Acta Technica Napocensis: Civil Engineering & Architecture Vol. 56, No. 2 (2013)
Journal homepage: http://constructii.utcluj.ro/ActaCivilEng
Special Issue: First International Conference for PhD Students in Civil Engineering, CE-PhD 2012.

Computation of Structural Fire Resistance of Steel Sections

Tudor Petrina[1]

[1] *Technical University of Cluj-Napoca, Faculty of Civil Engineering, 15 C Daicoviciu Str., 400020, Cluj-Napoca, Romania*

(Accepted 15 November 2013; Published online 15 December 2013)

Abstract

The main object of this study is to compute the structural fire resistance for several steel members under different loading conditions. This is done in chapter 4 using two advanced calculation models. Chapter 1 contains prescriptions according to European codes, needed for this research. In Chapter 2 the notion of structural fire resistance is explained and also information about the types of fire protection materials used in this research is given. In Chapter 3 a short presentation of the properties of the structural steel was made. A validation of the results is made within chapter 4 and 5 by comparing values provided by the two applications and also by means of manual computation according to the code.

Rezumat:

Scopul acestei lucrari este de a calcula rezistenta la foc a unor elemente structurale din otel in diferite conditii de incarcare. Acest lucru este realizat in capitolul 4 folosind doua modele avansate de calcul. In capitolul 1 se prezinta prevederile calculului la foc in normele europene, necesare in acest studiu. In capitolul 2 se explica notiunea de rezistenta la foc si sunt date unele informatii despre materiale de protectie la foc folosite in aceasta lucrare. Capitolul 3 contine o scurta prezentare a proprietatilor otelului structural. Validarea rezultatelor se face in capitolul 4 si 5 prin comparatia valorilor obtinute prin cele doua modele de calcul si de asemenea printr-un calcul manual aplicand formulele din normativ.

Keywords: fire action, fire curve, fire resistance, design strength, steel section, spray coatings

1. Fire design prescriptions according to SR EN 1991 „Actions on Structures", and SR EN 1993 „Design of Steel Structures"

1.1 Fire action on structures:

Part 1.2 "Actions on Structures Exposed to Fire" of SR EN 1991 (Actions on Structures) "deals with the fire loading, thermal and mechanical actions on structures exposed to fire, and thermal actions related to nominal and physically based thermal actions" [1]. Any structure designed according to part 1.1. and fulfilling the supplementary requirements of part 1.2. should have the required fire resistance. In the following, θ_g is the gas temperature, t is time.

The code defines three time – temperature fire curves: the standard time – temperature curve; the external fire curve; the hydrocarbon fire curve. The Standard time – temperature relation is according to ISO 834:

$$\theta_g = 20 + 345\log_{10}(8t+1) \tag{1}$$

This model is a general model that may be used when no accurate information on fire is known.
The External time – temperature curve ("for the outside of external walls, which can be exposed to fire from different parts of the facade" [3]) relation is:

$$\theta_g = 660(1 - 0.687e^{-0.32t} - 0.313e^{-3.8t}) + 20 \tag{2}$$

The hydrocarbon time – temperature curve represents a fire with hydrocarbon or liquid fuel:

$$\theta_g = 1080(1 - 0.325e^{-0.617t} - 0.675e^{-2.5t}) + 20 \tag{3}$$

According to [1], in order to obtain significant effects of the actions $E_{fi,d,t}$ during fire, the mechanical actions are combined as for "accidental" situation computation. The effects of actions may be derived from those computed for normal temperature:

$$E_{fi,d,t} = E_{fi,d} = \eta_{fi} \cdot E_d \tag{4}$$

where
E_d – computation value of significant effects of actions derived from fundamental combination according to SR EN 1990; $E_{fi,d}$ – constant computation value during fire; η_{fi} – safety factor [1].

1.2 Structural fire design for steel structures

The structural fire design may be carried out by the following three methods according to [2]:

- simplified design methods which give conservative results;
- advanced design methods in which engineering principles are applied in a realistic manner;
- methods based on test results.

1.3 Formulas to compute the design strength of a structural steel member according to SR EN 1993

According to [2], "the design strength $N_{fi,t,Rd}$ at time t of a tension member with a non-uniform temperature distribution across the cross-section may be determined from:"

$$N_{fi,t,Rd} = \sum_{i=1}^{n} A_i k_{y,\theta,i} f_y / \gamma_{M,fi} \tag{5}$$

According to [2], "the design strength $N_{fi,\theta,Rd}$ of a tension member with a uniform temperature θ_a should be determined from:"

$$N_{fi,\theta,Rd} = k_{y,\theta} N_{Rd} \left[\gamma_{M,0} / \gamma_{M,fi} \right] \tag{6}$$

According to [2], "the design buckling strength $N_{b,fi,t,Rd}$ at time t of a compression member with a Class1, Class2 or Class3 cross-section with a uniform temperature θ_a should be determined from:"

$$N_{b,fi,t,Rd} = (\chi_{fi} / 1,2) A k_{y,\theta,\max} f_y / \gamma_{M,fi} \tag{7}$$

where the meanings of the parameters inside the formulas can be found at pp. 30 and 31 of [2].

2. Structural fire resistance and Fire protection materials

2.1 Structural fire resistance

The structural fire resistance represents the ability of the structural elements to resist the applied load under fire condition and it is expressed as a measure of time until the element reaches the (reduced) bearing capacity. The value of this scalar can be obtained "by performing tests or by calculations and it shows the minimum period of time in which the element does not lose stability" [4]. The advanced calculation models such as SAFIR, VULCAN, FIN, THELMA and others "must fulfill certain conditions imposed by the Eurocodes and must be validated through relevant test results" [5].

The standard fire resistance tests are more significant than the real fire and they are performed using a time-temperature curve. Important fire tests results may be used such as those from the British Steel Programme, Arbed Recherches Tests and others.

2.2 Fire protection materials mentioned in this research

In the following chapters of this study the author treats several types of steel sections that are protected by different types of fire protection:

- Lightweight Concrete has insulating properties and transmits heat at a slower rate than normal weight concrete with the same thickness, and therefore generally provides increased fire resistance.
- Spray coatings – mineral fibre easily covers complex details of the structure.
- Thick spray coatings vermiculite are also often used.

3. Structural steel S355 – composition, properties and applications

The chemical composition of the structural steel is very important and it is regulated by European (and International) Standards. For example, in Table 1 below one may see the maximum percents of some elements.

Table 1: Percents of elements in the S355

	C%	Mn%	P%	S%	Si%
S355	0.23 max	1.60 max	0.05 max	0.05 max	0.05 max

The most important mechanical properties of a structural steel are the yield strength (see Table 2), and tensile strength (see Table 3).

Table 2: Yield strength of S355

Structural Steel Grade at 16mm	Minimum Yield Strength at nominal thickness 16mm
	N/mm2 (MPa)
S355	355 N/mm2

Table 3: Tensile strength of S355

Structural Steel Grade 3-16mm	Tensile Strength **MPa** at nominal thickness between 3mm and 16mm
S355	470 – 630 MPa

The application of the structural steel is mainly in construction industry. The S355 and other grades offer great strengths at reduced weight. The structures that may be constructed with S355 are, for example, high rise buildings, factories, bridges, train tracks and other.

4. Computation of structural fire resistances of several steel sections by use of SAFIR and FIN applications. Validation of SAFIR results.

In this chapter, computation of structural fire resistance is done for several steel sections for loaded/not loaded members and for protected/not protected sections. Two advanced calculation models were used: SAFIR developed by the University of Liege and FIN developed by FINE Software from Czech Republic. Both applications are installed on a computer in the Research Laboratory of the Civil Engineering Faculty in Cluj-Napoca and all the computations below were exclusively made by the author of this research. The action of fire is considered on all faces of the section, following the standard fire curve (Eq. (1)). A check of the temperature distribution inside the cross – section of the member is also done at a time equal to 10 minutes.

The results with SAFIR for a member made of a HEA300 are presented in Figures 2-3. This profile has thin flanges and web (14mm and 8.5mm, respectively). The characteristics of the section are presented in Figure 1:

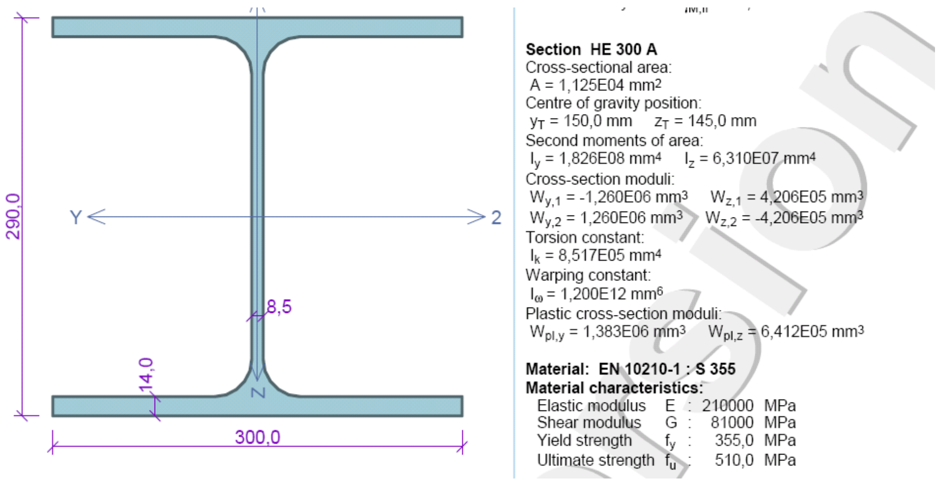


Figure 1. HEA300 section properties

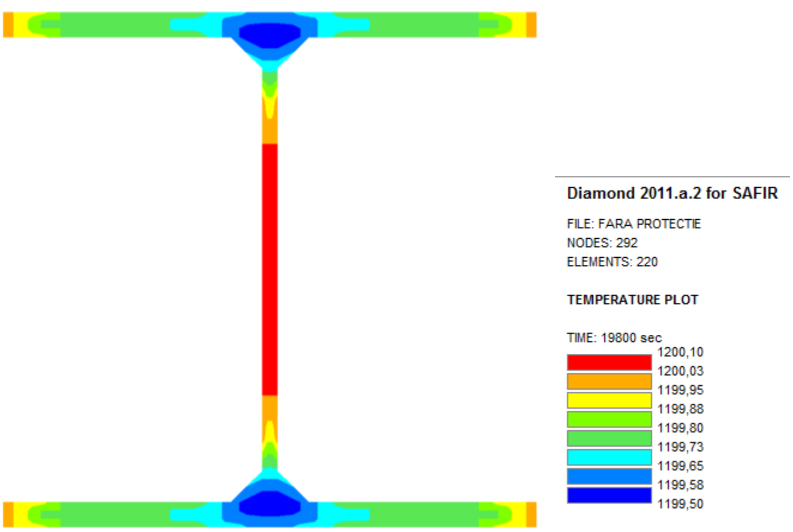


Figure 2. HEA300 not loaded, not protected;

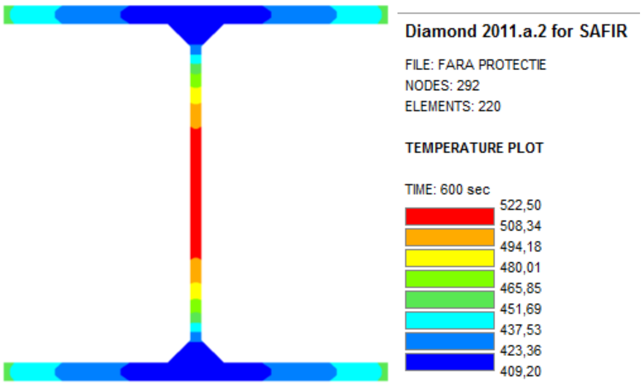


Figure 3. Temperature distribution at 10 min

It yields that the fire resistance in the case of HEA300, not loaded, not protected, using SAFIR is equal to 330 min.

The results with FIN are presented below:

Check: **PASS** **Fire resistance period: 330,2 min; Load 1.**

Decisive load: Load 1
Cross-section class: 1
Critical temperature: 1200,0°C
Fire resistance period: 330,2 min ≥ 10,0 min Pass
Check at time t = 10,0 min:
Gas temperature: 678,4°C Steel temperature: 439,6°C
Section ok

Figure 4. HEA300 not loaded, not protected;

Check: **PASS** **Fire resistance period: 19,4 min; Load 1.**

Decisive load: Load 1
Cross-section class: 1
Critical temperature: 691,5°C
Fire resistance period: 19,4 min ≥ 10,0 min Pass
Check at time t = 10,0 min:
Gas temperature: 678,4°C Steel temperature: 439,6°C
Critical comination check - tension and b. moment:
Internal forces: N = 1000,000 kN; M_y = 0,000 kNm; M_z = 0,000 kNm
Resistances: N_R = 3645,748 kN
| 0,274 + 0,000 + 0,000 | = | 0,274 | < 1 Pass
Section ok

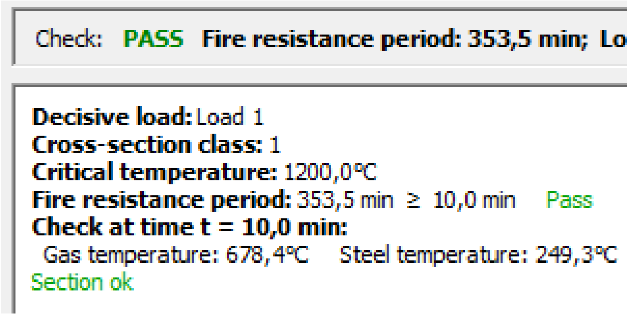
Figure 5. HEA300 not protected, tension = 1000kN

It yields that the fire resistance in the case of HEA300, not loaded, not protected, using FIN is equal to 330.2 min; when the member has an internal force of 1000kN (tension) and it is not protected, the fire resistance is 19.4 min.

In the following paragraph fire protected sections are studied using FIN:

Spray-coatings - mineral fibre : EC 3	
Special material characteristics	
Specific heat capacity	C_p = 1200,0 J/kg/K
Thermal conductivity	λ_p = 0,120 W/m/K
Type of protection	coating
Density	ρ = 300,0 kg/m3

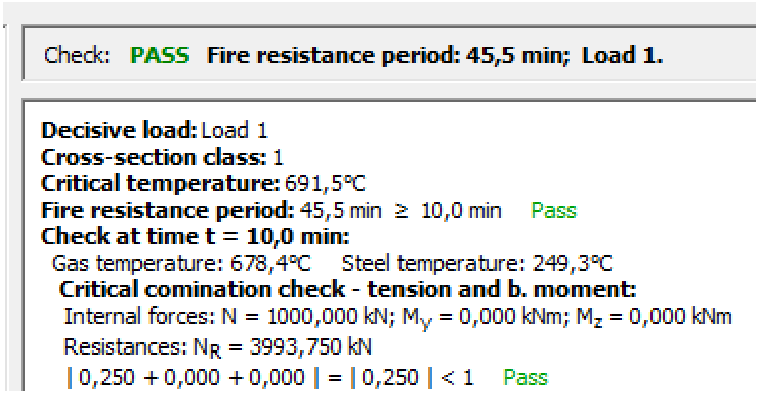
Figure 6. Summary of protection material characteristics.



Check: PASS **Fire resistance period: 353,5 min; Lo**

Decisive load: Load 1
Cross-section class: 1
Critical temperature: 1200,0°C
Fire resistance period: 353,5 min ≥ 10,0 min Pass
Check at time t = 10,0 min:
Gas temperature: 678,4°C Steel temperature: 249,3°C
Section ok

Figure 7. HEA300 protected, not loaded



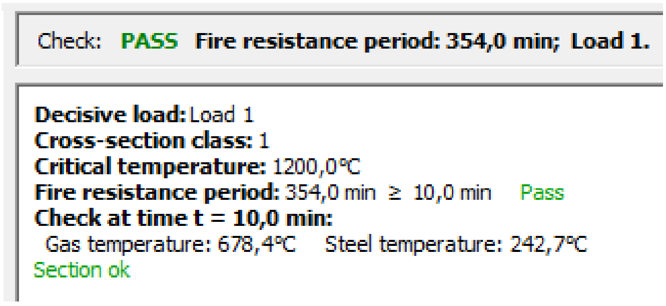
Check: PASS **Fire resistance period: 45,5 min; Load 1.**

Decisive load: Load 1
Cross-section class: 1
Critical temperature: 691,5°C
Fire resistance period: 45,5 min ≥ 10,0 min Pass
Check at time t = 10,0 min:
Gas temperature: 678,4°C Steel temperature: 249,3°C
Critical comination check - tension and b. moment:
Internal forces: N = 1000,000 kN; M_y = 0,000 kNm; M_z = 0,000 kNm
Resistances: N_R = 3993,750 kN
| 0,250 + 0,000 + 0,000 | = | 0,250 | < 1 Pass

Figure 8. HEA300 protected, tension = 1000kN

We get that the fire resistance in the case of HEA300, not loaded, protected, using FIN is equal to 353.5 min; when the member has an internal force of 1000kN (tension) and it is protected with the spray coating – mineral fibre, the fire resistance is 45.5 min.

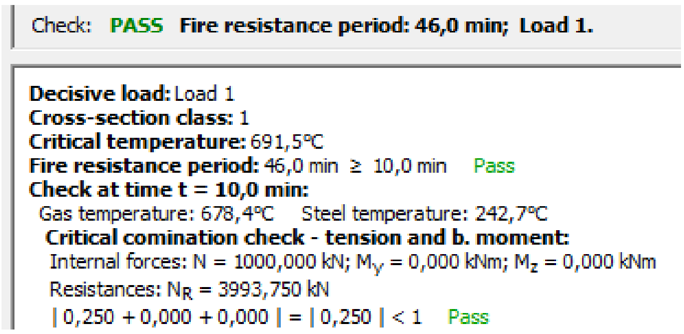
Let us use another fire protection – vermiculite thick spray coating. Here are the results:



Check: PASS **Fire resistance period: 354,0 min; Load 1.**

Decisive load: Load 1
Cross-section class: 1
Critical temperature: 1200,0°C
Fire resistance period: 354,0 min ≥ 10,0 min Pass
Check at time t = 10,0 min:
Gas temperature: 678,4°C Steel temperature: 242,7°C
Section ok

Figure 9. HEA300 protected, not loaded



Check: PASS **Fire resistance period: 46,0 min; Load 1.**

Decisive load: Load 1
Cross-section class: 1
Critical temperature: 691,5°C
Fire resistance period: 46,0 min ≥ 10,0 min Pass
Check at time t = 10,0 min:
Gas temperature: 678,4°C Steel temperature: 242,7°C
Critical comination check - tension and b. moment:
Internal forces: N = 1000,000 kN; M_y = 0,000 kNm; M_z = 0,000 kNm
Resistances: N_R = 3993,750 kN
| 0,250 + 0,000 + 0,000 | = | 0,250 | < 1 Pass

Figure 10. Protected, tension = 1000kN

Not loaded, protected by vermiculite thick spray coating, using FIN, the fire resistance is equal to 354 min; when the member has an internal force of 1000kN (tension) and it is also protected, the fire resistance is 46 min.

Another example: a structural member made of HEM180 section. This profile has thick (solid) flanges and web (24mm and 14.5mm respectively) and it has the cross-sectional area quasi – equal to that of HEA300 studied above. The properties of the section are presented in Figure 11. In figures 12-13 we have the results using SAFIR and in this case the computed fire resistance is 331 min:

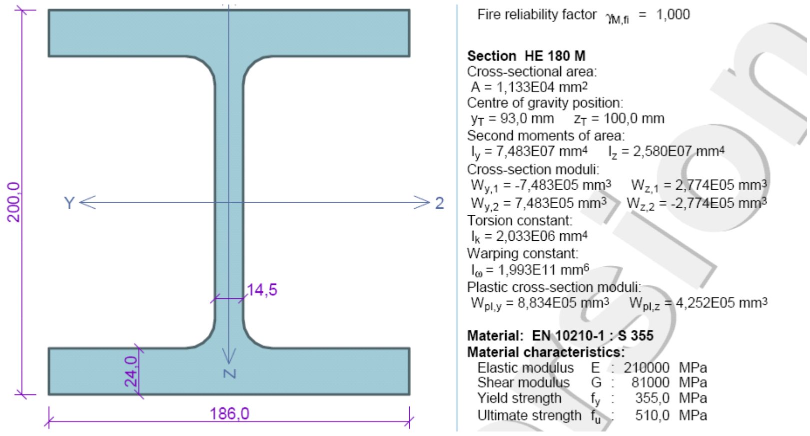


Figure 11. HEM180 section properties

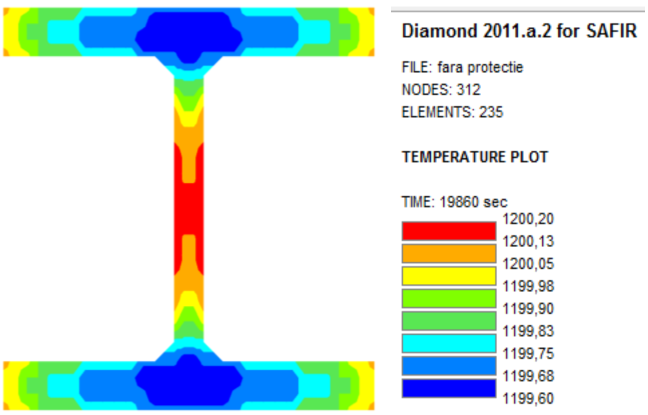


Figure 12. HEM180 not loaded, not protected;

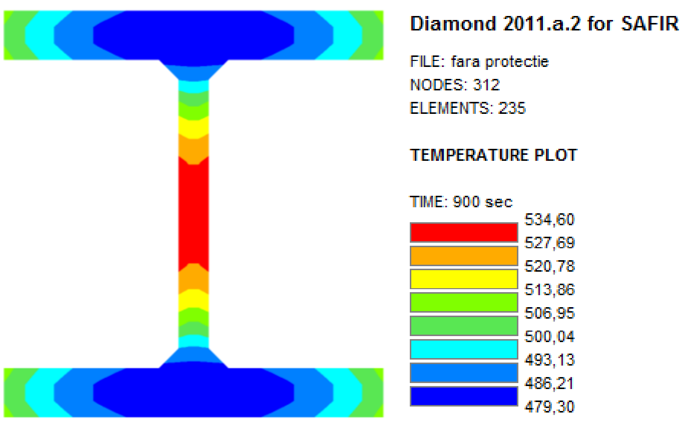


Figure 13. Temperature distribution at 15 min

The results using FIN are presented below:

Check: PASS Fire resistance period: 331,2 min; Load 1.

Decisive load: Load 1
Cross-section class: 1
Critical temperature: 1200,0°C
Fire resistance period: 331,2 min ≥ 10,0 min Pass
Check at time t = 10,0 min:
Gas temperature: 678,4°C Steel temperature: 326,1°C
Section ok

Figure 14. HEM180 not loaded, not protected;

Check: PASS Fire resistance period: 24,5 min; Load 1.

Decisive load: Load 1
Cross-section class: 1
Critical temperature: 692,2°C
Fire resistance period: 24,5 min ≥ 10,0 min Pass
Check at time t = 10,0 min:
Gas temperature: 678,4°C Steel temperature: 326,1°C
Critical comination check - tension and b. moment:
Internal forces: N = 1000,000 kN; M_y = 0,000 kNm; M_z = 0,000 kNm
Resistances: N_R = 4022,150 kN
| 0,249 + 0,000 + 0,000 | = | 0,249 | < 1 Pass

Figure 15. HEM180 not protected, tension = 1000kN

Protected with the spray coating – mineral fibre, the fire resistances are listed in figures 16-17:

Check: PASS Fire resistance period: 369,0 min; Lo

Decisive load: Load 1
Cross-section class: 1
Critical temperature: 1200,0°C
Fire resistance period: 369,0 min ≥ 10,0 min Pass
Check at time t = 10,0 min:
Gas temperature: 678,4°C Steel temperature: 181,8°C
Section ok

Figure 16. HEM180 protected, not loaded

Check: PASS Fire resistance period: 62,0 min; Load 1.

Decisive load: Load 1
Cross-section class: 1
Critical temperature: 692,2°C
Fire resistance period: 62,0 min ≥ 10,0 min Pass
Check at time t = 10,0 min:
Gas temperature: 678,4°C Steel temperature: 181,8°C
Critical comination check - tension and b. moment:
Internal forces: N = 1000,000 kN; M_y = 0,000 kNm; M_z = 0,00C
Resistances: N_R = 4022,150 kN
| 0,249 + 0,000 + 0,000 | = | 0,249 | < 1 Pass

Figure 17. HEM180 protected, tension = 1000kN

Protected with the vermiculite thick spray coating, the fire resistances are listed in figures 18-19:

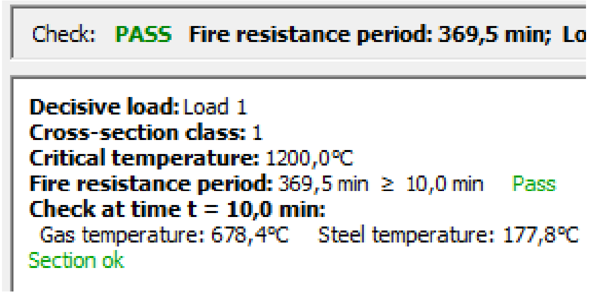


Figure 18. HEM180 protected, not loaded

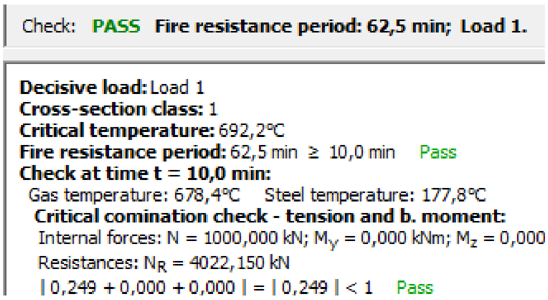
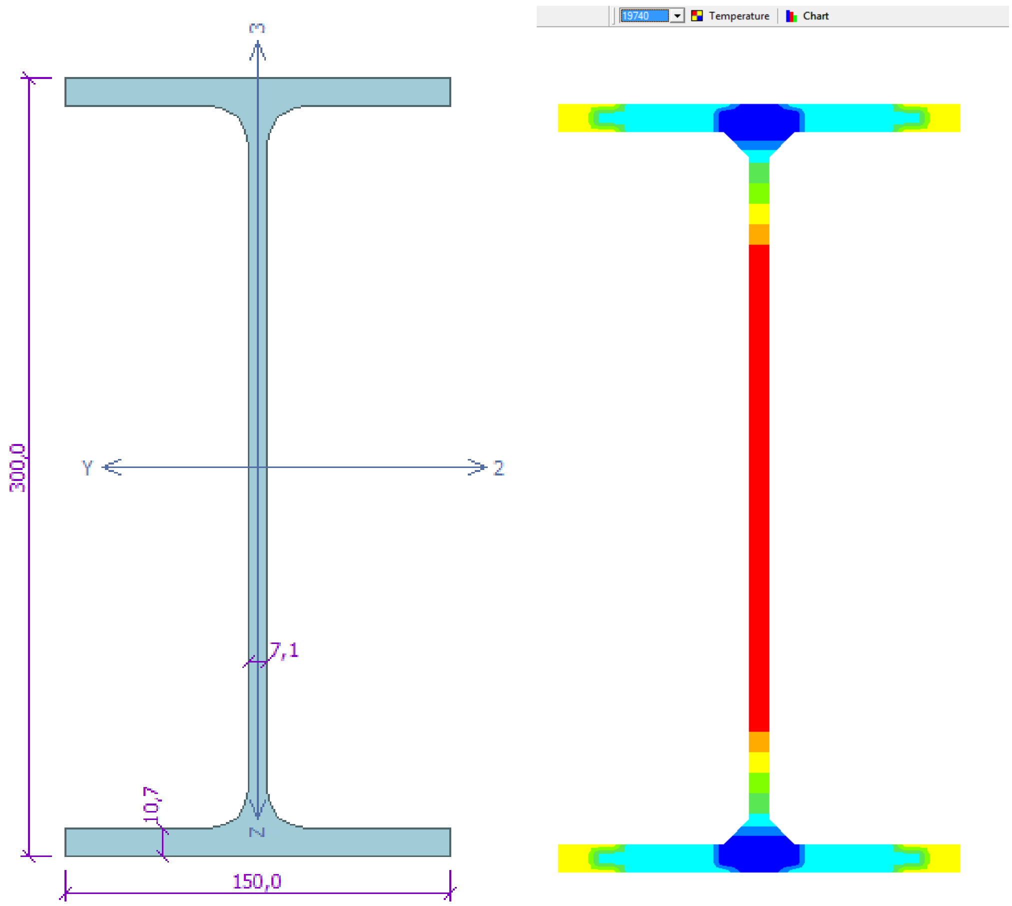
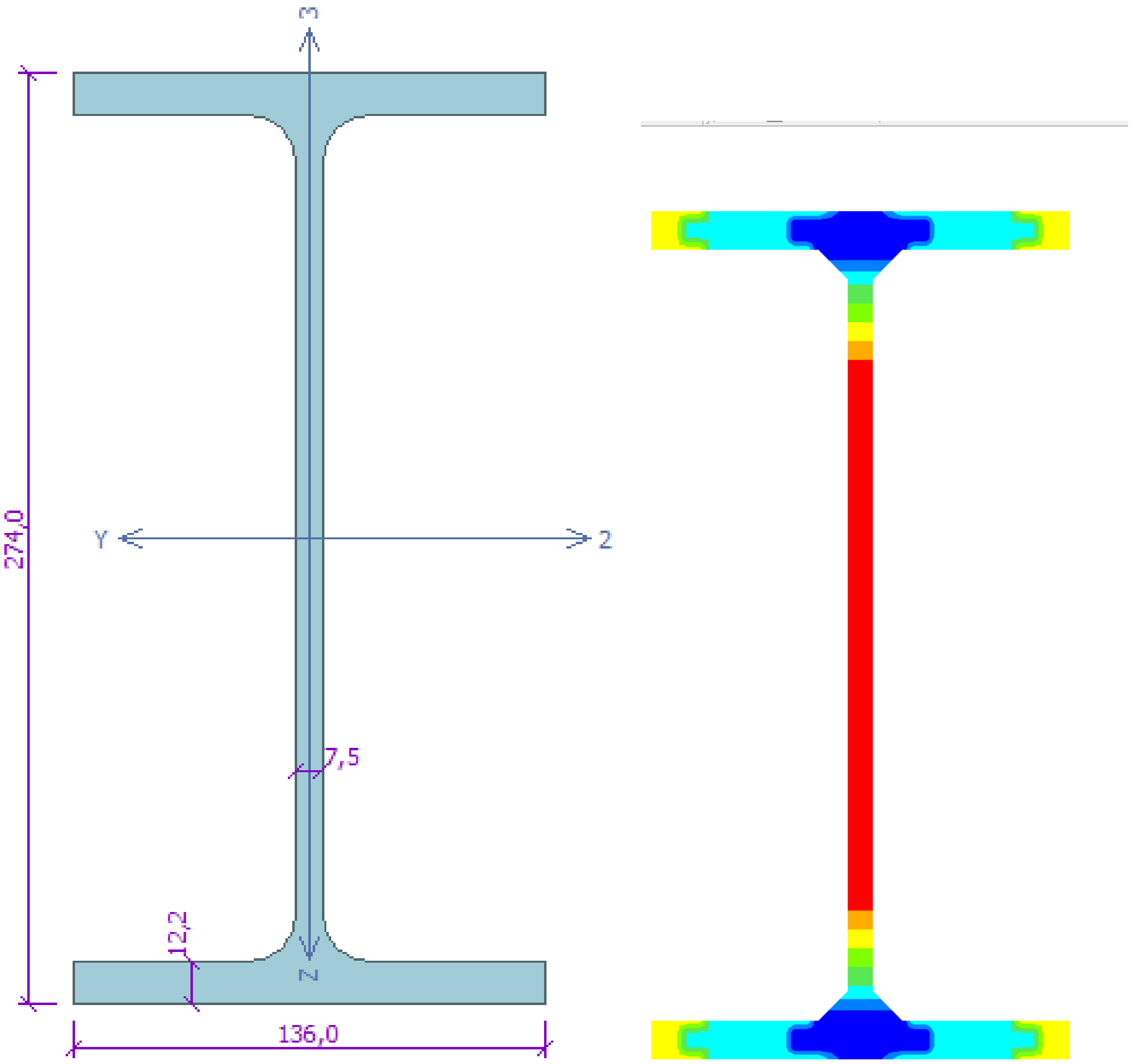


Figure 19. HEM180 protected, tension = 1000kN

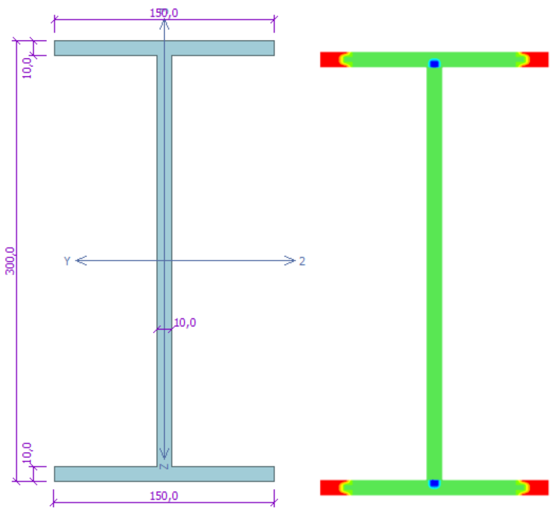
Other examples were also made during this research (See Figure 20); due to limitation of the length of the article, the author presents only the tabulated fire resistances for structural members made of IPE300, IPE O 270 and three other steel sections made up of steel plates welded together having the thickness of 10mm, 15mm, 20mm respectively. The fire resistances are listed in tables 4-5:



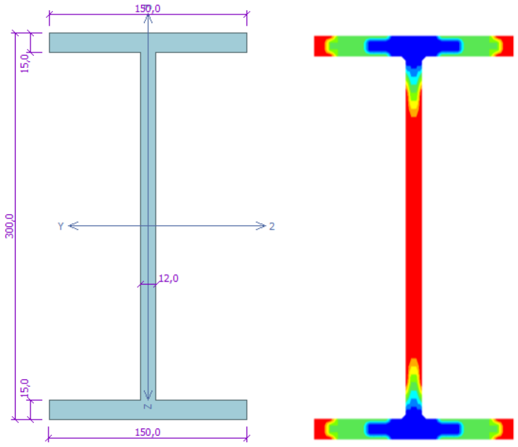
IPE300



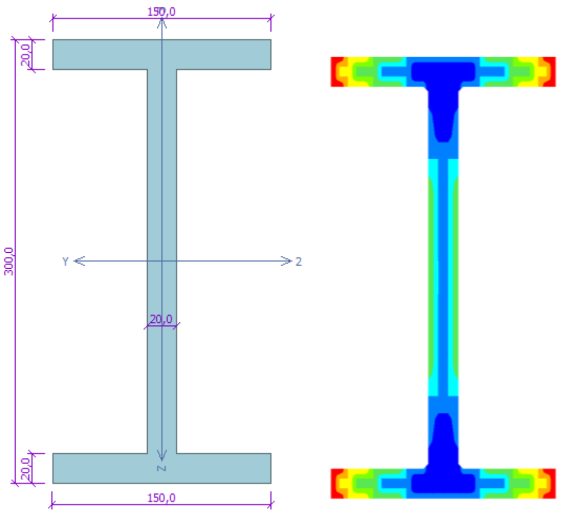
IPE270



Compound type1



Compound type2



Compound type3

Figure 20. Other examples of sections

Table 4: Comparing the fire resistances for unprotected/protected with spray coating steel sections.

SECTION	FIRE RESISTANCE (min)			
TYPE/ mm	WITHOUT PROTECTION		PROTECTED WITH SPRAY-FIBER	
	NOT LOADED	LOADED (N=1000kN)	NOT LOADED	LOADED (N=1000kN)
10	329,9	12,6	347	27,5
15	330,2	16,8	353,5	39
20	331	23,4	365,5	58,5
IPE270	330	12,4	348	27
IPE300	329,8	11,8	346	25,5
HEM180	331,2	24,5	369	62
HEA300	330,2	19,4	353,5	45,5

Table 5: Comparing the fire resistances for unprotected/protected with vermiculite thick coating.

SECTION	FIRE RESISTANCE (min)			
TYPE/ mm	WITHOUT PROTECTION		PROTECTED WITH SPRAY-FIBER	
	NOT LOADED	LOADED (N=1000kN)	NOT LOADED	LOADED (N=1000kN)
10	329,9	12,6	347,5	28
15	330,2	16,8	354	39,5
20	331	23,4	366,5	59,5
IPE270	330	12,4	348,5	27,5
IPE300	329,8	11,8	346,5	46
HEM180	331,2	24,5	369,5	62,5
HEA300	330,2	19,4	354	46

During the research another protection was applied to different members - the lightweight concrete, but the results given by FIN are not to be taken into consideration because there are no differences between the not protected and the protected surface. For all examples, similar values were obtained using the two applications developed by different organizations. The author considers that in this way the results obtained using SAFIR were validated by FIN.

5. Validation of FIN application by comparing to results obtained by manual computation of the reduced strength according to SR EN 1993

For each of the following examples solved by FIN the author takes the temperature distribution inside the section from the results provided using SAFIR and performs a manual check of the design strength according to [2] comparing it to the strength provided by FIN. "The design strength $N_{fi,t,Rd}$ at time t of a tension member with a non-uniform temperature distribution may conservatively be taken as equal to the design strength $N_{fi,\theta,Rd}$ of a tension member with a uniform steel temperature θ_a equal to the maximum steel temperature $\theta_{a,\max}$ reached at time t." [2]

For HEA300 not protected (to be compared with figure 5 in which strength is equal to 3645.748kN):

$$\left.\begin{aligned} f_y &= 355 N/mm^2 \\ A &= 11250 mm^2 \end{aligned}\right\} N_{Rd} = 355 \cdot 11250 = 3993750 N = 3993,75 kN$$

$$t = 10\min \rightarrow \theta_a = 439,6°C \rightarrow k_{y,\theta} = 0,91288$$

$$N_{fi,t,Rd} = 0,91288 \cdot 3993,75 \cdot 1 = 3645,81 kN$$

For HEM180 not protected (to be compared with figure 15 in which strength is equal to 4022.15kN):

$$\left.\begin{aligned} f_y &= 355 N/mm^2 \\ A &= 11330 mm^2 \end{aligned}\right\} N_{Rd} = 355 \cdot 11330 = 4022150 N = 4022,15 kN$$

$$t = 10\min \rightarrow \theta_a = 326,1°C \rightarrow k_{y,\theta} = 1$$

$$N_{fi,t,Rd} = 1 \cdot 4022,15 \cdot 1 = 4022,15 kN$$

For IPE300 not protected (to be compared with FIN result in which strength is equal to 1363.822kN):

$$\left.\begin{array}{l} f_y = 355N/mm^2 \\ A = 5381mm^2 \end{array}\right\} N_{Rd} = 355 \cdot 5381 = 1910255N = 1910,255kN$$

$$t = 10\min \rightarrow \theta_a = 521,3°C \rightarrow k_{y,\theta} = 0,71397$$

$$N_{fi,t,Rd} = 0,71397 \cdot 1910,255 \cdot 1 = 1363,86kN$$

For IPEO270 not protected (to be compared with FIN result in which strength is equal to 1494.547kN):

$$\left.\begin{array}{l} f_y = 355N/mm^2 \\ A = 5384mm^2 \end{array}\right\} N_{Rd} = 355 \cdot 5384 = 1911320N = 1911,320kN$$

$$t = 10\min \rightarrow \theta_a = 499,1°C \rightarrow k_{y,\theta} = 0,78198$$

$$N_{fi,t,Rd} = 0,78198 \cdot 1911,320 \cdot 1 = 1494,61kN$$

For compound section type 1 the results with FIN are presented in the below Figure.

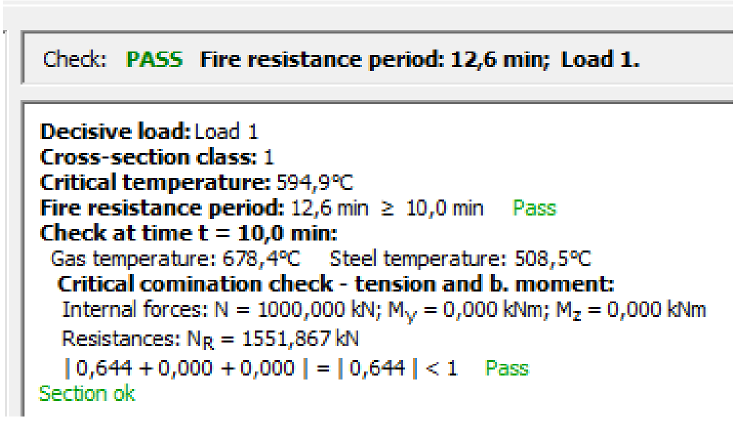


Figure 21: Compound section type 1 not protected, tension 1000kN

$$\left.\begin{array}{l} f_y = 355N/mm^2 \\ A = 5800mm^2 \end{array}\right\} N_{Rd} = 355 \cdot 5800 = 2059000N = 2059kN$$

$$t = 10\min \rightarrow \theta_a = 508,5°C \rightarrow k_{y,\theta} = 0,75365$$

$$N_{fi,t,Rd} = 0,75365 \cdot 2059 \cdot 1 = 1551,76kN$$

For compound section type 2 the results with FIN are presented in the below Figure.

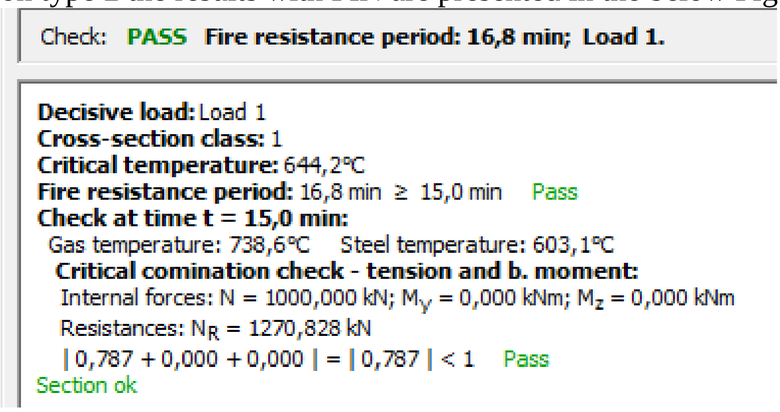


Figure 22: Compound section type 2 not protected, tension 1000kN

$$\left.\begin{aligned} f_y &= 355N/mm^2 \\ A &= 7740mm^2 \end{aligned}\right\} N_{Rd} = 355 \cdot 7740 = 2747700N = 2747,7kN$$

$$t = 15\min \rightarrow \theta_a = 603,1°C \rightarrow k_{y,\theta} = 0,46256$$

$$N_{fi,t,Rd} = 0,46256 \cdot 2747,7 \cdot 1 = 1270,97kN$$

For compound section type 3 the results with FIN are presented in the below Figure.

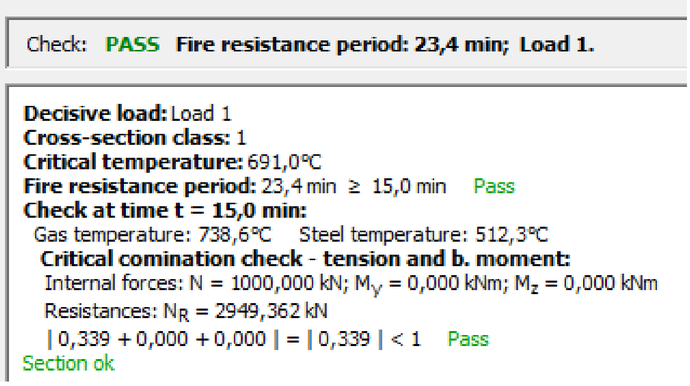


Figure 23: Compound section type 3 not protected, tension 1000kN

$$\left.\begin{aligned} f_y &= 355N/mm^2 \\ A &= 11200mm^2 \end{aligned}\right\} N_{Rd} = 355 \cdot 11200 = 3976000N = 3976kN$$

$$t = 15\min \rightarrow \theta_a = 512,3°C \rightarrow k_{y,\theta} = 0,74187$$

$$N_{fi,t,Rd} = 0,74187 \cdot 3976 \cdot 1 = 2949,47kN$$

Doing this checking, one may observe that the manual computed values were similar to those obtained using FIN. This means that we may use FIN for similar problems.

6. Conclusions

The two calculation models that were used during the research give good results for the computation of the fire resistances for loaded and not loaded steel members. The innovative approach of the study was that, for each structural member, we studied a pair of steel sections having quasi-equal area and bearing capacity. We also studied two possibilities of fire protections to use for each type of element. These evaluations give the possibility of a right choice of the cross-section and fire protection material when designing steel structures that have to resist fire for a period of time.

7. References

[1] SR EN 1991 „Actions on Structures", Part 1-2 „*Actions on Structures Exposed to Fire"* ASRO, 2006
[2] SR EN 1993 „Design of Steel Structures", Part 1-2 „*Structural Fire Design"* ASRO, 2006
[3] Milan Dj. Blagojevi * and Dušica J. Pesi, A New Curve for Temperature - Time Relationship in Compartment Fire, *Thermal Science*, **Vol. 15**, No. 2, pp. 341-349, 2011
[4] Tudor Petrina. Fire structural analysis according to European Codes, *Acta Technica Napocensis*, **Vol. 54**, No. 3, pp. 308-317, 2011
[5] D. Dubina, R. Zaharia. Verificarea rezistentei structurilor la actiunea focului prin calcul numeric, *Buletinul AGIR*, **Vol.2.**, pp. 14-22, 2011