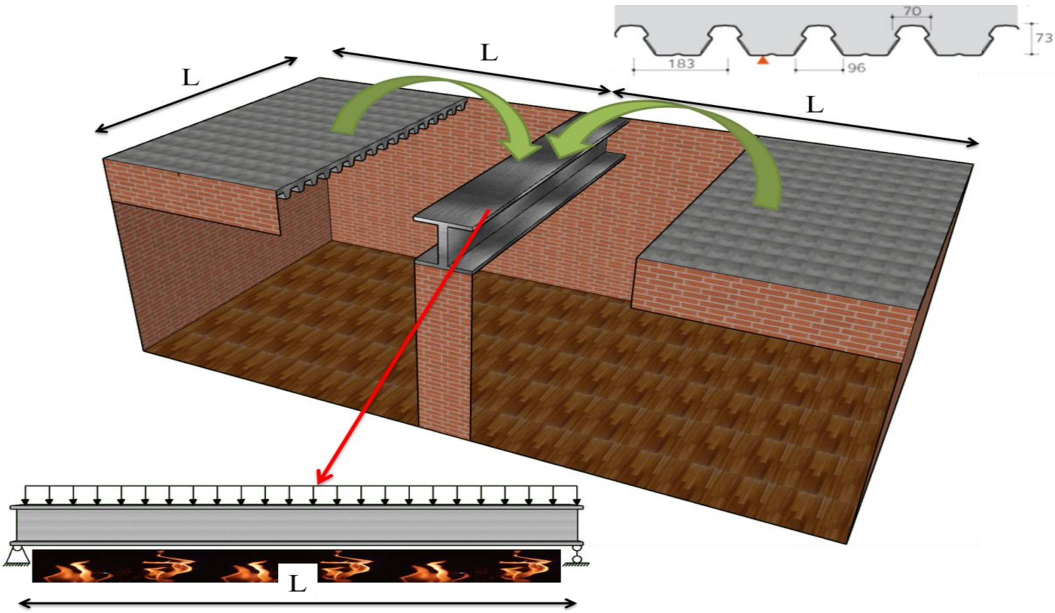

Figure 1 - Details of the compartment and its elements.

3.1. Example

One line of text preceding the table and one following the table should be skipped (left empty). In the following example the dimensions of slab and steel beam for a span of 3 m are calculated by applying the step by step method. First the permanent and variable loads applied on the slab which are summarized in Table 1 are calculated. Overall height of the composite slab is pre-considered to be 13cm with reinforced ϕ8 in the corrugation part and ϕ16 above the support. The steel sheet is chosen with a thickness of 0.75mm. Then, the capacity of the slab is checked, with the help of Bimware MASTER EC-4' software [20] for an ultimate limit state (ULS) load combination.

Table 1- Permanent and variable loads of the slab

Typology	Material (layer)	Thickness (m)	Loads (kg/m2)
Permanent	*Cement layer*	*0.03*	*65*
	Vapor layer	*0.0002*	*0.2*
	Glass wool	*0.02*	*2*
	Polyethylene	*0.0002*	*0.2*
	Concrete slab	*0.13*	*250*
	Steel sheet	*0.00075*	*10*
	Total		**327.5**
Variable	*Partitions weight*		80
	Permanent load for offices		250

3.2. Figures (Style Heading 3)

After the dimension of the slab for ULS combination of load and fire safety, the load applied to the steel beam is estimated. Distribution load for the ultimate limit state combination applied to the beam is valued at:

$$q_{fi,S} = \left(\sum_{j \ge 1} \gamma_{G,j} \cdot G_{k,j} + \sum_{i \ge 1} \gamma_{Q,i} \cdot Q_{k,i} \right) \cdot L = \left(1.35 \cdot 3.3 + 1.5 \cdot (0.8 + 2.5)\right) \cdot 3 \approx 28kN / ml$$

And distribution load for accidental combination applied to the beam has the value:

$$q_{acc} = \left(\sum_{j \ge 1} G_{k,j} + \sum_{i \ge 1} \psi_{2,1} \cdot Q_{k,i} \right) \cdot L = \left(1 \cdot 3.3 + 0.3 \cdot (0.8 + 2.5)\right) \cdot 3 \approx 12.9kN / ml$$

For a simple beam the corresponding internal loads for both combinations have the values:

$$\overbrace{\begin{aligned} M_{fi,S} &= \frac{q_{fi,S} \cdot L^2}{8} = \frac{28 \cdot 3^2}{8} = 31.5kNm \\ V_{fi,S} &= \frac{q_{fi,S} \cdot L}{2} = \frac{28 \cdot 3}{2} = 42kN \end{aligned}}^{ULS\ combination} \qquad \overbrace{\begin{aligned} M_{acc} &= \frac{q_{acc} \cdot L^2}{8} = \frac{12.9 \cdot 3^2}{8} = 14.5kNm \\ V_{acc} &= \frac{q_{acc} \cdot L}{2} = \frac{12.9 \cdot 3}{2} = 19.3kN \end{aligned}}^{Accidental\ combination}$$

Using the value of the bending moment for the ultimate limit state load combination and the yield strength of the steel the minimal plastic moment of resistance that the beam must have is:

$$W_{pl} \ge \frac{M_{pl,Rd} \cdot \gamma_{M0}}{f_y} = \frac{31.5 \cdot 10^3}{275} \approx 115cm^3$$

Referring to the plastic moment of resistance in the corresponding tables (9) we find the most appropriate cross section. For the actual case the corresponding cross section is IPE-180A.Then the degree of utilization of the elements is found:

$$\mu_0 = \max\begin{cases} \dfrac{M_{fi,d,t}}{M_{Rd}} \cdot \dfrac{\gamma_{M0}}{\gamma_{M,fi}} = \dfrac{14.5}{37.1} = 0.39 \\ \dfrac{V_{fi,d,t}}{V_{Rd}} \cdot \dfrac{\gamma_{V0}}{\gamma_{V,fi}} = \dfrac{19.3}{99.7} = 0.19 \end{cases} = 0.39$$

With the value of the degree of utilization we are then able to calculate the critical temperature of the steel beam:

$$\theta_{cr} = 39.19 \ln\left(\frac{1}{0.9674 \cdot \mu_0^{3.833}} - 1\right) + 482 = 39.19 \cdot \ln\left(\frac{1}{0.9674 \cdot 0.39^{3.833}} - 1\right) + 482 \approx 624℃$$

Then the next step is calculating the time-temperature curve of the fire and the specific heat respectively by referring to equations 8 and 9 (Figure 2).

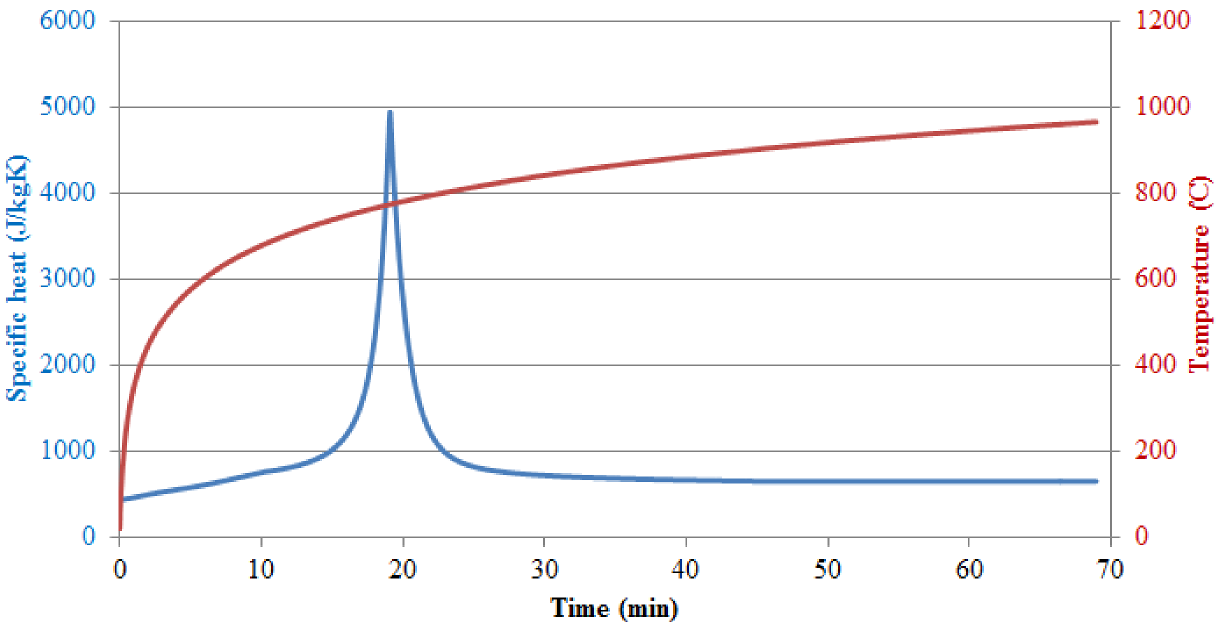

Figure 2 – Time-temperature curve according ISO-832 and the specific heat as a function of time

Finally, for an unprotected steel beam, with the help of equation 7 we can calculate the diagram of temperature progression.

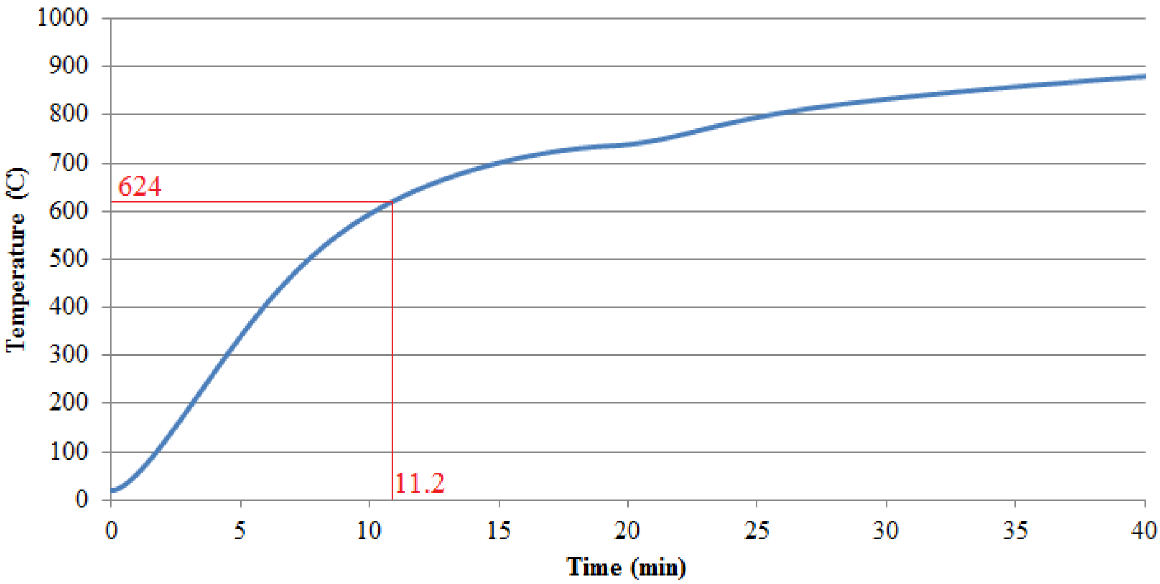

Figure 3 – Time-temperature curve of the steel beam

Based on the curve presented in Figure 3 the time required for the beam to reach its critical temperature is obtained.

Through the application of this case it is observed that fire risk analysis of beams presented by time load resistance, critical temperature and time resistance depends mainly on the element's degree of utilization and its cross sectional properties. Load resistance presented by the degree of utilization influences the critical temperature. Then based on cross sectional properties the beam's heating curve is calculated. In this curve the time resistance for the corresponding critical temperature is found.

4. RESULTS

By repeating the same equations for any span between 3-10m the results presented in Figure 4 are obtained. Results show that with the increment of the span, the critical temperature decreases while the time resistance of the double-T steel beam increases. These results bring in two major observations. First the increment of the span and consequently of the self-weight of the slab increase the beam's degree of utilization. Both of them increase the beam's bending moment and that influences the decrement of the critical temperature that it can resist. In order to resist the increment of bending moment the cross section of steel beam is chosen with adequate properties as shown in the figure. With the variation of the span a reduction of section factor is observed which positively influences the time required by the beam to reach its critical temperature. In conclusion, on the one hand the beam's span and self-weight negatively influence fire risk while one the other hand section factor has a positive influence.

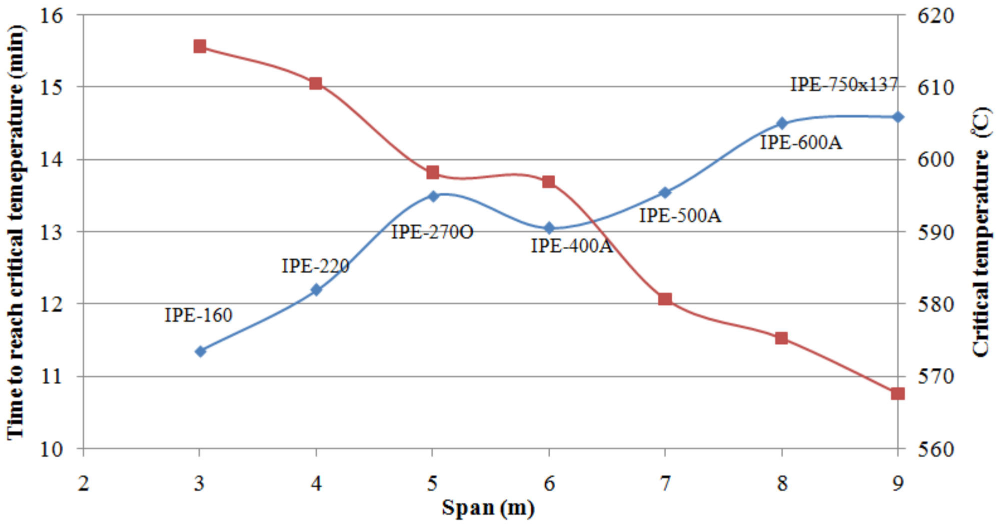

Figure 4 – Time to reach critical temperature for different spans of beams

To better understand the observation of the results given in Figure 4, below the variation of these parameters is separately analyzed. Figure 5 shows the influence of the span variation in the degree of utilization of the beam and the time required by the beam to reach its critical temperature. Calculations are made by keeping the self-weight of the composite slab constant at $230daN/m^2$, the section factor of the beam at $80m^{-1}$ (corresponds to IPE-550V) and the combination coefficient at 0.3. Based on these results, we observe a large decrement of the time resistance passing from 3 to 5m of span (about 180minutes). While the degree of utilization of the beam for bending moment increases constantly but is always under the accepted critical value (that is one).

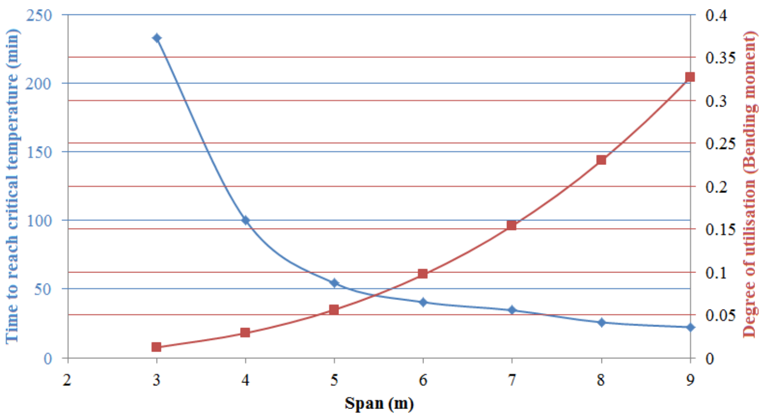

Figure 5 – Time to reach critical temperature for different spans of beams

The influence of combination coefficient in the time resistance and the degree of the utilization of the beam are presented in Figure 6. Here the span of beams is considered constant at 5m and the self-weight of the composite slab at 230 daN/m^2 and the section factor of the beam at 80m^{-1} (corresponds to IPE-550V). The combination coefficient has a significant influence when it is varied between 0.3 and 0.35. Within this range the time resistance of the beam decreases with around 50 minutes. Once again the degree of utilization increases but is always under the critical value.

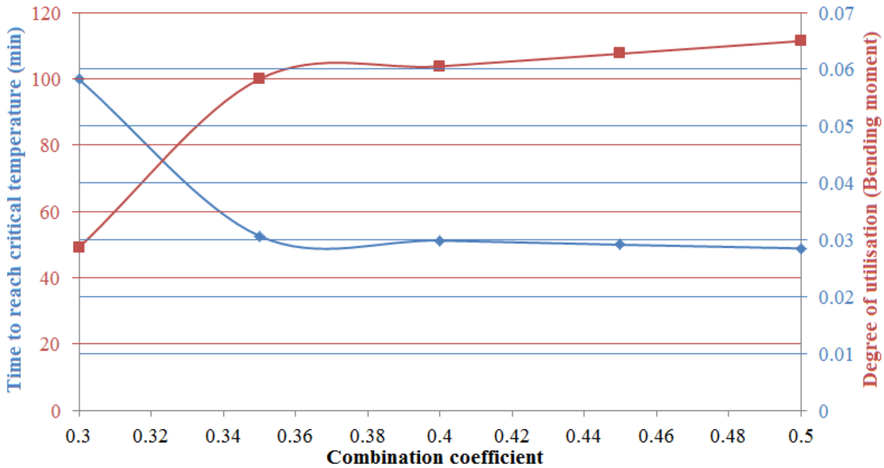

Figure 6 – Influence of variation of combination coefficient in time resistance and degree of utilization

Self-weight of composite slab is the next parameter that is varied in order to calculate its influence in the time resistance and the degree of utilization of the steel beam. Here the span of the beam is kept constant at 5m, the combination coefficient at 0.3 and the section factor of the beam at 80m^{-1}.Soft linear decrement of the time resistance of the beam is observed by the increment of the self-weight of composite slab (Figure 7). The degree of utilization is increased linearly but always remains under the critical value.

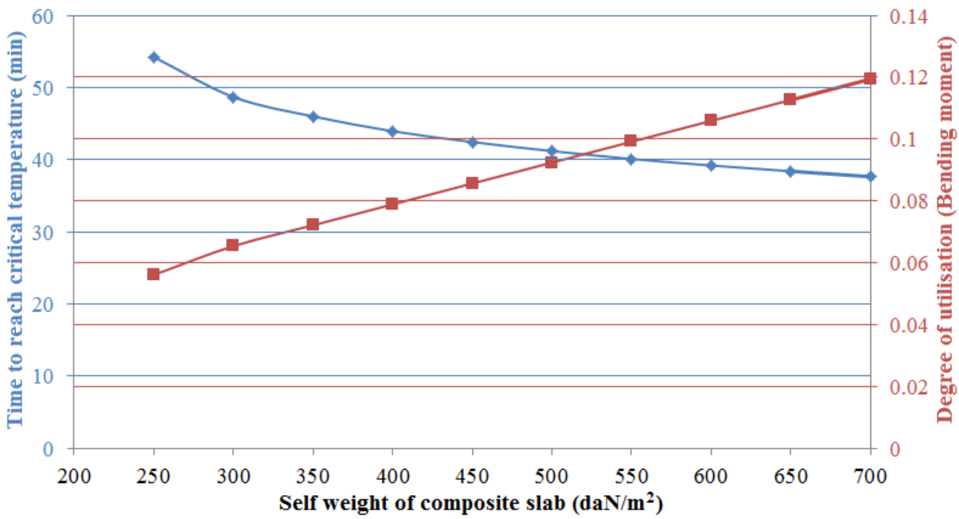

Figure 7 – Influence of variation of self-weight of composite slab in time and degree of utilization

For a constant self-weight of composite slab 230 daN/m^2, combination coefficient 0.3 and section factor 80m^{-1}, Figure 8 shows the results of the influence of section factor on time resistance. While the variation of section factor to the degree of utilization of the steel beam has no influence.

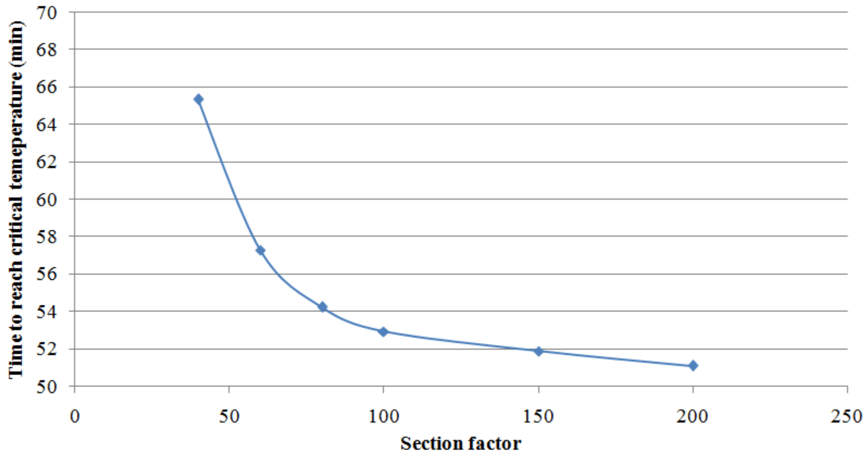

Figure 8 – Influence of variation of section factor to time resistance

Finally the relative influences of four parameters in time resistance of the steel beam are presented in Figure 9. Based on the results obtained we can conclude that the parameter of span has the highest influence followed by the combination coefficient, self-weight of the slab and then the section factor. A relative increment of the span with 100% can decrease the time resistance of the beam by 350%. While the increment of combination coefficient, self-weight and section factor by 100% can decrease the time resistance respectively by 120%, 50% and 25%.

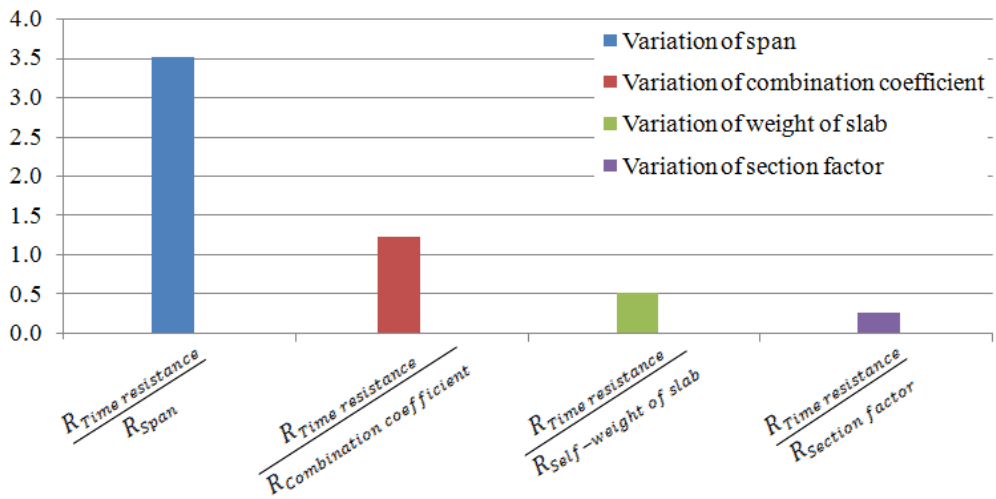

Figure 9 – Influence of parameter in time resistance of steel beam

5. CONCLUSION

This study provides an analysis of the parameters influencing the fire resistance of steel beams. Through the evaluation of 35 cases the most important parameters are identified and they can be classified into two groups. The parameters of span, self-weight of composite slab and combination coefficient are in the first group and the parameter of the section factor in the second one. All of them influence the time resistance of steel beam and increase the risk of fire failure. While the parameter of the second group influences the critical temperature directly those of the first group have transversal influence through the critical temperature. Finally, the parameter of span is identified to have the highest influence on critical temperature followed by that of combination factor, self-weight and section factor. In this study, spans from three to five meters are found as the most adequate. Even though the combination coefficient is a function of the importance of the building, in some cases it should be taken 0.3. Moreover, the structure of slabs should be as light as possible. Section factor has a small influence in the fire resistance of steel beams. However cross sections with a small section factor should be envisaged to be employed in construction. In conclusion, for fire safety, the structural engineers should put their efforts into designing structures with small spans and lighter slab structure. The load resistance condition, represented by the degree of utilization of steel cross section, was always fulfilled. In all cases the degree of utilization was higher with respect to bending moment. These conclusions can be helpful for structural engineers and architects. They give them some recommendations which can be used during the early design stage of building projects. This study is limited to double-T steel beams but in the future we recommend enlarging other structural elements.

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