Paradigm reference-global.com Ovidius University Annals Series: Civil Engineering, Year 27, 2025
DOI: 10.2478/ouacsce-2025-0012

Analyses on ensuring the load-bearing capacity of steel elements in fire conditions

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Abstract **Starting with May 2025, a new version of the Regulations on fire safety of constructions, P118-1/2025, must be applied and P118-1/1999 ceases to apply. From the comparison of the two versions of the standard, it results that in the new version higher fire resistances are required for the beams. The paper compares the thicknesses necessary to ensure fire protection in accordance with the requirements of the two regulations, using the fastest method in current practice, but which at the same time is conservative. Also, the critical temperatures for the most vulnerable elements of the lateral resisting system were determined by iterative calculation for two structures with the same conformity, but which are designed for a different level of seismic hazard. Thus, the fire resistance reserves that are obtained by adopting fire protection thicknesses corresponding to a critical temperature usually considered to be 500ºC were estimated.**

Keywords – critical temperature, fire resistance, fire stability level, , thickness of the protective layer.

1. INTRODUCTION

In Romania, latterly, the minimum requirements, and the performance levels for constructions, in order to meet the fundamental requirement "fire safety" are set out in the Normative on fire safety of constructions P118-1/2025, which replaced the P118-1/1999 variant starting with May. Therefore, in this paper comparisons will be made between the thermal protection solutions in accordance with the requirements of the two variants of this regulation.

This regulation (P118-1) stipulates the obligations of specialized designers regarding fire safety measures. Through this regulation, the tasks of the structural engineers are specified to ensure the fire resistance of the elements with a role in the fire stability of the construction (columns, load-bearing walls, floors, roofs, stairs, balconies, walkways, etc.), to determine the passive protections of the structures, to specify the critical temperature of the steel structures for which protection against the thermal actions generated by fires must be provided, based on calculations drawn up in accordance with Eurocodes [1].

ISSN 2392-6139 / ISSN-L 1584-599

The minimum fire resistance conditions that the main construction elements must meet are dependent on the depend on the construction or fire compartment classification at a certain level of fire stability. P118-1/2025 defines the level of fire stability by the global normed capacity of a construction or fire compartment to respond to the action of a standard fire. The level of fire stability of the building or the fire compartment is determined by its element with the most unfavourable classification in the normed values. This term is equivalent to the term degree of fire resistance used in P118-1/1999 and both are expressed by five levels denoted from I to V.

P118-1/2025 imposes the minimum fire resistance conditions for civil constructions differentiated not only by the level of the fire stability, but also by the height of the building, but also according to the equipment with automatic sprinkler/spray fire extinguishing systems, in addition to the requirements of the specific technical regulations, as illustrated in fig. 1.

Nr. Crt.	Type of construction elements	Fire stability level of the building/fire compartment										
		I h≥125 m	I 75m≤h <125m	I 45m≤ h<75m	I 28m<h <45m	I h≤28m	II	II (+)	III	III (+)	IV	V
1	COLUMNS (R)	240 (A1)	180 (A1)	180 (A1)	120 (A1)	120 (A1)	120 (A1)	90	60	45	30	- (15 **)
2	BEAMS (R)	180 (A1)	120 (A1)	120 (A1)	90 (A1)	90 (A1)	90 (A1)	90	60	45	30	- (15 **)
3	FLOORS, including terrace floors which constitute escape routes or which take on additional loads other than those originating only from snow (REI)	120 (A1)	120 (A1)	120 (A1)	90 (A1)	90 (A1)	90 (A1)	90	60	45	30	- (15 **)
4	TERRACE FLOORS that do not constitute escape routes or that take over loads coming only from snow) (RE)	120 (A1)	90 (A1)	90 (A1)	60 (A1)	60 (A1)	60 (A1)	45	45	30	15	-
	...											

(+) - Buildings equipped with automatic sprinkler/spray fire extinguishing systems , in addition to the requirements of specific technical regulations.

Fig. 1 The minimum conditions for the classification of the construction or fire compartment in fire stability levels for civil buildings –from Tab 2 P118-1/2025

Table 1 shows a comparison between the minimum fire resistances, the bearing capacity R, imposed by the new P118-1 and the replaced one and highlights that the new regulation imposes more severe resistances for the beams.

Table. 1 Comparatively minimum fire resistance for columns and beams

	Gr.I P118-1/ /1999	Level I P118-1/ /2025	Gr. II P118-1/ /1999	Level II P118-1/ /2025	Gr. III P118-1/ /1999	Level III P118-1/ /2025	IV P118-1/ /1999	Level IV P118-1/ /2025
Columns	R180	R120… R240	R120	R90, R120	R60	R60	R30	R30
Beams	R60	R90… R120	R45	R90	R45	R60	R15	R30

It should be emphasised that these higher requirements on load-bearing capacity in fire conditions should apply only to new or expanding constructions. Annex 10 of P118-2025 considers the situation of interventions on existing constructions that do not expand. In such situations, the fire performance of the construction elements that are replaced is required in accordance with the regulations applicable at the time of construction, but with the mention that the equipment with fire safety installations is done according to the current technical regulations. In this situation, there are minimum conditions regarding fire resistance similar to the replaced regulation, P118-1/1999.

P118-1/2025 imposes for civil above-ground buildings the same correlation conditions between the level of fire stability ensured, the number of above-ground levels, destination and the maximum simultaneous capacity of users, as in the previous version, P118-1/1999. Thus, for an office building with more than 5 levels, depending on the floor level of the last level used by users (below or above 28 m), it should fall within stability level II or I and requires the fulfillment of the criteria R120 for columns and R90 for beams.

Regarding the provision of bearing capacity, Art. 2.1.3.3 of P118-1/2025 requires the following:

- The protection of steel structures from the thermal actions of fires must correspond to the critical temperatures of the respective structures and the respective cross-sectional factors.
- In the absence of a specific calculation, the critical temperature value for steel elements with a cross-section of class 1, 2 and 3 used in buildings may be considered equal to 500°C, and for steel elements with a cross-section of class 4 it shall be determined according to the national annex of SR EN 1993-1-2; according to [2, 3] for these class 4 elements, the critical temperature can be considered 350°C degrees if the element is not in tension.

Manufacturers of fire protection materials (thermofoam paint protection, torcrete protection, cladding or other systems) provide data sheets based on tests in furnaces exposed to a single heating scenario. In many situations the data sheets are differentiated not only by fire resistance, but also by the type of element (column/ beam), section form, and by the number of sides exposed to fire. Based on these sheets, in current practice the thickness of the protective layer is easily determined for a standard fire, described by the ISO 834 curve, provided that the critical temperature of the element is known. The steps to establish the protective layer necessary to ensure the bearing capacity for the steel members could be schematized as in figure 2.

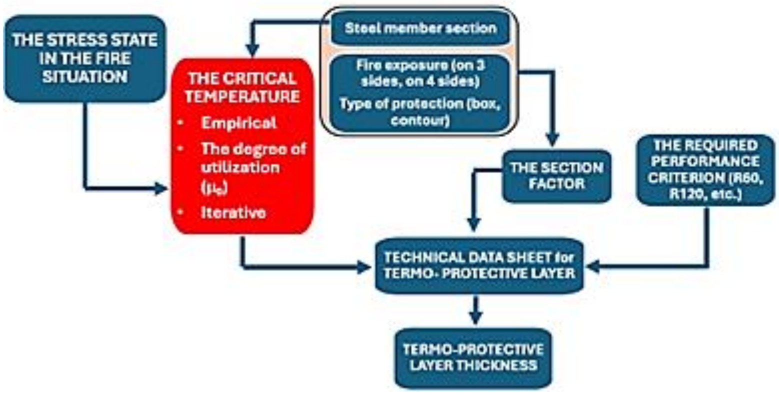


Fig. 2 Driagram to asses the thickness of the protective layer

This diagram highlights that in order to meet the basic requirement that steel structures maintain their bearing capacity during exposure to fire for a certain resistance in the fire situation, by an engineering approach, as a first step, careful evaluation of the critical temperature for structural elements is necessary.

2. CRITICAL TEMPERATURE DETERMINATION FOR STEEL ELEMENTS

In SREN 1993-1-2 it is defined as the critical temperature that temperature in the section for which the corresponding design resistance in the fire situation ($R_{fi,d,t}$) (diminished corresponding to this temperature) is equal to design effect of actions resulting from the accidental grouping for the fire design situation ($E_{fi,d}$).

Section 4.2.4. from the SREN 1993-1-2 gives a relationship for calculating the critical temperature according to the degree of use μ_0 at the initial moment, but with the mention that the relationship cannot be applied directly when loss of stability phenomena must be considered; the degree of use for tension elements and for class 1, 2 or 3 elements is obtained as the ratio between the design effect of actions resulting from the accidental grouping and the design resistance in the fire situation, but at time t = 0, i.e. at normal temperature.

For other situations involving loss of stability phenomena, the critical temperature is determined by an iterative laborious process: an initial temperature is proposed; depending on the type of loading, based on the relationships in section 4.2.3. of SREN1993-1-2 it is determined the design resistance of the element taking into account the decrease of resistance and deformation properties for the proposed temperature; determine the degree of utilization corresponding to this proposed temperature, then based on this degree of use, a critical temperature value can be obtained from Tab 4.1 or eq 4.2.2 of SREN1993-1-2; if this temperature value significantly differs from the previously proposed value, the design resistance assessment for this new temperature value shall be resumed until the difference between successive temperatures becomes acceptable; the temperature thus obtained is the critical temperature. Such an iterative evaluation involves a significant computational effort. Prestigious papers illustrate these difficulties. Thus, in [4] for a beam subjected to both compression and bending, *Example 5.3* shows that it may be difficult to assess the class of the section that depends on the temperature under consideration. Also in [4] *Example 5.7* numerically illustrates the different values obtained for the critical temperature for a beam depending on the presence of the lateral buckling phenomenon.

An alternative, given in [2], which greatly simplifies the determination of the critical temperature for tension members and for beams where lateral-torsional buckling is not a potential failure mode, it is proposed that the degree of use should be expressed in terms of the reduction factor for design load level in the fire situation $\mu_0 = \eta_{fi}\left[{}^{\gamma_{M,fi}}/_{\gamma_{M0}}\right] = \eta_{fi}$; this is how they are obtained the critical temperature values determined for a reduction factor of 0.65 or 0.7 as given in chapter 2.4.2.of [2] and which justify the consideration of a critical temperature between 500°C and 550°C and at the same time the recommendation given in P118-1.

Using a graphical representation of the dependence of the critical temperature on the degree of use [4] it immediately emerges that a specific calculation of the critical temperature (even if not iteratively, but only based on the degree of use) could lead to higher values higher than those determined empirically (500°C and respectively 350°C) and consequently to a more economical design of fire protection, in safe conditions.

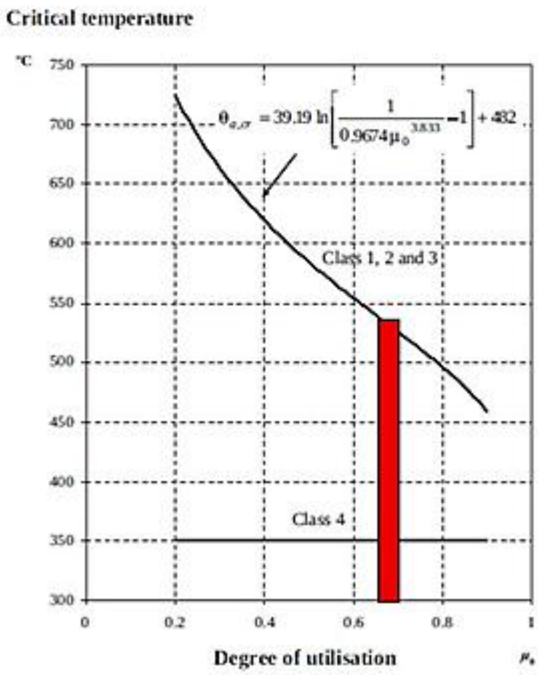


Fig. 3 Critical temperature depending on the degree of use [4]

It should also be noted that the classification of the sections can be done as for the calculation at normal temperature, considering a reduced value of the coefficient, $\varepsilon = 0.85\sqrt{235/f_y}$ [2].

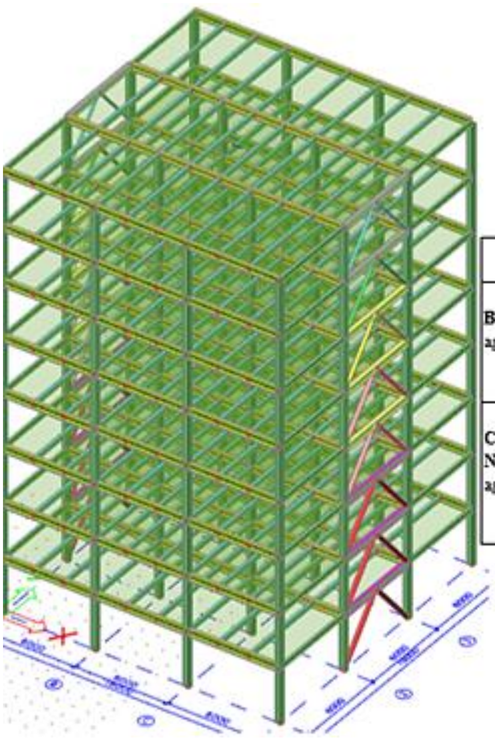
Fire resistance verification modules (FSV) implemented in structural design software, such as SCIA ENGINEER, allow the determination of the critical temperature through iterative calculation. The functionality *Fire resistance verification* implemented in SCIA ENGINEER can make fire resistance checks any of the three types of analysis: resistance domain, time domain, temperature domain. "SCIA Engineer determines the evolution of gas and material temperature over time, based on the rules of the code and the selected fire curve, type of exposure of the members, and fire protection, if defined. The modified resistances at elevated temperature are derived. An iterative procedure may be applied to determine the critical steel temperature in the temperature domain". If temperature domain analyze is used, "the critical steel temperature will be calculated with an iterative process. So first, an estimation of this critical temperature will be chosen and the unity check following EN 1993-1-2 will be executed, if this check is lower than one, a higher critical temperature is chosen or when this check is higher than one, a lower temperature is chosen. Now this unity check is recalculated just until the moment this unity check gives a result for this critical steel temperature between 0,99 and 1. This is a more accurate procedure to calculate the critical temperature and this method is also valid if stability phenomena or deformation criteria have to be taken into account." [5]

In order to calculate the design resitance corresponding to a certain temperature, the hypothesis of a uniform temperature in the cross-section is considered. For a member with a non-uniform temperature distribution (class 1 or class 2), the FSV module corrects the design resistance using an adaptation factor for non-uniform temperature across the cross-section (κ_1) and/or an adaptation factor for non-uniform temperature along the beam(κ_2), as stated in section 4.2.3.3 SREN 1993-1-2.

The results obtained after such an analysis clearly highlight that the stress state in a structure controls the critical temperature value, and strong elements, such as those in structures designed in areas characterized by high seismic harzard are characterized by higher critical temperatures.

3. RESULTS AND SIGNIFICANCES

The structures selected for the study are two of those analyzed in [6]: the structures were designed for the same dead and live loads, but for locations characterized by different seismic hazard Bucharest and respectively Cluj Napoca, as summarized in Fig. 5. In both situations gravity load resisting system is made of secondary beams IPE300. Lateral load resisting system is composed of moment resisting frame in X direction and centrically braced frames (CBF) on Y direction. The study will focus on the analysis of fire protection for lateral load resisting system.



	Columns	MRF beams	Story	Nondisipative beams (S355)	Braces (S275)
Bucharest ag=0.30g	HEM360 (S460)	IPE500 (S355)	8	HEA360	152.7x7.1
			7	HEA360	177.8x8
			6	HEA400	219.1x8
			4,5	HEA400	244.5x8
			1-3	HEB400	273x8
Cluj-Napoca ag=0.10g	HEB400 (S355)	IPE400 (S355)	8	HEA280	101.6x5.6
			7	HEA280	108.0x5.6
			6	HEA280	114.3x6.0
			5	HEA280	127.0x5.6
			4	HEA300	139.7x5.6
			1-3	HEA300	152.4x6.3

Fig. 4 The analyzed structure, and the elements sections

In the first stage, the financial impact was pursued by the more stringent criteria imposed for beams in the P118-1/2025 edition, given that the critical temperature is empirically considered 500oC for all resistance elements; for both types of protection, fire protectiv contruction board (PROMATECT-XS, board thickness 12.5, 15, 20, 25 mm) and a reactiv fire protective coanting (PROMAPAINT-SC4 or PROMAPAINT-SC3), the section factors were determined taking into account the type of protection (cladding/coating); for the beams, exposure on 3 sides was considered, and for the columns exposure on 4 sides.

Table 2 The section factor and the thicknes fire protectiv layers for the beams

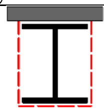
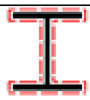
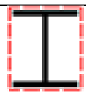
	 **PROMAPAINT®-SC4** **Reactive fire protective coating** 3-sided exposure				 **PROMATECT®-XS** **Fire protective construction board** 3-sided exposure			
	SF (m^{-1})	Dry film thickness (DFT) [mm]			SF (m^{-1})	Cladding thickness [mm]		
		R45	**R60**	**R90**		**R45**	**R60**	**R90**
HEA 280	136	0,530	0.888	1.598	85	12.50	12.50	20.00
HEA 300	126	0.500	0.855	1.567	78	12.50	12.50	15.00
HEA 360	107	0.415	0.771	1.492	70	12.50	12.50	12.50
HEA 400	101	0.389	0.745	1.462	68	12.50	12.50	12.50
HEB 400	83	0.247	0.626	1.331	56	12.50	12.50	12.50
IPE 500	134	0.524	0.880	1.592	104	12.50	12.50	20.00
IPE 400	153	0.534	0.930	1.641	116	12.50	15.00	25.00

Table 3 The section factor and the thicknes fire protectiv layers for the columns

	 **PROMAPAINT®-SC4 /SC3*** **Reactive fire protective coating** 4-sided exposure				 **PROMATECT®-XS** **Fire protective construction board** 4-sided exposure			
	SF (m^{-1})	Dry film thickness (DFT) [mm]			SF (m^{-1})	Cladding thickness [mm]		
		R60	**R90**	**R120***		**R60**	**R90**	**R120**
HEM360	61	0.503	1.238	2.500	45	12.50	12.5	15.0
HEB400	98	0.732	1.484	3.433	71	12.50	15.0	20.0

* PROMAPAINT®-SC3 is a reactive fire protective coating for steel structures which can provide fire resistance in the range R30 – R150, while PROMAPAINT®-SC4 can provide fire resistance in the range R15 - R90.

Considering that manufacturers provide only certain thicknesses of boards, it is found that in the case of cladding beams, an increase in criterion R does not always require an increase in the thickness of the board.

Next, the critical temperatures were determined through an iterative calculation, performed using the FSV module. The graphical representation of the results obtained for the moment resisting frame designed for Bucharest highlights as the most unfavorable situations critical temperatures of 778 ºC for columns (HEM360, S460) and 762 ºC for beams (IPE500 S355) (fig.6). For similar elements, designed for a lower level of seismic hazard, the critical temperatures obtained by iterative calculation are lower, but higher than those considered empirically: 667°C for columns (HEB400 S355) and 683°C for beams (IPE400 S355).

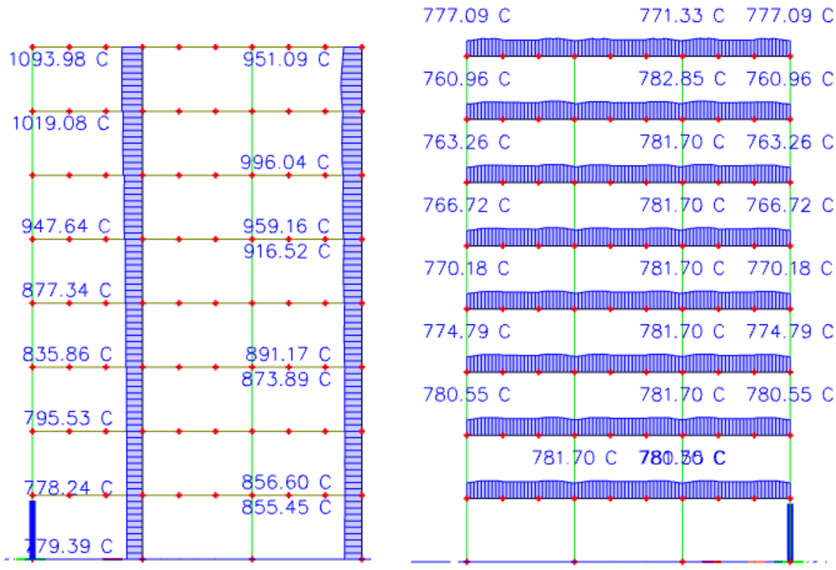


Fig. 5 Critical temperatures for the intermediate MRF, Bucharest

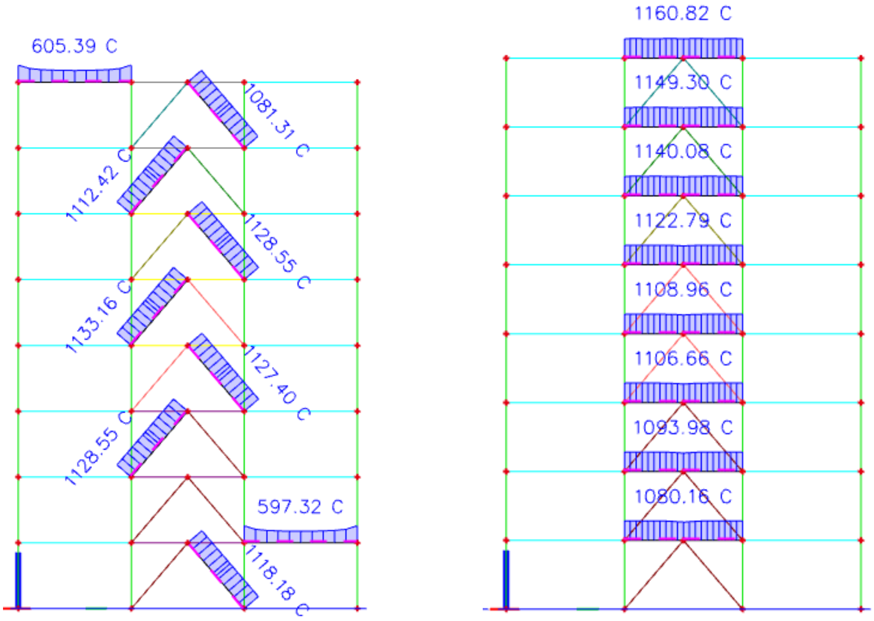
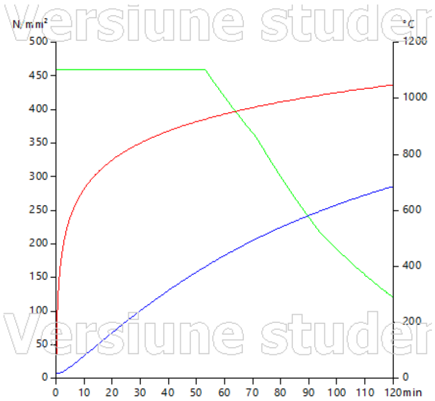


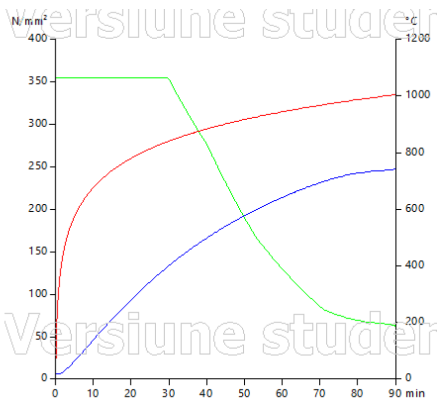
Fig. 6 Critical temperatures for CBF, Bucharest

The FSV module also allows the evaluation of the temperature in the section of the protected element, for any given temperature time curve, for a uniform temperature distribution per section. The protective material must be defined by the properties that are found in the relationship that expresses the temperature increase in a structural element protected in SREN1993-1-2, namely: density, thermal conductivity, specific heat and thickness.

Considering that by iterative calculation higher critical temperatures are obtained, the fire resistance reserve provided by the empirically determined fire protections was analyzed. The evolution of the temperature provided by the necessary protections to ensure R60 in the case of beams and respectively R90 in the case of columns was analyzed; thus, the minimum time of exposure to the standard fire for which the temperature of the material exceeds the critical temperature determined by iterative calculation was determined (t_{cr}) The results are centralized in the table 4. In this analysis the relevant characteristics of the protective material have been density 915kg/m^3 and thermal conductivity 0.275 W/mK [7]



HEM360, PROMATECT XS, 12.5 mm, tcr=176min



IPE500, PROMATECT XS, 12.5 mm, tcr=101min

Fig.7 Temperature evolution in the protected elements section - the blue curve, for standard fire ISO834 – red curve; the yield strength f_y – green curve

Table 4 Fire resistance reserves, expressed in the time domain

Cross-section	a_g	Element type, exposure	Critical temperature (most vulnerable element) [°C]	Cladding thickness [mm] adopted for imposed R (θcr=500°C)	t_{cr} (min)/R
HEM360		Column, 4 sides	778	12.5 / R90	176 (R120)
IPE500	0.30g	Beam, 3 sides	762	12.5 / R60	101 (R90)
HEB400		Beam, 3 sides	1080	12.5 / R60	280 (R240)
HEB400		Column, 4 sides	667	15.0 / R90	95 (R90)
IPE400	0.10g	Beam, 3 sides	683	15.0 / R60	76 (R60)
HEA300		Beam, 3 sides	1007	12.5 / R60	193 (R180)

The above results indicate some resistance reserves, due both to the underestimation of the critical temperature by the quick method and by the modulation of the protective boards thickness.

Using the same software module, it is possible to easily adopt a thickness of the protective layer correlated with the degree of use of the section and respectively with the critical temperature, as long as the density and thermal conductivity are given in the product sheet. In the case of reactive fire protective paints manufacturers frequently indicate density and consumption, expansion ratio, but do not publish values for thermal conductivity or heat capacity. For this reason, a similar analysis was not done for the reactive paint protection.

4. CONCLUSION

The results obtained for the case study illustrate the impact of the implementation of the new Regulations on fire safety of constructions on ensuring the bearing capacity in fire conditions, by proposing the thickness of the protective layer in correlation with the level of fire stability that must be provided to the building.

As expected, a higher fire resistance will impose additional costs and resources for the protection of metal elements compared to the previous edition of the standard, but these could be diminished if the evaluation of the critical temperature were based on the degree of use of the section and the stress state.

Given that the thickness of the protective layer is proposed conservatively considering a critical temperature of 500ºC, for the lateral load resisting system it is found that there are fire resistance reserves if an iterative calculation of the critical temperature is made, especially if this system is designed for a high seismic hazard.

5. REFERENCES

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