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PARTIALLY ENCASED SECTION: STRENGTH AND STIFFNESS UNDER FIRE CONDITIONS

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ABSTRACT

Fire resistance of partially encased sections (HEB and IPE) depends on the temperature evolution during fire exposure. Eurocode 4, part 1.2 [1], proposes the assessment of the cross section using the method of the four components under fire (flanges, web, concrete and reinforcement). This study aims to assess the balanced summation model of Eurocode (informative annex G) with respect to the plastic resistance to axial compression and the effective flexural stiffness of the cross section with respect to the weak axis. New formulae will be proposed to evaluate fire resistance, based on new simple formulas to determine the flange average temperature, the residual height and average temperature of the web, the residual cross section and average temperature of concrete, the reduced stiffness and strength of reinforcement. The advance calculation method was used to validate new and safe formulae, based on the analysis of the cross section totally engulfed in fire.

Keywords: Partially Encased Sections; Fire Resistance; Simplified Calculation Methods; Advanced Calculation Methods.

1. INTRODUCTION

Partially encased section members are usually made of hot rolled steel profiles, reinforced with concrete between the flanges. The composite section is responsible for increasing the torsional and bending stiffness when compared to the same section of the steel profile. In addition to

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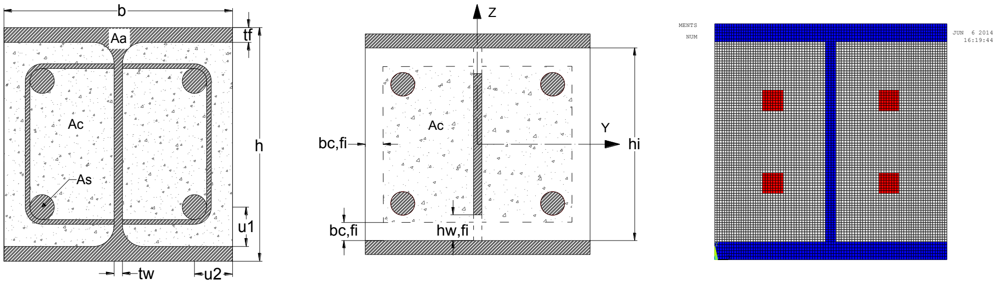
these advantages, the reinforced concrete is responsible for increasing the fire resistance. The fire resistance of partially encased sections depends on the temperature effect in each component. According to Eurocode 4, Part 1.2 [1], the fire resistance can be evaluated by the four components method (the flanges of steel profile, the web of steel profile, concrete and reinforcement) when submitted to standard fire and for different fire resistance classes (R30, R60, R90 and R120). This study aims to assess the parameters of Annex G: average temperature of the flange, part of the web to be neglected, residual area and average temperature of the concrete and reducing reinforcement characteristics. To study the effect of fire, two types of cross section were selected, corresponding to set of cross section geometry: IPE range from 200 to 500 and HEB range from 160 to 500. Figure 1 represents the generic partially encased section, identifying the four components and showing the finite element mesh used. The nonlinear solution method (ANSYS) was used to evaluate the temperature field. The finite element method requires the solution of Eq. 1 in the cross section domain and Eq. 2 in the boundary. In these equations: T represents the temperature of each material; ρ defines specific mass; $C_{p(T)}$ defines the specific heat; $\lambda_{(T)}$ defines the thermal conductivity; α_c specifies the convection coefficient; T_g represents the gas temperature of the fire compartment; Φ specifies the view factor; ε_m represents the emissivity of each material; ε_f specifies the emissivity of the fire; σ specifies the Stefan-Boltzmann constant. It is assumed the use of standard fire curve ISO834 [2] around the cross section (4 exposed sides).

$$\nabla\cdot(\lambda_{(T)}\cdot\nabla T)=\rho_{(T)}\cdot C_{p(T)}\cdot\partial T/\partial t \qquad (\Omega) \tag{1}$$

$$(\lambda_{(T)}\cdot\nabla T)\cdot\vec{n}=\alpha_c(T_g-T)+\Phi\cdot\varepsilon_m\varepsilon_f\cdot\sigma\cdot(T_g^4-T^4) \qquad (\partial\Omega) \tag{2}$$



a) b) c)

Figure 1: Partially encased section: Model, parameters and approximation.

2. PARTIALLY ENCASED SECTIONS

The cross sections were designed according to the tabulated method applied to column design in fire conditions [1], considering the minimum reinforcement ratio $A_s/(A_s+A_c)$, the minimum concrete cover dimensions (u) and the minimum cross section dimensions (b , h).Table 1 presents the main dimensions, in particular the number of reinforcing bars, the diameter of each rebar Φ and the concrete cover dimensions in both principal directions, u_1, u_2 .

Table 1- Section properties.

Profile	Reinforcing bars	h_i [mm]	Φ [mm]	A_s [mm^2]	A_c [mm^2]	u_1 [mm]	u_2 [mm]	u [mm]	$\frac{A_s}{A_s + A_c}$	$\frac{t_w}{t_f}$	A_m/V [m^{-1}]
HEB160	4	134.0	12	452	19916	40	40	40	2,22	0,62	25.00
HEB180	4	152.0	12	452	25616	40	40	40	1,74	0,61	22.22
HEB200	4	170.0	20	1257	31213	50	50	50	3,87	0,60	20.00
HEB220	4	188.0	25	1963	37611	50	50	50	4,96	0,59	18.18
HEB240	4	206.0	25	1963	45417	50	50	50	4,14	0,59	16.67
HEB260	4	225.0	32	3217	53033	50	50	50	5,72	0,57	15.38
HEB280	4	244.0	32	3217	62541	50	50	50	4,89	0,58	14.29
HEB300	4	262.0	32	3217	72501	50	50	50	4,25	0,58	13.33
HEB320	4	279.0	32	3217	77275	50	50	50	4,00	0,56	12.92
HEB340	4	297.0	40	5027	80509	50	50	50	5,88	0,56	12.55
HEB360	4	315.0	40	5027	85536	50	50	50	5,55	0,56	12.22
HEB400	4	352.0	40	5027	95821	70	50	59	4,98	0,56	11.67
HEB450	4	398.0	40	5027	108801	70	50	59	4,42	0,54	11.11
HEB500	4	444.0	40	5027	121735	70	50	59	3,97	0,52	10.67
IPE200	4	183.0	12	452	16823	50	40	45	2,62	0,66	30.00
IPE220	4	201.6	20	1257	19730	50	40	45	5,99	0,64	27.27
IPE240	4	220.4	20	1257	23825	50	40	45	5,01	0,63	25.00
IPE270	4	249.6	25	1963	30085	50	40	45	6,13	0,65	22.22
IPE300	4	278.6	25	1963	37848	50	40	45	4,93	0,66	20.00
IPE330	4	307.0	25	1963	44854	50	40	45	4,19	0,65	18.56
IPE360	4	334.6	32	3217	50988	50	40	45	5,93	0,63	17.32
IPE400	4	373.0	32	3217	60715	70	40	53	5,03	0,64	16.11
IPE450	4	420.8	32	3217	72779	70	40	53	4,23	0,64	14.97
IPE500	4	468.0	40	5027	83800	70	50	59	5,66	0,64	14.00

3. BALANCED SUMMATION METHOD

Eurocode 4 of 1.2 [1] enables the calculation of the effective flexural stiffness of the cross section around the weak axis $(EI)_{fi,eff,z}$ and the plastic resistance to axial compression $N_{fi,pl,Rd}$, considering the contribution of the four components, assuming the section exposed to standard fire by four sides. Each component should be assessed by temperature evolution in each component, affecting the resistance of the cross section. The design values may be obtained by the balanced summation method, according to Eq. 3.

$$\begin{gathered} N_{fi,pl,Rd} = N_{fi,pl,Rd,f} + N_{fi,pl,Rd,w} + N_{fi,pl,Rd,c} + N_{fi,pl,Rd,s} \\ (EI)_{fi,eff,z} = \varphi_{f,\theta}(EI)_{fi,f,z} + \varphi_{w,\theta}(EI)_{fi,w,z} + \varphi_{c,\theta}(EI)_{fi,c,z} + \varphi_{s,\theta}(EI)_{fi,s,z} \end{gathered} \tag{3}$$

The contribution of each component depends on the temperature effect. The average temperature of the flange, $\theta_{f,t}$ may be approximated by Eq. 4, assuming the empirical coefficients k_t and the reference value $\theta_{0,t}$ [1].

$$\theta_{f,t} = \theta_{0,t} + k_t(A_m/V) \tag{4}$$

The effect of fire affects the resistance of the web, by heat conduction. The reduction of the height of the web, $h_{w,fi}$, part to be neglected in fire design, may be calculated according to Eq. 5. The parameter H_t is also defined accordingly [1].

$$h_{w,fi} = 0.5(h - 2t_f)(1 - \sqrt{1 - 0.16(H_t/h)}) \tag{5}$$

The direct effect of the fire on both sides of the section and the indirect effect by heat conduction allow to specify the 500 ºC isothermal limit to bearing capacity of concrete, defining the extension of concrete to be neglected, $b_{c,fi}$ in both principal directions (y,z). The thickness reduction of concrete should be calculated according to table 2. The average temperature in concrete $\theta_{c,t}$ may also be calculated [1].

Table 2 - Thickness reduction of the concrete.

Standard fire resistance	$b_{c,fi}$[mm]
R30	4.0
R60	15.0
R90	0.5(Am/V)+22.5
R120	2.0(Am/V)+24.0

The temperature effect in steel reinforcement considers the reduction of the elastic modulus and yield stress. Both reduction factors are determined according to standard fire resistance and the average value of the concrete cover dimensions, u , see Eqs. 6-8 and table 3.

$$u = \sqrt{u_1 \cdot u_2} \tag{6}$$

$$u = \sqrt{u_2 \cdot (u_2 + 10)} \quad ,(u_1 - u_2) > 10\,[mm] \tag{7}$$

$$u = \sqrt{u_1 \cdot (u_1 + 10)} \quad ,(u_2 - u_1) > 10\,[mm] \tag{8}$$

Table 3 – Reduction factors $k_{y,t}$ and $k_{E,t}$ for reinforcement.

	$k_{y,t}$	$k_{y,t}$	$k_{y,t}$	$k_{y,t}$	$k_{E,t}$	$k_{E,t}$	$k_{E,t}$	$k_{E,t}$
u [mm]	R30	R60	R90	R120	R30	R60	R90	R120
40	1,000	0,789	0,314	0,170	0,830	0,604	0,193	0,110
45	1,000	0,883	0,434	0,223	0,865	0,647	0,283	0,128
50	1,000	0,976	0,572	0,288	0,888	0,689	0,406	0,173
55	1,000	1,000	0,696	0,367	0,914	0,729	0,522	0,233
60	1,000	1,000	0,822	0,436	0,935	0,763	0,619	0,285

4. ADVANCED CALCULATION METHOD

The temperature field in the cross section was determined by the finite element method (ANSYS). The plane element "PLANE55" was selected to perform a nonlinear transient thermal analysis. This element uses linear interpolation functions and 4 integration points to determine the conductivity matrix, see Figure 2. The model used 4, 6 and 8 elements in the web thickness, flange thickness and in both directions of reinforcement, respectively. Perfect contact between materials or components was considered. Standard fire boundary conditions were applied in the exposed surface, according to EN1991-1-2 [3]. Material properties were defined according to the corresponding Eurocodes for each material [4-5].

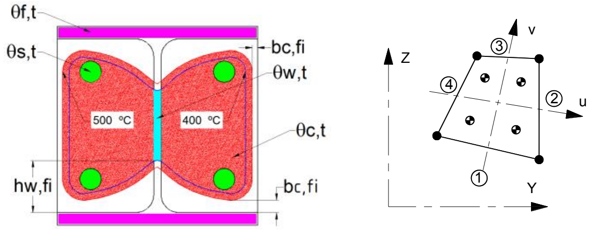


Figure 2 – Criteria and Finite element “PLANE55”.

The advanced calculation method used the following criteria to define the effect of fire in each component: The temperature of the flange, $\theta_{f,t}$ was determined by the arithmetic average of nodal temperature. The reduction of the web height, $h_{w,fi}$ was determined according to the 400 °C isothermal [6]. The residual cross section of concrete depends on the extension of concrete to be neglected, $b_{c,fi}$, being determined according to the 500 °C isothermal [5], while the temperature effect on steel reinforcement was calculated by the arithmetic average temperature of this component.

5. COMPARISON AND NEW FORMULAE

The effect of fire was determined for each component of 24 cross sections. Figure 3 represents the average temperature of the flange, depending on the section factor and on the standard fire resistance class. Each graph depicts the results of the simplified calculation method (EN1994-1-2), the results of the advanced calculation method (ANSYS) and the results of the new formulae (New proposal). Eurocode 4 Part 1.2 [1] presents conservative values for some sections factors and unsafe values to others. The average temperature of the flange of HEB and IPE sections is safe for standard fire R30, partially safe for R60 and unsafe for the remaining classes.

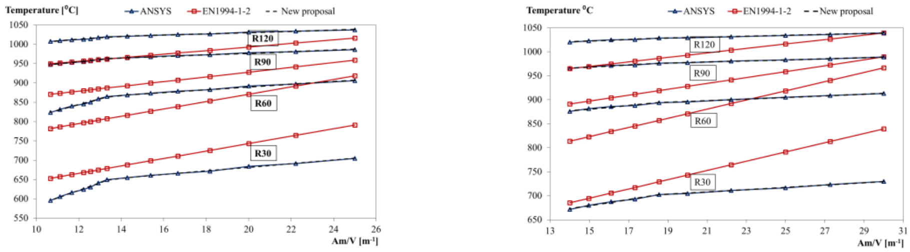


Figure 3 – Average temperature of the flange. HEB sections (left). IPE Sections (right).

The new proposal is based on the same formulae of Eurocode 4 (Eq. 4), but using a bilinear approximation for temperature, using a new empirical coefficient k_t and a new reference value $\theta_{0,t}$, see table 4.

Table 4 – Parameters to determine flange temperature (Section HEB and IPE).

Sections	10<Am/V<14		14<=Am/V<25		10<Am/V<19		19<=Am/V<30	
Standard	HEB		HEB		IPE		IPE	
Fire	$\theta_{0,t}$ [^{0}C]	k_t [m^{0}C]	$\theta_{0,t}$ [^{0}C]	k_t [m^{0}C]	$\theta_{0,t}$ [^{0}C]	k_t [m^{0}C]	$\theta_{0,t}$ [^{0}C]	k_t [m^{0}C]
R30	387	19,55	588	4,69	582	6,45	656	2,45
R60	665	14,93	819	3,54	824	3,75	862	1,72
R90	887	5,67	936	2,04	935	2,20	956	1,09
R120	961	4,29	998	1,62	997	1,68	1010	0,96

The effect of fire on the web of the cross section was determined by the 400 °C isothermal criterion. This procedure defines the affected zone of the web and predict the web reduction height, see Figure 4. The numerical results demonstrate a strong dependence on the section factor, regardless of the fire resistance class, unlike the simplified method of EN1994-1-2. The results of EN1994-1-2 are unsafe for all fire resistance classes and for all section factors. The new proposal presents a parametric expression that depends on section factor and standard fire resistance class, Eqs. (9-10). Both equations have the application limits defined in table 5.

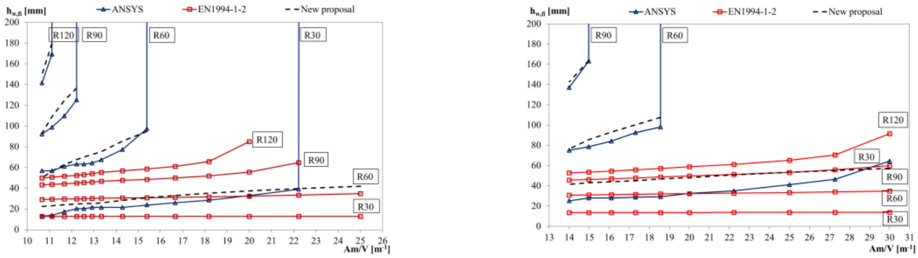


Figure 4 – Web height reduction. HEB sections (left). IPE Sections (right).

$$2h_{w,fi} / h_i \times 100 = 0.0035 \times t^2 \times (A_m/V) - 0.03 \times t^{2.02} + (A_m/V)/2 \quad ,(HEB) \qquad (9)$$

$$2h_{w,fi} / h_i \times 100 = 0.002 \times t^2 \times (A_m/V) - 0.03 \times t^{1.933} + (A_m/V) \quad ,(IPE) \qquad (10)$$

Table 5 – Application limits for HEB and IPE cross sections.

Standard fire resistance	Section factor (HEB)	Section factor (IPE)
R30	Am/V <22.22	Am/V <30.00
R60	Am/V <15.38	Am/V <18.56
R90	Am/V <12.22	Am/V <14.97
R120	Am/V <11.11	-

The arithmetic average temperature $\theta_{w,t}$ of the effective web section was defined by the nodes under the limiting condition and plotted in Figure 5 (ANSYS). Temperature results of EN1994-1-2 were determined by the inverse method, using the reduction factor of the yielding stress $\sqrt{1-0.16(H_t/h)}$. The new proposal was adjusted to numerical results.

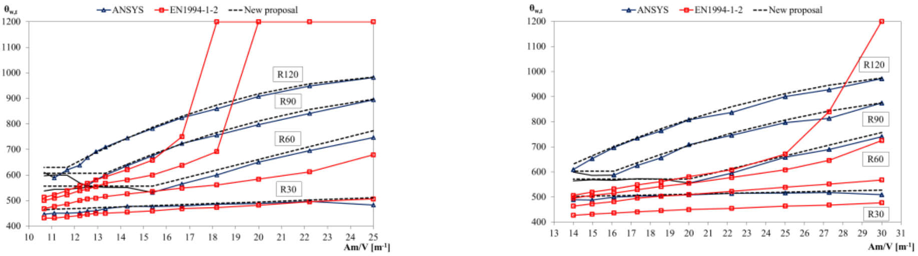


Figure 5 – Average web temperature. HEB sections (left). IPE Sections (right).

The numerical result of the third component was determined by the 500 ºC isothermal. The external layer of concrete to be neglected was measured in both principal directions, defining $b_{c,fi,vertical}$ and $b_{c,fi,horizontal}$. According to EN1994-1-2 [1], the thickness of concrete to be neglected depends on section factor for standard fire resistance of R90 and R120. The numerical results demonstrates a strong dependence on section factors for all standard fire resistance classes. Figure 6 presents the new proposal for $b_{c,fi,vertical}$ and $b_{c,fi,horizontal}$ for HEB sections. Similar results were obtained to IPE sections. Tables 6-7 provide the new formulae to determine the thickness of concrete to be neglected in fire design.

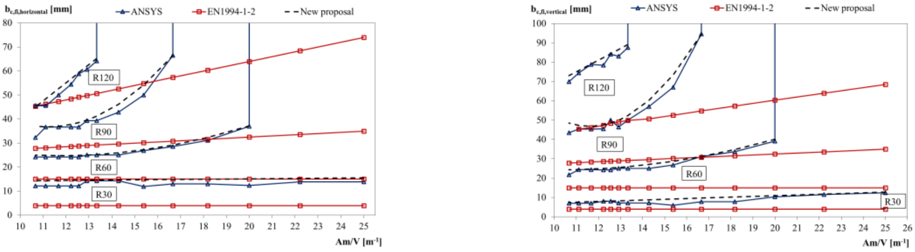


Figure 6 – Thickness reduction of the concrete area for HEB sections.

Table 6 - Thickness reduction of the concrete in sections HEB.

$$b_{c,fi} = a \times (A_m/V)^2 + b \times (A_m/V) + c$$

	$b_{c,fi,horizontal}$			$b_{c,fi,vertical}$			
Standard Fire	a	b	c	a	b	c	Section factor
R30	0,0000	0,0809	13,5	0,000	0,372	3,5	10<=Am/V<=25
R60	0,1825	-4,2903	50,0	0,1624	-3,2923	41,0	10<=Am/V<=20
R90	1,0052	-22,575	163,5	1,8649	-43,287	298,0	10<=Am/V<=17
R120	0,0000	7,5529	-35,5	0,000	6,0049	9,0	10<=Am/V<=13

Table 7 - Thickness reduction of the concrete in sections IPE.

$$b_{c,fi} = a \times (A_m/V)^2 + b \times (A_m/V) + c$$

	$b_{c,fi,horizontal}$			$b_{c,fi,vertical}$			
Standard Fire	a	b	c	a	b	c	Section factor
R30	0,0000	0,2206	10,5	0,0000	0,9383	-3,0	14<=Am/V<=30
R60	0,2984	-8,8924	93,0	0,5888	-15,116	135,0	14<=Am/V<=22
R90	1,3897	-38,972	313,0	2,0403	-50,693	393,0	14<=Am/V<=17
R120	0,0000	18,283	-199,0	0,0000	48,59	-537,0	14<=Am/V<=15

The average temperature of the residual concrete section is represented in Figure 7. The new proposal introduces a parametric approximation, based on the standard fire resistance and section factor, Eqs. 11-12.

$$\theta_{c,t} = +3.1 \times t^{0.5} \times (A_m/V) + 0.003 \times t^{1.95} \quad ,(HEB) \qquad (11)$$

$$\theta_{c,t} = +2.67 \times t^{0.5} \times (A_m/V) + 3.4 \times t^{0.61} \quad ,(IPE) \qquad (12)$$

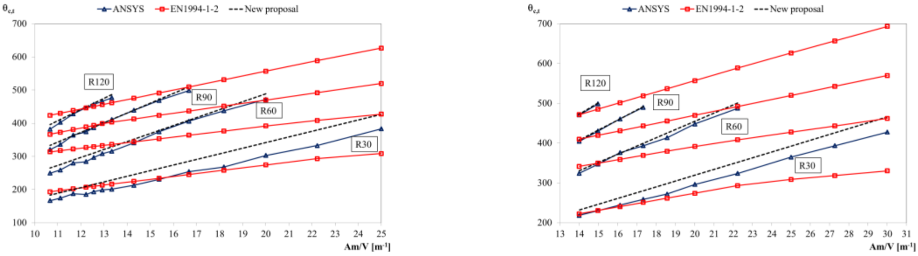


Figure 7**-** Average temperature of residual concrete. HEB sections (left). IPE Sections (right).

Figure 8 depicts the average temperature of rebars determined by the numerical results. The results of EN1994-1-2 were indirectly determined through the most critical reduction factor. Alternatively, the new parametric formula is presented for the calculation of the average temperature of rebars. Eqs. 13-14 were developed to the new proposal.

$$\theta_{s,t} = 0.1 \times t^{1.1} \times (A_m/V) + 7.5 \times t - 0.1 \times t^{1.765} - 8 \times u + 390 \quad ,(HEB) \tag{13}$$

$$\theta_{s,t} = 14.0 \times (A_m/V) + 11.0 \times t - 0.1 \times t^{1.795} - 8 \times u + 115 \quad ,(IPE) \tag{14}$$

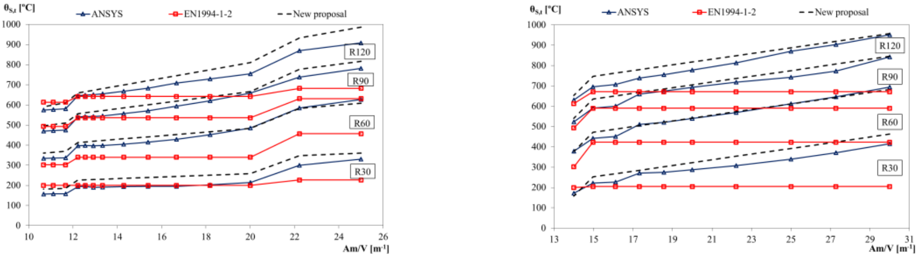


Figure 8 – Average temperature of rebars. HEB sections (left). IPE Sections (right).

5. FIRE RESISTANCE ACCORDING TO NEW PROPOSAL

Figures 9-10 present the margin of safety of the new proposal for the plastic resistance to axial compression and the effective flexural stiffness around the weak axis.

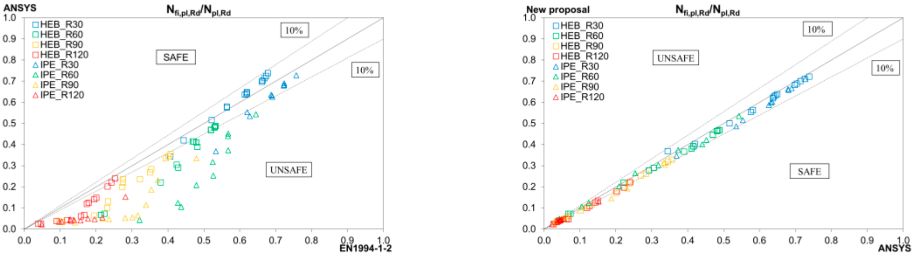


Figure 9 – Comparison results for plastic resistance to axial compression.

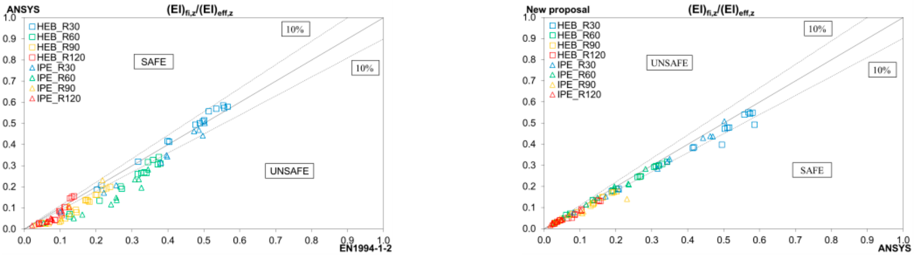


Figure 10 – Comparison results for the effective flexural stiffness around the weak axis.

6. CONCLUSIONS

The simplified method proposed in Annex EN1994-1-2 G is unsafe for certain classes of fire resistance compared to numerical results. This paper presented new formulae, with safety guarantee to the calculation of plastic resistance to axial compression and effective flexural stiffness of the cross-section in fire conditions.

7. REFERENCES

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