



RESEARCH AND ADVANCED TECHNOLOGY IN FIRE SAFETY



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RESEARCH AND ADVANCED
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IN FIRE SAFETY



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RESEARCH AND ADVANCED TECHNOLOGY IN FIRE SAFETY

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Contents

	<u>Page</u>
Contents.....	i
Preface.....	iii
Método de cálculo para soportes de instalaciones frente a la acción del fuego en túneles	1
Numerical Analyses of Pore Pressure Rise and Thermal Stress in Concrete Cylinders of Various Strengths during Fire Exposure.....	21
An Experimental study on the Influence of compressive strength and water content of concrete on the occurrence of explosive spalling	39
Performance in Fire of FRP-Reinforced Concrete Systems	55
Modelling Human Behaviour in Escape and Evacuation Simulation.....	69
Taking into account groups for evacuation analysis.....	85
Objective indices to evaluate Fire-fighter’s Cardiorespiratory State Based on Frequency Analysis of Heart Rate	101
Framework for an integrated simulation system for Wildland-Urban Interface fire evacuation	119
A Roadmap of WUI Fires Research Requirements: A Canadian Perspective.....	135
Effect of air flow on the spread of forward and opposed smouldering combustion in biomass	147
Emissions and Health Effects of Haze from Peat Fires	159
Flame Spread Along Fences Near a Structure in a Wind Field.....	173
A Study on Thermal Sensitivity of Sprinkler Heads for Residential Buildings	189
An Analytical Hydraulic Model for Clean Agent Discharge	201
Assessment of the predictive capabilities different modelling tools to forecast fire effects in residential compartments	217
Strategies for Fire-Fighting Under-Ventilated Fires.....	235

Fire Performance of a Full-Scale Loaded Cold-Formed Steel Framed Assembly in a Large Scale Furnace Test.....	255
Balanced Summation model for the calculation of the buckling resistance of partially encased columns under fire: New improvements.....	271
Performance Fire of Composite Columns Made from High and Normal Strength Concrete: influence of thermal and mechanical parameters	289
The possible role of fire in the sinking of the Titanic - structural response of a steel bulkhead subjected to localised heating.....	305
Prediction model for compartment effects on burning upholstered furniture.....	315
Reaction-to-Fire Behaviour of Partial Quantities of Timber Surface Linings in Compartments	331
Effects of boundary conditions variation on chemical reactions during STA measurements	347
Revisión del modelado y simulación para la predicción de explosiones en incendios de espacios confinados	359
On the operation of longitudinal ventilation systems in tunnels	375
<i>POSTER SESSION</i>	393

P r e f a c e

These proceedings include papers presented at the International Conference on “Research and Advanced Technology in Fire Safety” FireSafety 2017 which took place at University of Cantabria, Santander, Spain on October 20th-21st, 2017. During last decade, our research group organized several on-day events and, in this sense, the success of this conference is a tribute for that continued effort to exchange knowledge on this discipline.

We are very proud to have been able to attract experts from all parts of the world, which some of them could also attend the Fall meeting of subcommittees 1, 3 and 4 of ISO TC92 Fire Safety hosted at University of Cantabria. This congress represented such an excellent “agora” for researchers and engineers to present and discuss new and innovative approaches. In addition, this event was a unique opportunity for Spanish-speaker scientific and technological community to receive them from top references. The need for expertise in this field is also increasing in this geographical context and I feel confident we were offering a leading forum for engineers, regulators and other stakeholders.

The papers selected by our Scientific Committee Board is a testament to the calibre of the research that is on-going around the world. Unfortunately, we could not accept all the papers submitted for oral sessions although we had a strong poster session to tackle interesting emerging research. Moreover, two Invited Lectures about “PANIC IN FIRE EMERGENCIAS: MYTH OR REALITY?” and “TRAVELLING FIRES FOR STRUCTURAL DESIGN” were given by Prof. Dr. Daniel Nilsson, Lund University (Sweden) and Prof. Dr. Guillermo Rein, Imperial College (UK) respectively.

We express a special recognition to the Scientific Committee Members for the evaluation and selection of the papers for the International Conference. The Scientific Advisory Board were integrated by the out-standing Professors and Researches, Dr. Orlando Abreu (University of Cantabria, SPA), Dr. Alain Alonso (University of Cantabria, SPA), Dr. Daniel Alvear (University of Cantabria, SPA), Dr. Vytenis Babrauskas (Fire Science and Technology Inc., USA), Dr. Luke Bisby (University of Edinburgh, UK), Dr. Jorge A. Capote (University of Cantabria, SPA), Dr. Ricky Carvel (University of Edinburgh, UK), Dr. Marcos Chaos (Lawrence Livermore National Laboratory, USA), Dr. Wan-Ki Chow (Hong Kong Polytechnic University, CHN), Dr. Arturo Cuesta (University of Cantabria, SPA), Dr. Michael Delichatsios (University of Ulster, UK), Dr. Bogdan Dlugogorski (Murdoch University, AUS), Dr. Sergey Dorofeev (FM Global, USA), Dr. Dougal Drysdale (University of Edinburgh, UK), Dr. Rita F. Fahy (NFPA, USA), Dr. Carlos Fernández-Pello (University of California, Berkeley, USA), Dr. Charles M. Fleischmann (University of Canterbury, NZL), Dr. Pedro L. García (National Distance Education University, SPA), Dr. Steve Gwynne (NRC, Canada), Dr. George Hadjisophocleous (University of Carleton, CAN), Dr. Yuji Hasemi (Waseda University, JPN), Dr. Juan Hidalgo (Queensland University, AUS), Dr. Wolfram Jahn (Pontificia Universidad Católica de Chile, CHL), Mr. Chris Jelenewicz (SFPE, USA), Dr. Christopher W. Lautenberger (Reax Engineering, USA), Dr. David Lázaro (University of Cantabria, SPA), Dr. Mariano Lázaro (University of Cantabria, SPA), Dr. Amable Liñán (Polytechnic University of Madrid, ESP), Dr. Andre Marshall (University of Maryland, USA), Dr. Brian Meacham (Worcester Polytechnic Institute, USA), Dr. Bart Merci (Gent University, BE), Dr. Frederick W. Mowrer (California Polytechnic State University, USA), Dr. Daniel Nilsson (Lund University, SWE), Dr. Paulo Piloto (Institute Polytechnic of Bragança, PRT), Dr. David Purser (Hartford Environmental Research, UK), Dr. James G. Quintiere

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We want to express our gratitude to the authors and speakers who have dedicated their time and effort in presenting their experiences, methodologies and scientist - technical advances in the International Conference.

Finally, I would like to thank our event partners and collaborators (Government of Cantabria, City of Santander, University of Cantabria, Simulsoft- Mass Motion, Grupo KOMTES, NTCI, and NEFTAL) for their cooperation and help.



Prof. Daniel Alvear
Congress Chairman
GIDAI – Fire Safety – Research and Technology
Universidad de Cantabria

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Balanced Summation model for the calculation of the buckling resistance of partially encased columns under fire: New improvements

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ABSTRACT

The fire resistance of partially encased columns (HEB and IPE) depends on the temperature evolution under fire. This paper aims to assess the effect of the balanced summation model into the design of the axial buckling load of partially encased columns under fire, according to EN 1994-1-2. New improvements will be proposed to evaluate the fire resistance, based on new simple formulas to determine the flange temperature, the residual height and temperature of the web, the residual cross section and temperature of concrete, the reduced stiffness and strength of reinforcement. The new proposal is based on the validation of a numerical simulation using ANSYS.

1 INTRODUCTION

Partially encased columns (PEC) are normally made of hot rolled steel profiles, reinforced with concrete between the flanges. The composite section is responsible to increase the torsional and bending stiffness without increasing the section dimension, when compared to the same section of steel profile, being the concrete portion very significant to increase the fire resistance. Since the thermal conductivity of concrete is relatively small, the temperature field in the composite cross section is highly non-uniform. There is no simplified method available to the heat transfer analysis, therefore the numerical simulation is required to analyse the fire effect.

In this study, the simplified method was used to calculate the buckling resistance of PEC. This method was applied following the guidelines of annex G of EN1994-1-2 [1], as well as the guidelines of the new proposal [2]. In addition to these two methods, new simulations were carried out in order to obtain new results, expanding the study, seeking to compare, evaluate and validate the new proposal, and if necessary propose an improvement in some of its formulations. For this study, two types of cross section were selected to verify the effect of fire: HEB ranging from 160 to 500 and IPE ranging from 200 to 500, totalling 24 profiles. The cross sections were tested under the standard fire curve determined by ISO834 [3], for different fire resistance classes (R30, R60, R90, R120). The buckling load has been calculated for columns with heights of 3m and 5m, with three different boundary conditions (pinned end

at extremities, fixed ends at extremities and mixed at extremities). The effective length of the column L_{θ} for the ultimate limit state may be different from that considered at room temperature. Eurocode takes into consideration the fact that the surrounding cold part of the structure can provide unchanged rotation stiffness, leading to effective buckling lengths of $0.5L$ (fixed ends) and $0.7L$ (mixed ends). Nevertheless, authors decided to evaluate the effective buckling length of $1.0L$ (pinned extremities). The materials used for the calculations were selected according to the most commonly used in practice, being the steel grade S275 for the cross section of the profile, steel grade B500 for reinforcement and concrete grade C20/25 for the encasement. The cross sections were defined according to the tabulated data [1] to design partially encased columns under fire conditions. This led us to the minimum dimensions and minimum distances between components. The design of these profiles depends on the applied load and the relations between the thickness of the web and the thickness of the flange, see table 1. These tabulated data are also applied to other different steel grades, such as S235 and S355, for a minimum reinforcement value between 1 and 6%. The tabulated data specifies values for the most common cross sections, based on experimental and empirical results. These results are usually conservatives and may be used for a preliminary design.

The simplified calculation method was originally developed by Jungbluth [4], and used to calculate the fire resistance of the partially encased columns, dividing the cross section in four components (flanges, web, reinforcement and concrete), figure 1. The current perspective of this method is defined by EN1994-1-2 [1] and is based on simple formulas and empirical coefficients that seem to be unsafe. Due to this fact, a new formulae was proposed [2] seeking safer results and a new improvement is herein presented.

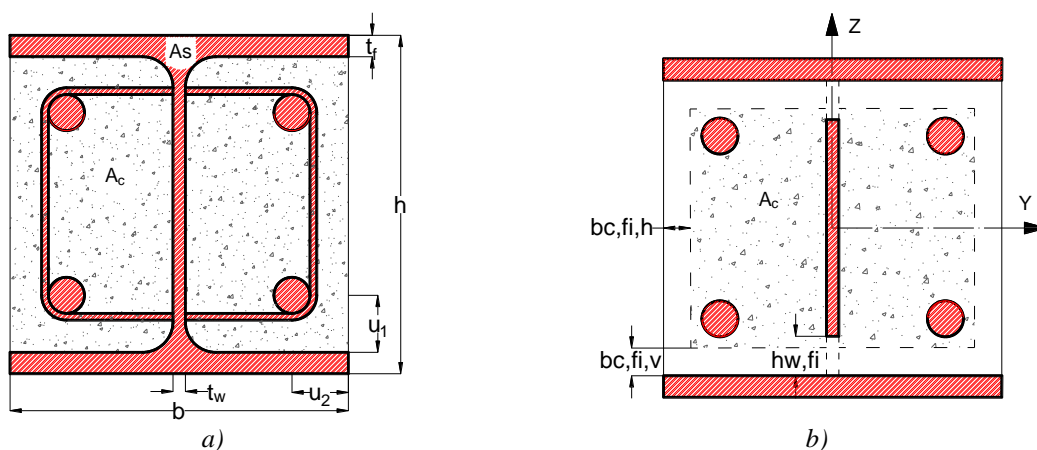


Fig. 1. a) Partially encased columns; b) Balanced summation model.

Table 1 presents the main dimensions of the cross sections as well as the number of rebars used and their respective diameters and the concrete cover dimensions in both principal directions.

Profile	Bars (n)	h_i	Φ (mm)	A_s (mm ²)	A_c (mm ²)	u_1 (mm)	u_2 (mm)	u (mm)	$A_s / A_s + A_c$	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	55	4.98	0.56	11.67
HEB450	4	398.0	40	5027	108801	70	50	55	4.42	0.54	11.11
HEB500	4	444.0	40	5027	121735	70	50	55	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	45	5.03	0.64	16.11
IPE450	4	420.8	32	3217	72779	70	40	45	4.23	0.64	14.97
IPE500	4	468.0	40	5027	83800	70	50	55	5.66	0.64	14.00

Table 1. Section properties.

2 BALANCED SUMMATION METHOD

The balanced summation method differs from the general calculation method in calculation of the geometric and material properties of the composite cross section. In the general calculation method [1], the composite cross section is divided into numerous small areas, taking into consideration the effect of the fire over the steel profile, concrete and reinforcement, allowing the calculation of the buckling load of PEC under fire conditions, simply calculating the effective flexural stiffness around the weak axis and the plastic resistance load.

The balanced summation model [1] takes into consideration the contribution of each of the four components, assuming the cross section is submitted to standard fire [3] by the four sides. Each component will be affected by the temperature evolution, in particular: Both flanges require the calculation of the average temperature (temperature is affecting the mechanical properties of the material without reduction of the second order moment of area for the stiffness and the area for the plastic resistance); The web requires the calculation of the portion of the area to be neglected (temperature is affecting the second order moment of area

for the stiffness and the area for the plastic resistance, keeping the elastic modulus at room temperature, but using a reduced strength); The concrete requires the calculation of the residual area, assuming to be at uniform temperature (temperature is affecting the second order moment of area for the stiffness and the area of the concrete for the plastic resistance, affecting also the mechanical properties of the concrete); The reinforcement requires the calculation of the average temperature (affecting only the mechanical properties).

The stability of PEC requires the procedure identified by Eqs 1-5. This procedure requires the calculation of the critical load $N_{fi,cr,z}$, taking into consideration the effective flexural stiffness $(EI)_{fi,eff,z}$ and the plastic load $N_{fi,pl,Rd}$. Both quantities may be determined by the balanced summation method of the four components, being the effective flexural stiffness affected by the reduction coefficients given in Table 2. The sub index identified in each term is related with each one of the four components. The design for the axial buckling load of PEC under fire conditions depends on the reduction coefficient χ_z and on the non-dimensional slenderness ratio $\bar{\lambda}_\theta$, when using the curve “c” of EN1993-1-1 [5].

$$(EI)_{fi,eff,z} = \varphi_{f,\theta}(EI)_{fi,f,z} + \varphi_{w,\theta}(EI)_{fi,w,z} + \varphi_{c,\theta}(EI)_{fi,c,z} + \varphi_{s,\theta}(EI)_{fi,s,z} \quad (1)$$

$$N_{fi,pl,Rd} = N_{fi,pl,Rd,f} + N_{fi,pl,Rd,w} + N_{fi,pl,Rd,c} + N_{fi,pl,Rd,s} \quad (2)$$

$$N_{fi,cr,z} = \pi^2(EI)_{fi,eff,z}/L_\theta^2 \quad (3)$$

$$\bar{\lambda}_\theta = \sqrt{N_{fi,pl,Rd}/N_{fi,cr,z}} \quad (4)$$

$$N_{b,fi,Rd,z} = \chi_z N_{fi,pl,Rd} \quad (5)$$

Standard Fire Resistance	$\varphi_{f,\theta}$	$\varphi_{w,\theta}$	$\varphi_{c,\theta}$	$\varphi_{s,\theta}$
R30	1	1	0.8	1
R60	0.9	1	0.8	0.9
R90	0.8	1	0.8	0.8
R120	1	1	0.8	1

Table 2. Reduction coefficients for bending stiffness.

2.1 EUROCODE 4 PART 1-2 (ANNEX G)

In next four topics, the simple calculation method proposed by EN1994-1-2 [1] will be presented, providing the necessary information to apply the balanced summation method, to find the buckling resistance of PEC under fire.

2.1.1 Flange

Due to the fire standard event and taking into consideration the scenario of the column engulfed in fire, both flanges will present the same behaviour. The average flange temperature can be calculated by the Eq. 6. The main parameters and coefficients are defined by Table 3.

$$\theta_{f,t} = \theta_{0,t} + k_t(A_m/V) \quad (6)$$

Where $\theta_{f,t}$ represents the average flange temperature; $\theta_{0,t}$ is the reference value, k_t represents the empirical coefficient, and (A_m/V) the section factor [m^{-1}].

Standard Fire Resistance	$\theta_{0,t}$ [°C]	K_t [m°C]
R30	550	9.65
R60	680	9.55
R90	805	6.15
R120	900	4.65

Table 3. Parameters for the flange temperature.

The average temperature allows the calculation of the reduction factor for the steel material properties, normally used for both the yield strength and elastic modulus, affecting the calculation of effective flexural stiffness and the plastic resistance to axial compression.

2.1.2 Web

The effective web height is affected by the fire, due to the thermal heat flow conduction through both materials (steel and concrete). The simple calculation method suggests that part of this component can be neglected. Therefore, the web height reduction $h_{w,fi}$, when measured from the inner side of the flange, can be calculated using the Eq. 7, using the empirical number H_t presented in Table 4 and the total depth of the steel section h . t_f represents the flange thickness.

$$h_{w,fi} = 0,5(h - 2t_f)(1 - \sqrt{1 - 0,16(H_t/h)}) \quad (7)$$

Standard Fire Resistance	H_t [mm]
R30	350
R60	770
R90	1100
R120	1250

Table 4. Parameters for web height reduction.

The residual area of the web will affect the calculation of the effective flexural stiffness, but the elastic modulus should be consider with the same value at room temperature. The plastic resistance to axial compression is affected by the reduction of the geometry and also by the reduction coefficient for the yielding stress.

2.1.3 Concrete

The direct and indirect effect of the fire in the concrete part allows defining the residual area able to bear compressive forces. Because of this, the external layer of concrete, defined by the parameter $b_{c,fi}$, should be calculated, ignoring the distinct behaviour in both principal directions. The value or expression for this external layer of concrete is defined in Table 5. This external layer depends on the section factor for the case of higher fire ratings.

Standard Fire Resistance	$b_{c,fi}$ [mm]
R30	4
R60	15
R90	$0.5 \cdot (A_m/V) + 22.5$
R120	$2.0 \cdot (A_m/V) + 24.0$

Table 5. Thickness reduction of the concrete.

The average concrete temperature $\theta_{c,t}$ can also be calculated, depending on the section factor and using the fire rating class, see Table 6. Linear interpolation can be used to find other intermediate solutions.

R30		R60		R90		R120	
A_m/V [m ⁻¹]	$\theta_{c,t}$ [°C]	A_m/V [m ⁻¹]	$\theta_{c,t}$ [°C]	A_m/V [m ⁻¹]	$\theta_{c,t}$ [°C]	A_m/V [m ⁻¹]	$\theta_{c,t}$ [°C]
4	136	4	214	4	256	4	265
23	300	9	300	6	300	5	300
46	400	21	400	13	400	9	400
-	-	50	600	33	600	23	600
-	-	-	-	54	800	38	800
-	-	-	-	-	-	41	900
-	-	-	-	-	-	43	1000

Table 6. Average concrete temperature.

The calculation of the average temperature of the concrete allows the calculation of the reduction factor for the compressive strength of concrete $k_{c,\theta}$ and the secant modulus $E_{c,sec,\theta}$, both affecting the effective flexural stiffness and plastic resistance to axial compression.

2.1.4 Reinforcements

The reduction factor $k_{y,t}$ for the yield stress and the reduction factor for the elasticity modulus $k_{E,t}$ for the steel rebars are determined as a function of fire rating class and the geometrical average of axial distances u regarding to the covered distances of the steel reinforcement. The average value of geometry u is obtained by the covering distances u_1 and u_2 , using Eq. 8 in [mm], defined from the distance between the reinforcement axis to the inner edge of the flange and also to the external concrete surface, established respectively in z and y directions of the cross section. The linear interpolation can be made to find the appropriate factors when not presented directly in Table 7 and Table 8.

$$u = \sqrt{u_1 \cdot u_2} \quad (8)$$

Where u depends on the axial distances and can also be calculated according to Eq. 9 and Eq.10.

$$u = \sqrt{u_2(u_2 + 10)}, (u_1 - u_2) > 10 [mm] \quad (9)$$

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

Standard Fire Resistance	u [mm]	40	45	50	55	60
R30		1	1	1	1	1
R60	$k_{y,t}$	0.789	0.883	0.976	1	1
R90		0.314	0.434	0.572	0.696	0.822
R120		0.170	0.223	0.288	0.367	0.436

Table 7. Reduction factor $k_{y,t}$ for reinforcement.

Standard Fire Resistance	u [mm]	40	45	50	55	60
R30		0.830	0.865	0.888	0.914	0.935
R60	$k_{E,t}$	0.604	0.647	0.689	0.729	0.763
R90		0.193	0.283	0.406	0.522	0.619
R120		0.110	0.128	0.173	0.233	0.285

Table 8. Reduction factor $k_{E,t}$ for reinforcement.

2.2 NEW PROPOSAL

After a previous numerical study [2], the simplified calculation method, Annex G [1], used for the design of PEC under fire was found to be sometimes unsafe or uneconomical. In order to improve the simple calculation method, a new proposal was made, providing new formulas, coefficients, tables and applications limits so that the calculation process of these elements is as close as possible to their real behaviour. The improved method for the new proposal will be presented, seeking to evaluate and validate this model, using numerical simulations.

2.2.1 Flange

The new proposal for the calculation of the average flange temperature $\theta_{f,t}$ is based on a bilinear approximation, see Eq. 11. There is a new proposal for the empirical coefficients k_t and new reference values $\theta_{0,t}$, as presented in Table 9. This new proposal also differentiates the type of profile (HEB or IPE).

$$\theta_{f,t} = \theta_{0,t} + k_t(A_m/V) \quad (11)$$

Standard Fire Resistance	HEB				IPE			
	$10 < A_m/V < 14$		$14 \leq A_m/V < 25$		$10 < A_m/V < 19$		$19 \leq A_m/V < 30$	
	$\theta_{0,t}$ [°C]	K_t [m°C]	$\theta_{0,t}$ [°C]	K_t [m°C]	$\theta_{0,t}$ [°C]	K_t [m°C]	$\theta_{0,t}$ [°C]	K_t [m°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	2.2	956	1.09
R120	961	4.29	998	1.62	997	1.68	1010	0.96

Table 9. Parameters for average flange temperature.

The average temperature allows the use of the same procedure to calculate the effective flexural stiffness and the plastic resistance to axial compression.

2.2.2 Web

The fire effect on the web profile is defined by the 400°C isothermal criterion [6]. This criterion defines the web part that can be neglected, $h_{w,fi}$, with respect to the calculation of the resistance of this element. The new formulae presents a huge dependence of the section factor when submitted to standard fire, unlike the version of EN1994-1-2. As an alternative to the current version, the new proposal presents a parametric expression, which depends on the section factor and fire rating, Eqs. 12-13. The application limits of these equations are defined by Table 10, and are differentiated for HEB and IPE profiles, respectively.

$$2h_{w,fi}/h_i \times 100 = 0.0035t^2(A_m/V) - 0.03t^{2.02} + (A_m/V)/2 \rightarrow (HEB) \quad (12)$$

$$2h_{w,fi}/h_i \times 100 = 0.002t^2(A_m/V) - 0.03t^{1.933} + (A_m/V) \rightarrow (IPE) \quad (13)$$

Where h_i represents the distance between the inner edges of the flange [mm] and t represents the fire rating [min].

Standard Fire Resistance	Section Factor (HEB) $A_m/V <$	Section Factor (IPE) $A_m/V <$
R30	22.22	30
R60	15.38	18.56
R90	12.22	14.97
R120	11.11	-

Table 10. Limits for web height reduction.

The residual area of the web will affect the calculation of the effective flexural stiffness and the plastic resistance to axial compression, but the elastic modulus and the yield stress are not affected by the temperature.

2.2.3 Concrete

The fire effect on the concrete is determined by the 500°C isothermal criterion [1]. In this new proposal the external concrete layer to be neglected is differentiated between both principal direction ($b_{c,fi,v}$ and $b_{c,fi,h}$), and also depends on the section factor, Eq. 14. The application coefficients are defined by Table 11 and Table 12, with their limits presented in Table 13.

$$b_{c,fi} = a(A_m/V)^2 + b(A_m/V) + c \quad (14)$$

Standard Fire Resistance	$b_{c,fi,h}$ [mm]			$b_{c,fi,v}$ [mm]		
	a [m ² .mm]	b [m.mm]	c [mm]	a [m ² .mm]	b [m.mm]	c [mm]
R30	0	0.0809	13.5	0	0.372	3.5
R60	0.1825	-4.2903	50	0.1624	-3.2923	41
R90	1.0052	-22.575	163.5	1.8649	-43.287	298
R120	0	7.5529	-35.5	0	6.0049	9

Table 11. Coefficients for concrete thickness reduction for HEB sections.

Standard Fire Resistance	$b_{c,fi,h}$ [mm]			$b_{c,fi,v}$ [mm]		
	a [m ² .mm]	b [m.mm]	c [mm]	a [m ² .mm]	b [m.mm]	c [mm]
R30	0	0.2206	10.5	0	0.9383	-3
R60	0.2984	-8.8924	93	0.5888	-15.116	135
R90	1.3897	-38.972	313	2.0403	-50.693	393
R120	0	18.283	-199	0	48.59	-537

Table 12. Coefficients for concrete thickness reduction for IPE sections.

Standard Fire Resistance	Section Factor	
	HEB	IPE
R30	$A_m/V < 25$	$A_m/V < 30$
R60	$A_m/V < 20$	$A_m/V < 23$
R90	$A_m/V < 17$	$A_m/V < 18$
R120	$A_m/V < 14$	$A_m/V < 15$

Table 13. Applications limits for average concrete temperature and thickness reduction.

Where a, b and c are empirical coefficients. The new proposal allows the calculation of the average temperature of the residual concrete, $\theta_{c,t}$, according to Eqs. 15-16. This procedure is based on the section factor as well as the fire rating [min], and the application limits are also defined by Table 13.

$$\theta_{c,t} = 3.1t^{0.5}(A_m/V) + 0.003t^{1.95} \rightarrow (HEB) \quad (15)$$

$$\theta_{c,t} = 2.67t^{0.5}(A_m/V) + 3.4t^{0.61} \rightarrow (IPE) \quad (16)$$

This procedure allows the calculation of the reduction factor for the compressive strength of concrete $k_{c,\theta}$ and the secant modulus $E_{c,sec,\theta}$, both affecting the effective flexural stiffness and plastic resistance to axial compression.

2.2.4 Reinforcements

The fire effect on the reinforcing steel bars depends of the calculation of the average temperature. A new parametric formula is presented to determine this effect, according to Eqs. 17-18. This new formula takes into consideration the fire rating, the section factor as well as the geometrical average of axial distances u , being the u parameter determined according to EN1994-1-2 [1].

$$\theta_{s,t} = 0.1t^{1.1}(A_m/V) + 7.5t - 0.1t^{1.756} - 8u + 390 \rightarrow (HEB) \quad (17)$$

$$\theta_{s,t} = 14(A_m/V) + 11t - 0.1t^{1.795} - 8u + 115 \rightarrow (IPE) \quad (18)$$

The temperature is affecting the mechanical properties, allowing the calculation of the reduction factors, influencing both the effective flexural stiffness and the plastic resistance to axial compression.

3 ADVANCED CALCULATION METHOD

The calculation of the temperature field on the cross section of PEC was done by the finite element method, using ANSYS software. The finite element method requires the solution of Eq. 19 in the domain of the cross section, (Ω) and Eq. 20 in the boundary ($\partial\Omega$), when exposed to fire.

$$\nabla(\lambda_{(T)} \cdot \nabla T) = \rho_{(T)} \cdot C p_{(T)} \cdot \partial T / \partial t \quad (\Omega) \quad (19)$$

$$\lambda_{(T)} \cdot \nabla T \cdot \vec{n} = \alpha_c (T_g - T) + \Phi \cdot \varepsilon_m \cdot \varepsilon_f \cdot \sigma \cdot (T_g^4 - T^4) \quad (\partial\Omega) \quad (20)$$

In these equations: T represents the temperature of each material; $\rho_{(T)}$ defines the 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, using standard fire ISO 834 [2] around the cross section (4 exposed sides); Φ specifies the view factor; ε_m represents the emissivity of each material; ε_f specifies the emissivity of the fire; σ represents the Stefan-Boltzmann constant.

The two-dimensional model uses PLANE55, with four nodes and one degree of freedom per node, allowing to perform a transient nonlinear thermal analysis. The analysis was defined with an integration time step of 60 s, which can decrease to 1 s and increase up to 120 s. The criterion for convergence uses a tolerance value for the heat flow, smaller than 0.1%, with a minimum reference value of 1×10^{-6} . The selected element uses linear interpolation functions to determine the conductivity matrix and 4 integration points (2x2), see Fig. 2. The high number of elements is justified by the need to measure the residual area of both components (web and concrete). The steel rebars were assumed with a square geometry, being their sides related to the original circular area. This model considers perfect contact between the four components.

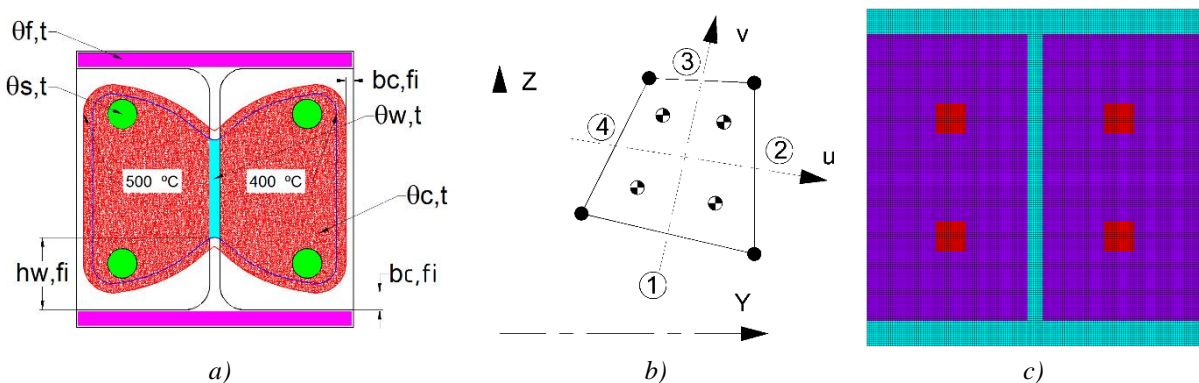


Fig. 2. a) Limit conditions, b) Finite element "PLANE55", c) 2D finite element mesh.

The boundary conditions were imposed according to EN1991-1-2 [7] on the external surface of the cross section and the initial condition of 20°C were defined to all nodes. The thermal properties of the materials has been defined according to their own standards. For the concrete, a water contents of 3% and a thermal conductivity corresponding to its upper limit was consider [1,8]. For steel, all thermal properties were assumed temperature dependent and in accordance to EN1993-1-2 [9]. This method used the following criteria: The 400°C isothermal line was defined to calculate the web height reduction and for the average web temperature; The 500°C isothermal line was used to define the residual area of concrete and to calculate the average temperature; The average temperature of the flange and the average temperature of the rebars allows the calculation of the reduction factors. Fig. 3 shows four examples of the temperature field for each standard fire rating class.

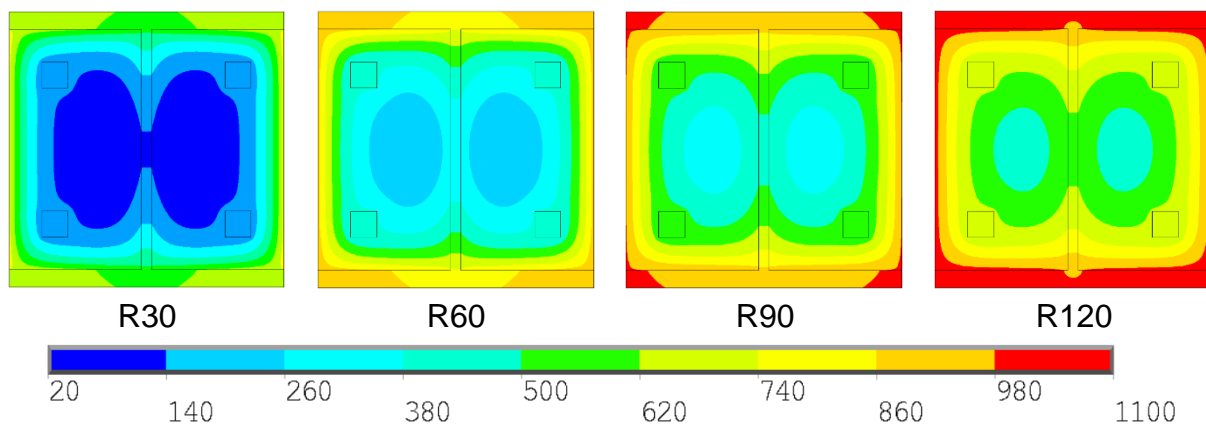


Fig. 3. Numerical simulation results: HEB 300 for each fire rating.

4 COMPARISON OF RESULTS AND IMPROVEMENT OF NEW PROPOSAL

A total of 24 simulations were developed to account for the temperature field calculation. The results follow the criteria presented in previous sections. The results presented herein will compare the simplified method currently available in EN1994-1-2, with the new proposal, new improvements and also with the advanced calculation method.

4.1 Flange

Fig. 4 compares the results of the three simplified methods used for the calculation of the flange average temperature. The solution of the current version of EN1994-1-2 demonstrates that the method is safe for R30, and unsafe for the other ratings. It is important to notice that the results of the new proposal are in good agreement with the numerical results, however, seeking to guarantee the safety of the new proposal, a few adjustments were made in the empirical coefficient k_t and in the reference value $\theta_{0,t}$. These new parameters are presented in Table 14.

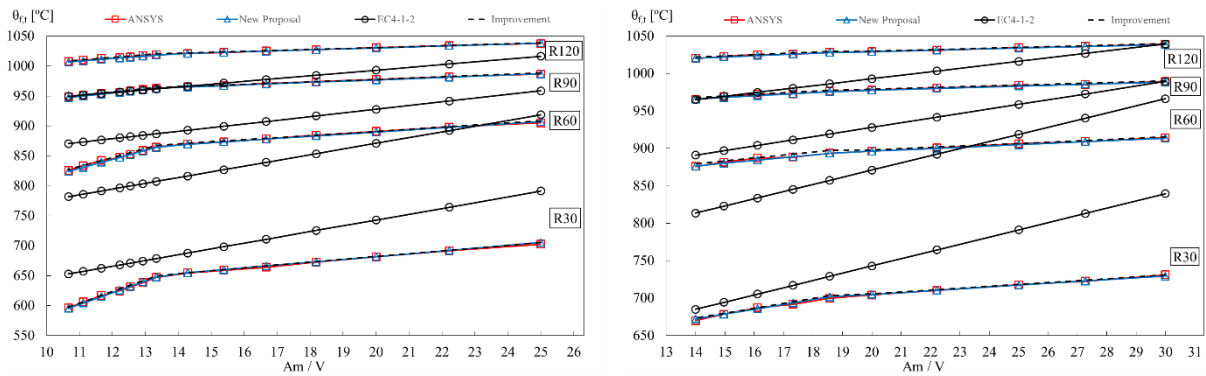


Fig. 4. Average flange temperature on HEB and IPE sections.

Standard Fire Resistance	HEB				IPE			
	10 < A _m /V < 14		14 ≤ A _m /V ≤ 25		14 < A _m /V < 19		19 ≤ A _m /V ≤ 30	
	θ _{0,t} [°C]	K _t [m°C]	θ _{0,t} [°C]	K _t [m°C]	θ _{0,t} [°C]	K _t [m°C]	θ _{0,t} [°C]	K _t [m°C]
R30	389	19.55	588	4.70	581	6.60	656	2.50
R60	668	14.95	821	3.50	824	3.95	863	1.75
R90	889	5.65	937	2.05	937	2.20	957	1.10
R120	963	4.30	999	1.60	998	1.70	1010	1.00

Table 14. Improved parameters for average flange temperature.

4.2 Web

The web height reduction $h_{w,fi}$ was determined by the identification of the 400°C isothermal line of nodes. The numerical results are compared in Fig. 5 with the results obtained with the simplified methods. In order to simplify the formula of the new proposal, new Eqs. 19-20 and their application limits are presented in Table 15, making the calculation of this component as simple as possible.

$$h_{w,fi} = (0.00175t^2(A_m/V) - 0.015t^{2.02} + (A_m/V)/4)h_i \rightarrow (HEB) \tag{21}$$

$$h_{w,fi} = (0.001t^2(A_m/V) - 0.015t^{1.933} + (A_m/V)/2)h_i \rightarrow (IPE) \tag{22}$$

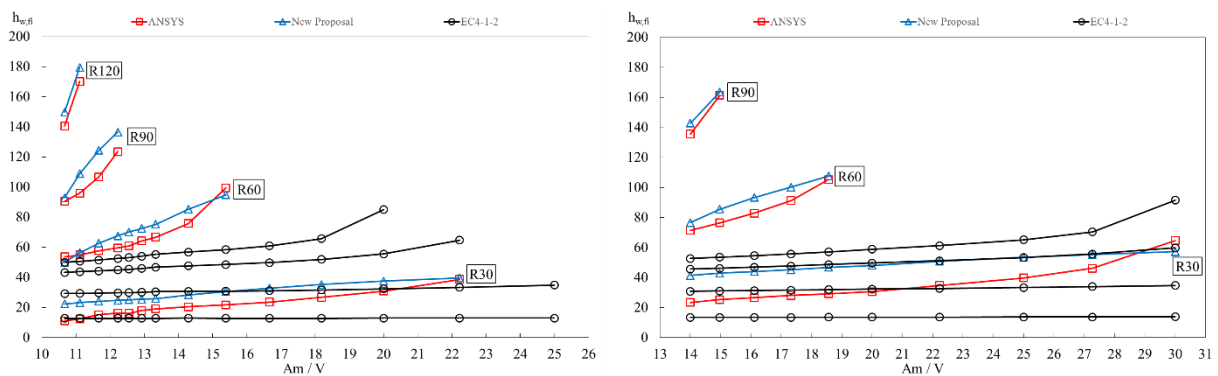


Fig. 5. Web height reduction on HEB and IPE sections.

Standard Fire Resistance	Section Factor HEB $A_m/V \leq$	Section Factor IPE $A_m/V \leq$
R30	22.22	30
R60	15.38	18.56
R90	12.22	14.97
R120	11.11	-

Table 15. Improved limits for web height reduction.

The improvement of the simple calculation method allows the calculation of the average temperature of the residual web. This new formula is presented in Eq. 21, with strong dependence on the section factor. Table 16 presents the empirical parameter and the reference temperature to be applied. The application limits also follow Table 15.

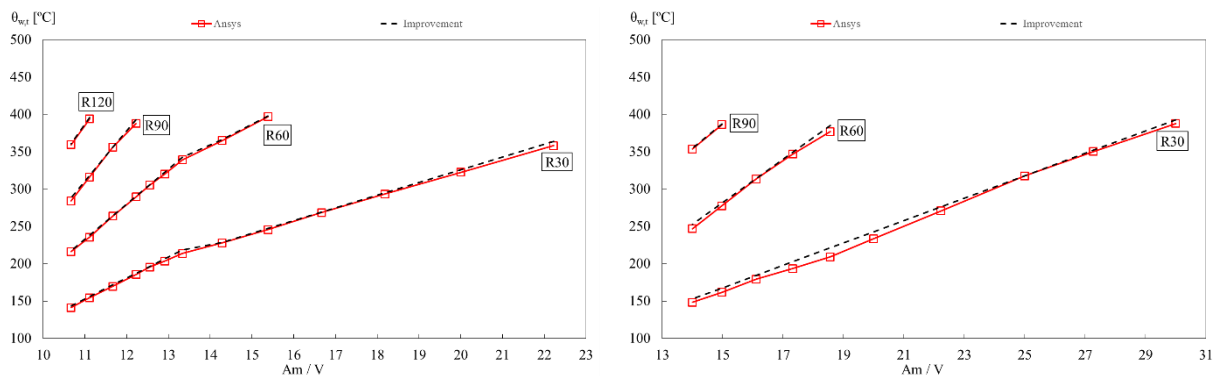


Fig. 6. Average web temperature on HEB and IPE sections.

$$\theta_{w,t} = -\theta_{0,t} + k_t(A_m/V) \quad (23)$$

Standard Fire Resistance	HEB				IPE	
	$10 < A_m/V < 14$		$14 \leq A_m/V < \text{Table 15}$		$14 < A_m/V < \text{Table 15}$	
	$\theta_{0,t}$ [°C]	K_t [m°C]	$\theta_{0,t}$ [°C]	K_t [m°C]	$\theta_{0,t}$ [°C]	K_t [m°C]
R30	155	28.0	14	17.0	57	15.0
R60	284	47.0	48	29.0	153	29.0
R90	426	67.0	-	-	107	33.0
R120	471	78.0	-	-	-	-

Table 16: New parameters for average web temperature.

4.3 Concrete

The results were obtained using the definition of the 500°C isothermal criterion. The thickness of concrete to be neglected is compared for all the simplified methods and numeral results. According to EN1994-1-2 [1], the thickness of concrete to be neglected depends on section factor, for the fire rating of R90 and R120. The new proposal and improvement demonstrate a strong dependence on the section factor for all fire ratings, see Fig. 7 and Fig. 8.

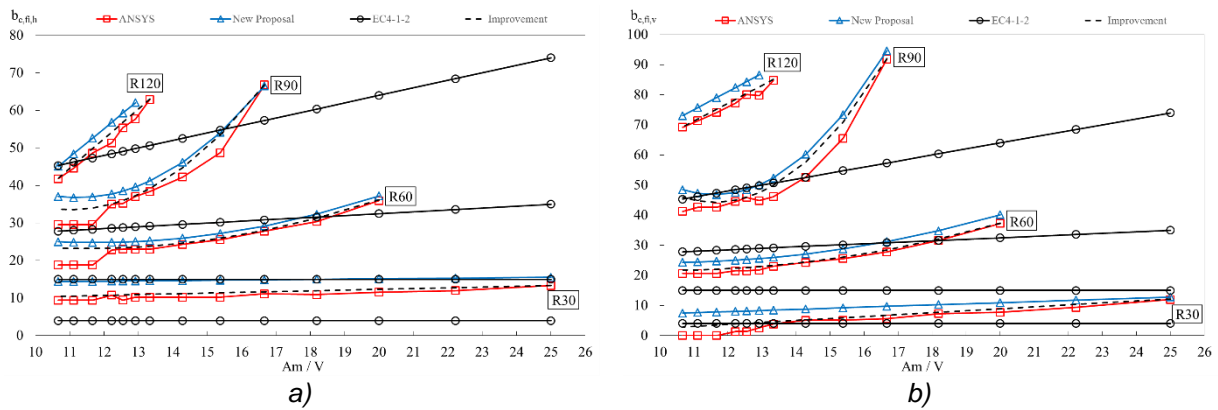


Fig. 7. a) Neglected horiz. concrete on HEB sections; b) Neglected vert. concrete on HEB sections.

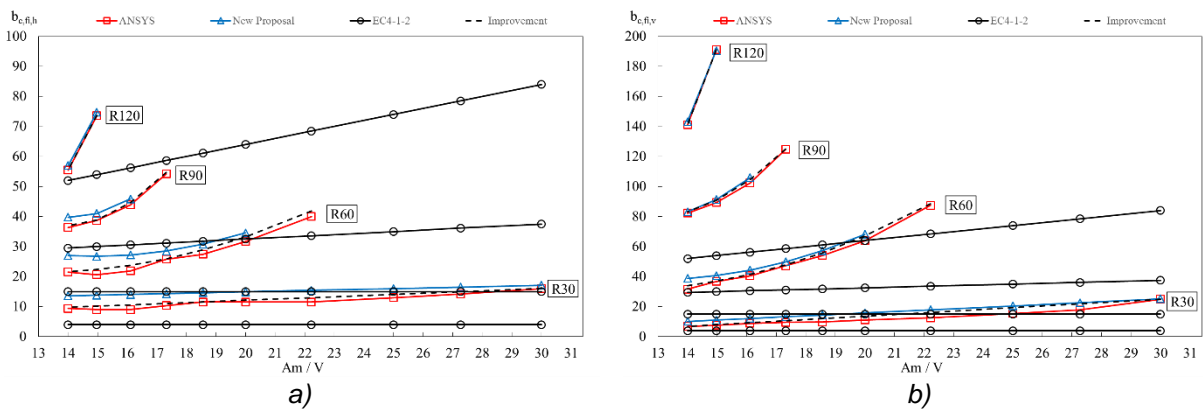


Fig. 8. a) Neglected horiz. concrete on IPE sections; b) Neglected vert. concrete on IPE sections.

It is worth to mention that the results obtained through the new proposal and through the advanced calculation method are in good agreement, however, some parameter presented by the new proposal were improved, trying to achieve a better and safer approximation to the numerical results. These new parameter are described in Tables 17 and 18, and their application limits are obtained in Table 19.

Standard Fire Resistance	$b_{c,fi,h}$ [mm]			$b_{c,fi,v}$ [mm]		
	a [m ² .mm]	b [m.mm]	c [mm]	a [m ² .mm]	b [m.mm]	c [mm]
R30	0	0.202	8.3	0	0.65	-4.07
R60	0.18	-4.14	47	0.162	-3.3	38.5
R90	1.04	-22.9	159.6	1.865	-43.29	295.5
R120	0	7.93	-42.7	0	5.93	6

Table 17. Improved coefficients for concrete thickness reduction for HEB sections.

Standard Fire Resistance	$b_{c,fi,h}$ [mm]			$b_{c,fi,v}$ [mm]		
	a [m ² .mm]	b [m.mm]	c [mm]	a [m ² .mm]	b [m.mm]	c [mm]
R30	0	0.39	4.33	0	1.13	-8.92
R60	0.24	-6.24	62	0.5	-11.5	97
R90	1.4	-38.5	301.5	2.03	-51	399.2
R120	0	18.61	-205	0	51.51	-580

Table 18. Improved coefficients for concrete thickness reduction for IPE sections.

Standard Fire Resistance	Section Factor	
	HEB	IPE
R30	$A_m/V \leq 25$	$A_m/V \leq 30$
R60	$A_m/V \leq 20$	$A_m/V \leq 23$
R90	$A_m/V \leq 17$	$A_m/V \leq 18$
R120	$A_m/V \leq 14$	$A_m/V \leq 15$

Table 19. Improved applications limits for average concrete temperature and thickness reduction.

The average temperature of concrete is compared in Fig. 9. It is possible to see that the current version of EN1994-1-2 is unsafe for some cross sections and fire ratings, and uneconomical for other conditions. The new proposal agrees with the results of the numerical simulation. Despite the difference for the results of 30 minutes of fire, the formulas presented by new proposal will not be changed, however, its applications limits should follow the values of Table 19.

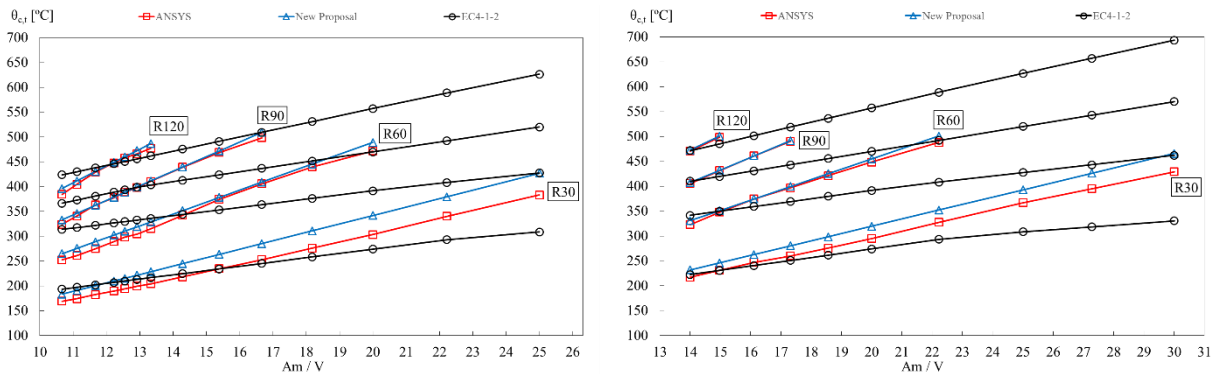


Fig. 9. Average concrete temperature on HEB and IPE sections.

4.4 Reinforcements

Fig. 10 compares the average temperature of rebars. The results agree well and despite some differences, the new proposal will not be changed, because in the safe side.

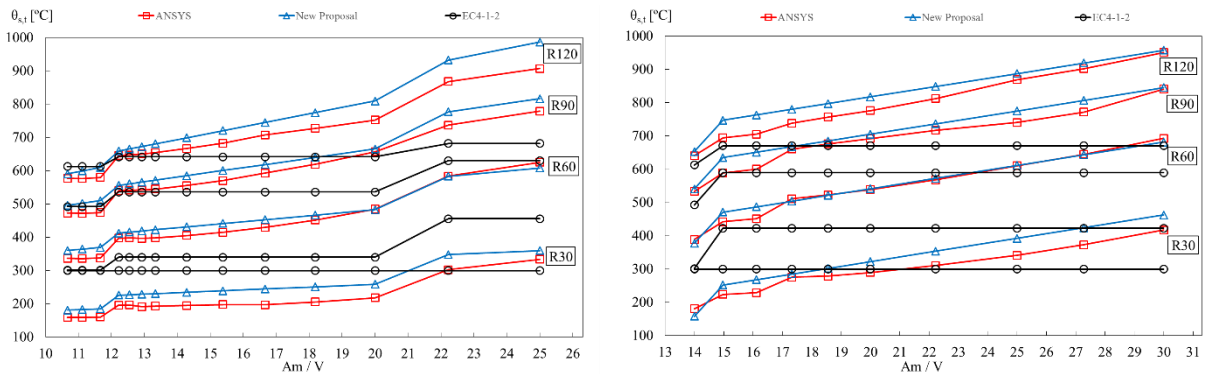


Fig. 10. Average reinforcements temperature on HEB and IPE sections.

5 BUCKLING RESISTANCE

The buckling resistance of PEC under fire is calculated taking into consideration two different column lengths (3 m and 5 m) and three different buckling modes. The results are depicted in Fig. 11 for each fire rating of 30, 60, 90 and 120 minutes, considering the formulae for the new proposal (NP) and the new improvement (A). The buckling resistance increases with the reduction of the effective buckling length and with the reduction of the non-dimensional slenderness. The improvement of the new proposal (A) leads to safer results.

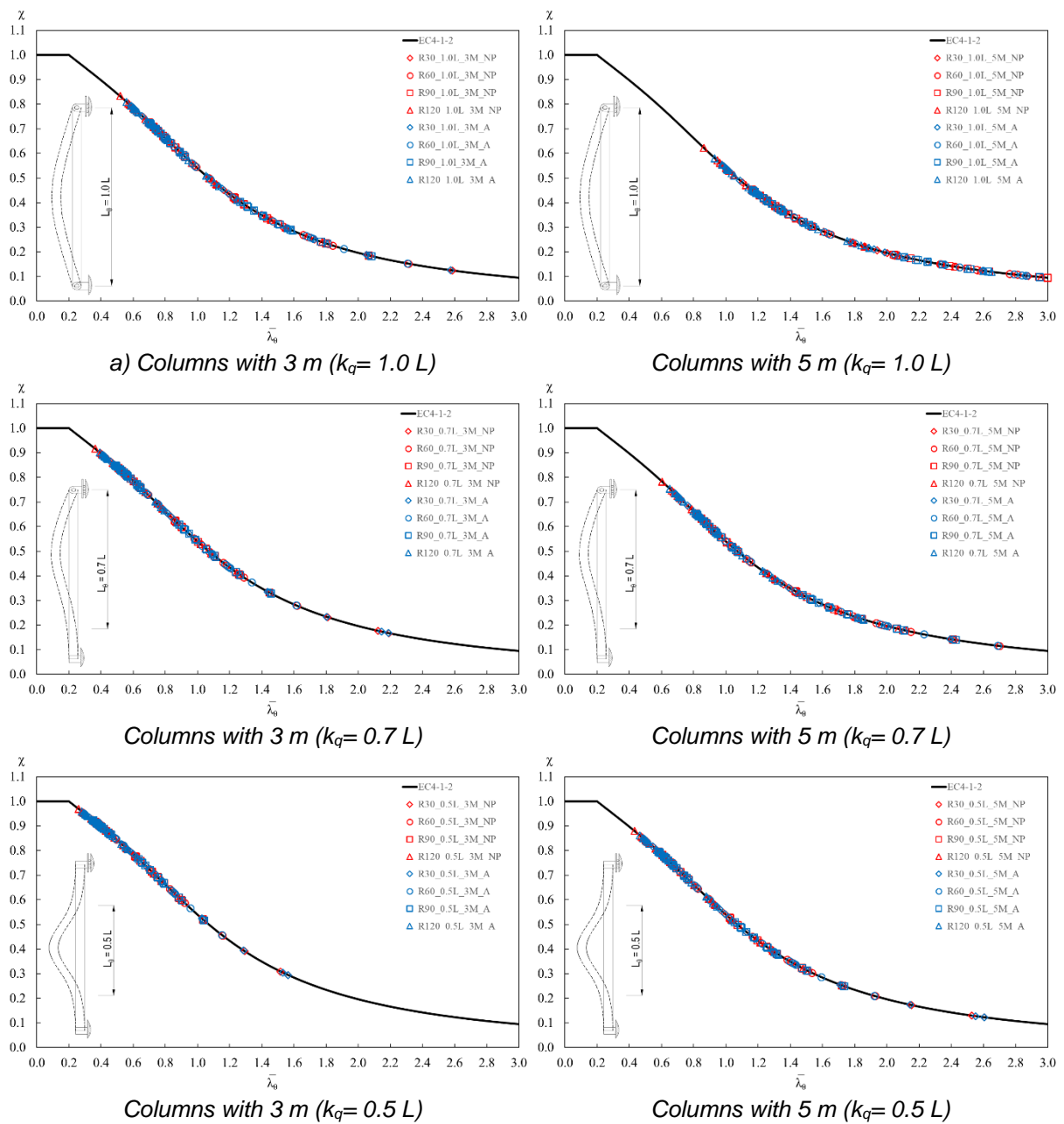


Fig. 11. Buckling resistance for every cross sections.

6 CONCLUSIONS

This study was dedicated to evaluate the performance of the simple calculation method, used for the calculation of the buckling resistance of PEC. The simplified method proposed in Annex G EN1994-1-2 [1] is unsafe when compared to the numerical results. The results of new proposal are based on the same method, but using safer formulas, however, some improvements can be made for the flange, web and concrete components, where new tables and limits have been presented. A new formula was presented for the calculation of the average temperature of the web, seeking to improve the balanced summation method.

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