Behaviour of slender plates in case of fire of different stainless steel grades

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ABSTRACT: Stainless steel has countless desirable characteristics for a structural material. Although initially more expensive than conventional carbon steel, stainless steel structures can be competitive because of their smaller or none need for thermal protection material and lower life-cycle cost, thus contributing to a more sustainable construction. Regarding structural fire resistance, in order to have a comprehensive understanding of the overall members' resistance, it is important to first analyse the cross-section resistance, directly affected by local instabilities occurrence on the composed thin plates. This work presents a numerical study on the behaviour of isolated plates at elevated temperatures, corresponded to the web (internal element) and flanges (outstand element) of I-cross sections, comparing the numerically obtained ultimate load bearing capacities with simplified calculation formulae for the application of the effective width method. Comparisons between the numerical results and the EC3 formulae for determining the effective area of thin plates is also presented.

1 INTRODUCTION

The application of stainless steel as a structural material has been increasing, due to a number of desirable qualities such as its durability, resistance to corrosion and aesthetic appearance (Gardner, L., 2005 & Euro Inox, 2006). Despite having a high initial cost, stainless steel can be a competitive material if life cycle cost analysis is considered, due to its low maintenance needs. Moreover, it has a higher fire resistance when compared to carbon steel (CEN, 2005b) allowing in some cases the absence of thermal protection.

The austenitic stainless steels are generally the most used groups for structural applications but some interest has being recently shown for increasing the use of ferritic and austenitic-ferritic (Duplex) steels for structural purposes due to specific advantages. Some of those advantages are the very good resistance to wear and stress corrosion cracking of the duplex grade and the lower percentage of Nickel of the ferritic grade, which reduces its price.

Regarding structural fire resistance, in order to have a comprehensive understanding of the overall members' resistance, it is important to first analyse the cross-section resistance, which is directly affected by local instabilities occurrence on the composed thin plates.

For structural design purposes, Eurocode 3 (EC3) (CEN, 2006a) considers that the walls slenderness determine the cross-section classification (from Class 1 - stocky sections to Class 4 - slender sections). Subsequently, the cross-section resistance is calculated considering plastic section properties for Classes 1 and 2 sections, elastic section properties for Class 3 sections and effective section properties, applying the effective width method, for Class 4 sections. In addition, for cross-section of Classes 1, 2 and 3 at elevated temperatures the strength at 2% total strain should be considered as the yield strength and for Class 4 cross-sections it should be applied the 0.2% proof strength (CEN, 2005b).

Although the subject of local buckling at elevated temperatures has been studied by different authors (Couto et al., 2014, Couto et al., 2015, FIDESC4, 2014, Knobloch & Fontana, 2006, Maraveas et at., 2017, Quiel & Garlock, 2010), the mentioned research works only address carbon steel elements and research of the local buckling effect on stainless steel sections at elevated temperatures is scarce and mostly focus on the member behaviour.

According to Part 1-2 of EC3 (CEN, 2005b) design rules, stainless steel stress-strain relationships at elevated temperatures are characterized by having an always non-linear behaviour with an extensive hardening phase, when compared with carbon steel constitutive law. As existing fire design guidelines for stainless steel, such as in EN 1993-1-2 (CEN, 2005b), are based on the formulations developed for carbon steel members (CEN, 2005a, CEN, 2006b), in spite of their different material behaviour, it is still necessary to develop knowledge on stainless steel structural behaviour at elevated temperatures.

This research work has the main objective of analysing the accuracy of EC3 present calculation proposals for stainless steel cross-sections in case of fire, subjected to compression or bending, by means of Geometrical and Material Non-linear Analysis with Imperfections applying the Finite Element software SAFIR (Franssen & Gernay, 2017). Plates behaviour at elevated temperatures is analysed considering compression or bending and different boundary conditions for modelling isolated outstand elements (flanges) and internal elements (webs), following the methodology used for the development of carbon steel design approaches (Couto et al., 2014, FIDESC4, 2014, CEN, 2006b). In this parametric study, as different stainless steel grades exibit different stress-strain relationships behaviours at elevated temperatures (CEN, 2005b), the following grades were considered: i) 1.4301 (Austenitic grade); ii) 1.4003 (Ferritic grade); iii) 1.4462 (duplex).

Comparisons between the obtained numerical results, the EC3 design methods and a recent proposal for Class 4 carbon steel sections (Couto et al., 2015), are made, being concluded that new design expressions should be developed for the effective with method application on stainless steel I-sections subjected to fire.

2 SIMPLIFIED DESIGN RULES

2.1 *Eurocode3*

According to EN 1993-1-2 (CEN, 2005b), the section resistance of a stainless steel member in case of fire is calculated in the same way as for carbon steel, changing only the mechanical properties of the material to consider uniform elevated temperatures in the section.

Regarding the cross-section classification, Equation 1 was used to determine the factor ε, a parameter necessary for the determination of the EC3 classification limits (Franssen & Vila Real, 2015).

$$\varepsilon_\theta = 0.85\left[\frac{235}{f_y}\frac{E}{210000}\right]^{0.5} \tag{1}$$

The design resistance value of axially compressed members of Class 1, 2 or 3 cross-sections with a uniform temperature θ_a is determined from Equation 2.

$$N_{fi,t,Rd} = A\ f_{y,\theta}\ /\gamma_{\mathrm{M,fi}} \tag{2}$$

For Class 4 sections, according to Annex E of EN 1993-1-2, the effective area (A_{eff}), obtained from EN 1993-1-5 (CEN, 2006b), should be considered instead of the gross cross-section area A. In a fire situation higher strains are acceptable when compared to normal temperature design, therefore, instead of 0.2% proof strength usually considered at normal temperature, for cross-section of classes 1, 2 and 3 at elevated temperatures the stress corresponding to 2% of total strain should be adopted as the yield strength (CEN, 2005b).

$$f_{y,\theta} = f_{2\%,\theta} = k_{2\%,\theta} f_y \tag{3}$$

However, for Class 4 cross-sections, according to Annex E of EN 1993-1-2, the proof strength at 0.2% strain should be used, thus

$$f_{y,\theta} = f_{0.2p,\theta} = k_{0.2p,\theta} f_y \tag{4}$$

The mentioned reduction factors are given on Annex C of EN 1993-1-2 for stainless steel at high temperatures for the different analysed stainless steel grades.

In beams, the design value of the bending moment resistance of a cross-section with a uniform temperature θ_a is determined from:

$$M_{fi,\theta,Rd} = k_{y,\theta}\left[\gamma_{\mathrm{M,0}}/\gamma_{\mathrm{M,fi}}\right] M_{c,Rd} \tag{5}$$

Being $M_{c,Rd}$ for Classes 1 and 2 the plastic bending moment capacity, for Class 3 the elastic bending moment capacity, and for Class 4 sections the effective bending moment capacity, at normal temperature, determined with the effective section properties obtained from EN 1993-1-5. The effective area and effective section modulus ($W_{eff,y}$) are determined through the application of the effective width method, considering the reduction of resistance due to local buckling effects (CEN, 2006b). On this regard, the EN 1993-1-4 (CEN, 2006a) provides specific equations for the determination of the plate reduction factors (ρ) to the width of elements composing the stainless steel sections, as presented in Equation 6 and Table 1. It can be observed that the reduction factor for internal elements do not depend on the stress distribution as proposed in carbon steel plates (CEN, 2005a).

$$b_{eff} = \rho . b \tag{6}$$

Table 1. Reduction factor for stainless steel sections elements.

Cross-section elements	Reduction factor
Welded outstand elements	$\rho = \frac{1}{\bar{\lambda}_{\mathrm{p}}} - \frac{0.242}{\bar{\lambda}_{\mathrm{p}}^2} \leq 1$
Welded internal elements	$\rho = \frac{0.772}{\bar{\lambda}_{\mathrm{p}}} - \frac{0.125}{\bar{\lambda}_{\mathrm{p}}^2} \leq 1$

The plate slenderness – $\bar{\lambda}_{\mathrm{p}}$ – value is determined with Equation 7.

$$\bar{\lambda}_{\mathrm{p}} = \sqrt{\frac{\mathrm{f_y}}{\sigma_{\mathrm{cr}}}} = \frac{\bar{\mathrm{b}}/\mathrm{t}}{28.4\,\varepsilon\,\sqrt{\mathrm{k}_\sigma}} \tag{7}$$

2.2 *Proposal for Class 4 carbon steel sections at elevated temperatures*

As mentioned before, recent research works (Couto et al., 2015, Knobloch & Fontana, 2006) proposed the use of the stress corresponding to 2% of total strain as the steel yield strength also for Class 4 cross-sections at elevated temperatures, as it is done for the remaining sections, providing the plate reduction factors would be calculated as presented in Table 2. The accuracy of the application of this proposal for stainless steel sections is tested in this paper.

Table 2. Reduction factor proposed for carbon steel sections elements in case of fire (Couto et al., 2015).

Cross-section elements	Reduction factor
Outstand elements	$\rho = \frac{\left(\bar{\lambda}_{\mathrm{p}} + 1.1 - \frac{0.52}{\varepsilon}\right)^{1.2} - 0.188}{\left(\bar{\lambda}_{\mathrm{p}} + 1.1 - \frac{0.52}{\varepsilon}\right)^{2.4}} \leq 1.0$
Internal elements	$\rho = \frac{\left(\bar{\lambda}_{\mathrm{p}} + 0.9 - \frac{0.26}{\varepsilon}\right)^{1.5} - 0.055(3 + \psi)}{\left(\bar{\lambda}_{\mathrm{p}} + 0.9 - \frac{0.26}{\varepsilon}\right)^{3}} \leq 1.0$

3 PLATES BEHAVIOUR

3.1 *Numerical modelling*

Members composed of different cross-section shapes may exibit diferent plates behaviour. For instance in I-shape sections subjected to compression have both flanges and web in compression, whereas when the members are subjected to bending in the strong axis, a flange is in compression while the web is subjected to bending. Rectangular hollow sections subjected to compression will have only internal elements subjected to compression and when subjected to bending will have an internal element subjected to compression and others internal elements subjected to bending.

To determine the ultimate load of rectangular plates the program SAFIR was used. Each shell element has four nodes with six degrees of freedom (three translations and three rotations). Simply supported conditions where applied to the plates by restraining the vertical displacements, in addition the rotations at the edges of the plate were also restrained to simulate the web-flange continuity. For the outstand elements, the vertical displacements were restrained on three sides while for the internal elements the vertical displacements were restrained in all four sides, this methodology follows the same principles as in Couto et al., (2014). Figure 1 presents the obtained deformed shapes of an outstand element subjected to compression, an internal element subjected to compression and an internal element subjected to bending.

Geometric imperfections were introduced into the numerical model by changing the nodal coordinates affine to the buckling mode shapes obtained with the program CAST3M (CEA, 2012) and applying the interface RUBY (Couto et al., 2013). For the amplitude of the imperfections, it was considered 80% of b/50 for outstand elements and 80% of b/100 for internal elements, following the recommendations of EN 1090-2 (CEN, 2011). Plates of the stainless steel grade 1.4301, 1.4003 and 1.4462 (CEN, 2006a) subjected to four temperatures were considered 350ºC, 400ºC, 450ºC and 500ºC (common critical temperatures in slender sections).

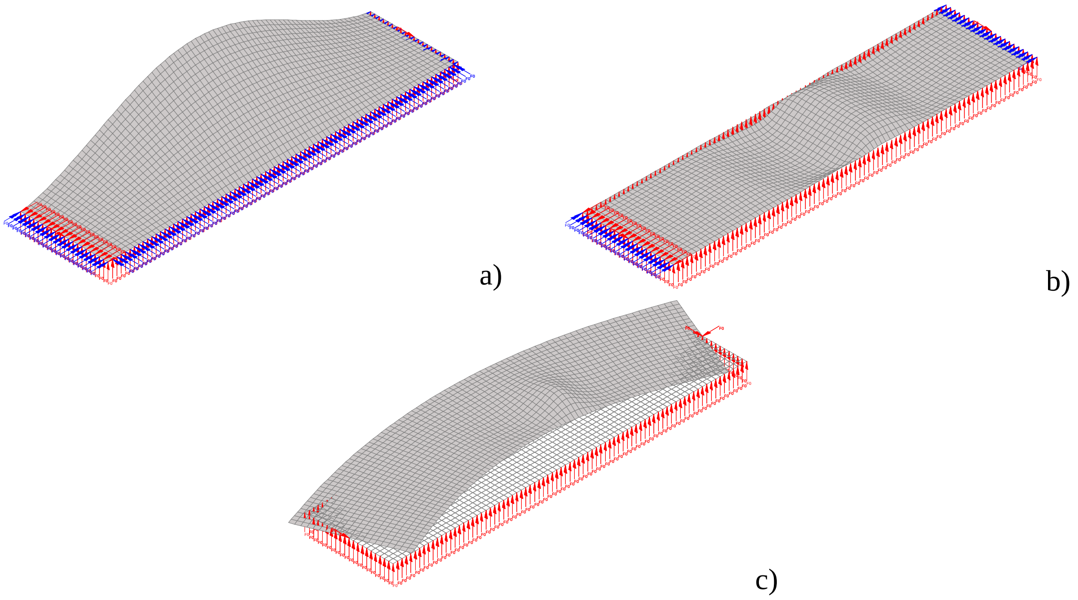


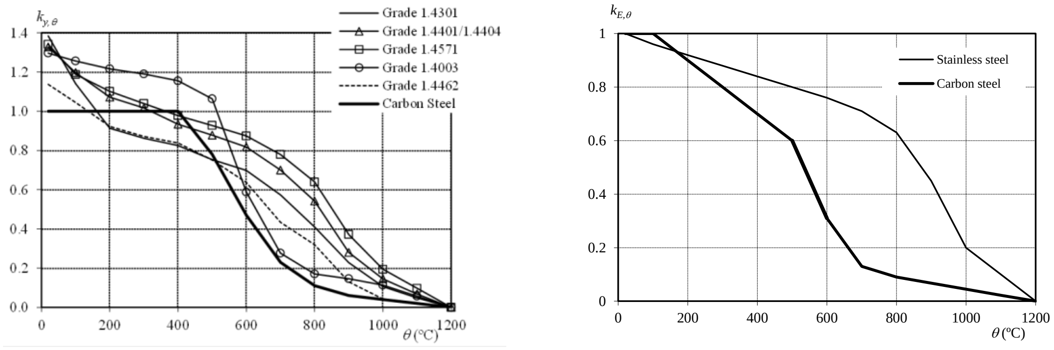
Figure 1. Deformed shapes (x5): a) outstand element subjected to compression; b) internal element subjected to compression; c) internal element subjected to bending.

The nominal values applied of yield strength, ultimate strength and elastic modulus of stainless steel in the numerical models are presented in Table 3.

Table 3. Nominal values for different stainless steel grades (CEN, 2006a).

Type	Grade	Yield strength f_y (MPa)	Ultimate strength f_u (MPa)	Elastic modulus E (GPa)
Austenitic	1.4301	210	520	200
Ferritic	1.4003	280	450	220
Duplex	1.4462	460	660	200

These mechanical properties are reduced at elevated temperatures as presented in Figure 2, which vary for each grade.



a) b)

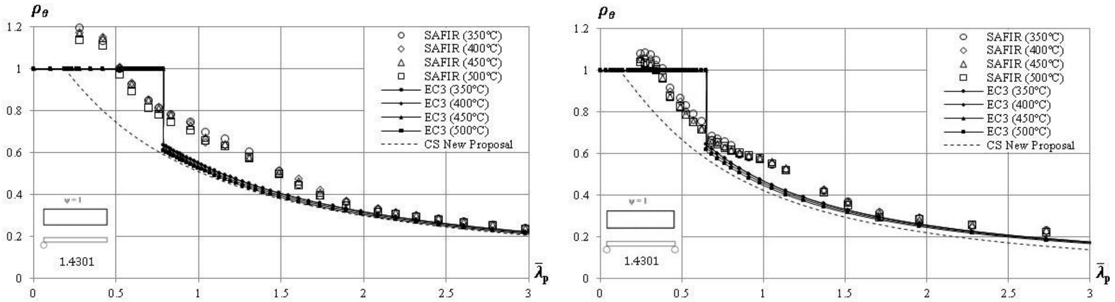
Figure 2. Mechanical properties reduction at elevated temperatures (CEN, 2005b): a) yield strength retention; b) young modulus reduction.

3.2 *Plates subjected to compression*

The results obtained for outstand and internal plate elements subjected to compression are here presented. At elevated temperatures, the equation to determine the reduction factor has to be adapted due to the transition that occurs from Class 3 to Class 4 section because of the change on the limit strength, leading to a discontinuity in the curve, as presented in Equation 8.

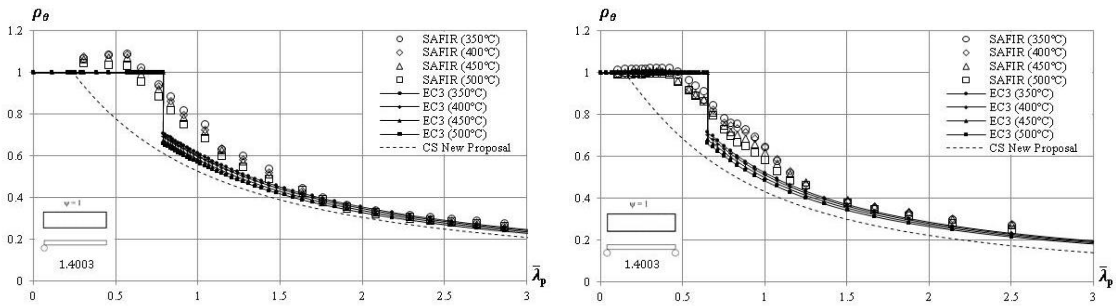
$$\rho_\theta = \frac{N_{c,Rd}}{N_{Rd}} = \rho \frac{f_{y,\theta}}{f_{2,\theta}} \tag{8}$$

Figure 3 to 5 presents the comparisons between the ultimate load bearing capacities, for outstand and internal plate elements subjected to compression, obtained with EC3, the new proposal for Class 4 carbon steel elements ("CS New Proposal" in the chart) and SAFIR.



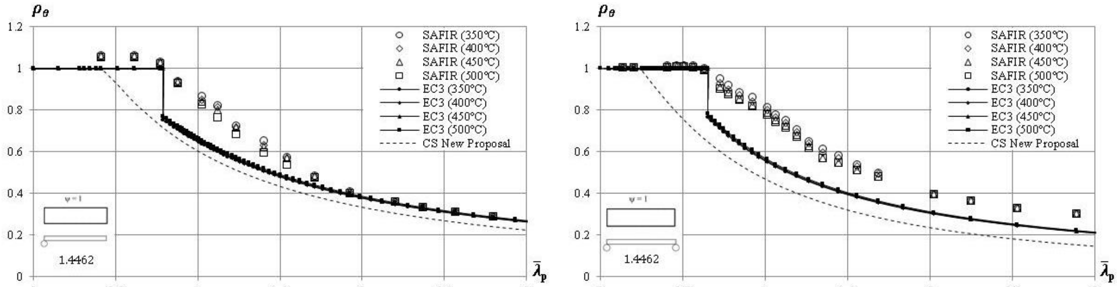
a) b)

Figure 3. Results for a) outstand elements and b) internal elements subjected to compression for austenitic stainless steel at elevated temperatures.



a) b)

Figure 4. Results for a) outstand elements and b) internal elements subjected to compression for ferritic stainless steel at elevated temperatures.



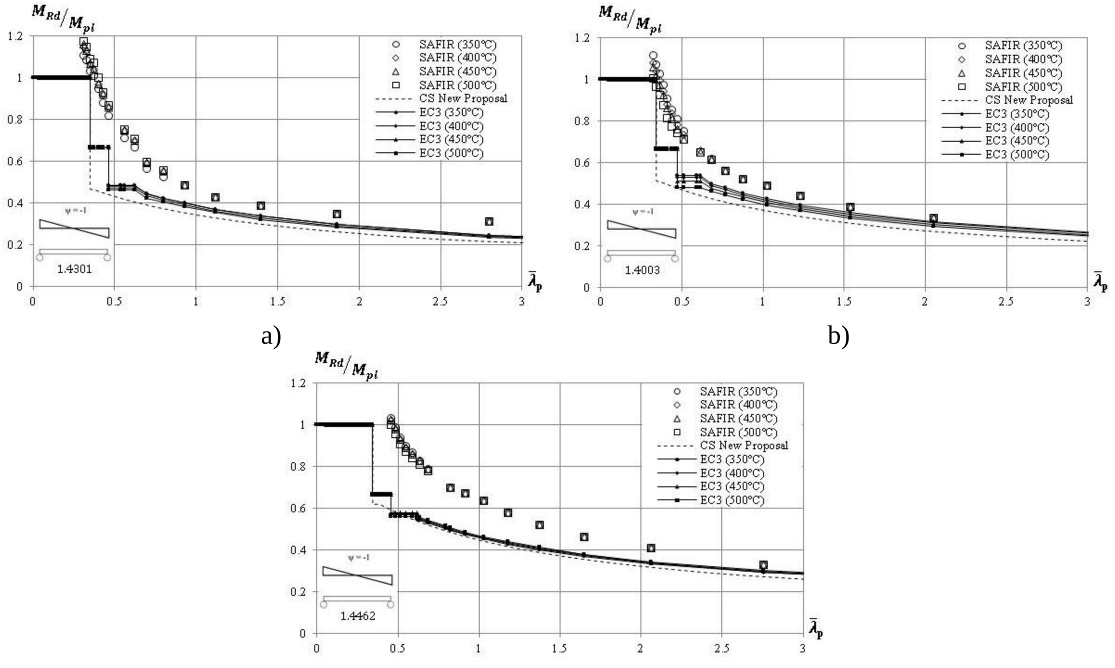
a) b)

Figure 5. Results for a) outstand elements and b) internal elements subjected to compression for austenitic-ferritic (Duplex) stainless steel at elevated temperatures.

For both outstand and internal elements subjected to compression, the proposal for carbon steel Class 4 sections (Couto et al., 2014) eliminates the un-conservative nature given by the plateau of EC3 for austenitic (Figure 3) and ferritic stainless steel (Figure 4). The results for austenitic-ferritic stainless steel (Figure 5) revealed that the rules are over conservatives. Nonetheless, the results highlight the need of improved design equations specifically developed for stainless steel plates subjected to compression at elevated temperatures, considering the stainless steel grade.

3.3 *Plates subjected to bending*

The obtained results for internal plate elements subjected to bending are presented in Figure 6. The ultimate bending moments obtained in each plate for all methods were divided by the plastic bending moments.



a) b)

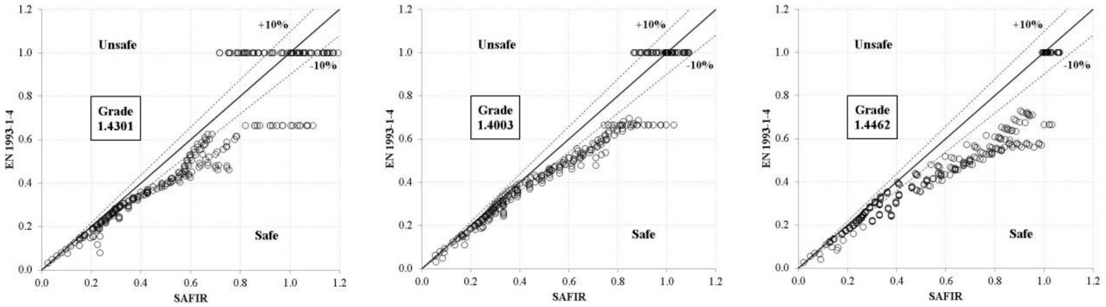
c)

Figure 6. Results for internal elements subjected to bending for a) austenitic, b) ferritic and c) austenitic-ferritic (Duplex) stainless steel at elevated temperatures.

The different plateaus, in this figure, observed in Eurocode procedure of EN 1993-1-4 correspond to the transitions between Class 2 and Class 3 sections (from plastic to elastic resistance) and from Class 3 to Class 4 where at elevated temperatures the yield strength changes, as mentioned before. The curves from both proposals are over conservative when compared with the numerical results, which leads to conclude that specific formulae for stainless steel plates should be developed, which can be observed specifically for austenitic-ferritic stainless steel.

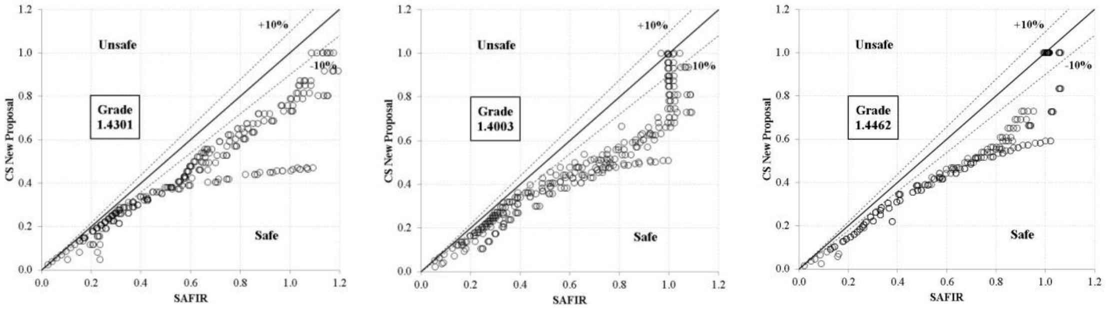
3.4 *Statistical analysis*

The average value (μ) and the standard deviation (s) are important values to take into account in the statistical analysis for the different methodologies of EC3 and different Proposals. For each stainless steel grade and for each analysed curve it is possible to evaluate the ratio between the analytical value and the corresponding SAFIR (Figure 7 and 8).



a) b) c)

Figure 7. Comparison between EN 1993-1-4 and SAFIR – Grades a) 1.4301, b) 1.4003 and c) 1.4462



a) b) c)

Figure 8. Comparison between CS New Proposal and SAFIR – Grades a) 1.4301, b) 1.4003, c) 1.4462

From Figure 7 and 8 and Table 4 it is possible to observe that the different design rules are not adapted for stainless steel thin plates with low average values and high standard deviations. The number of unsafe results is also relevant for the accuracy of these design rules.

Table 4. Statistical evaluation for different stainless steel grades at high temperatures

Steel Grade	Design rule	No. of simulations (n)	Average value (μ)	Standard deviation (s)	% Unsafe
1.4301	EN 1993-1-4	283	0.8916	0.1564	14.1%
	CS New Proposal	283	0.7568	0.1798	0.0%
1.4003	EN 1993-1-4	302	0.9025	0.1029	17.2%
	CS New Proposal	302	0.7391	0.1915	1.0%
1.4462	EN 1993-1-4	276	0.8223	0.1283	1.4%
	CS New Proposal	276	0.7576	0.1262	1.4%

4 CONCLUSIONS

This work presented a numerical study regarding the plates' behaviour of different stainless steel grades (austenitic, ferritic and austenitic-ferritic (Duplex) stainless steel), composing the cross-sections of members in fire situation.

In order to better understand the behaviour of these stainless steel sections, thin plates at elevated temperatures were analysed. This study, on compressed outstand elements, compressed internal elements and internal elements subjected to bending, concluded that EC3 does not provide accurate and safe approximations to their numerically obtained counterparts regarding the ultimate load bearing capacities. Following this conclusion, a recent proposal for carbon steel plates (Couto et al., 2014) was also investigated. It was observed that using this proposal allowed to overcome the unsafety that was previously observed for Class 3 sections, but results remained too conservative for Class 4 sections.

In summary, the prediction of the resistance of stainless steel members for the case of fire is still not completely understood, thus motivating and justifying the development of more studies with the objective to achieve more precise and safe formulations for these members.

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