

Lateral-torsional buckling of ferritic stainless steel beams in case of fire

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Abstract

This work presents a numerical study of the behaviour of ferritic stainless steel I-beams subjected to lateral-torsional buckling and compares the obtained results with the beam design curves of Eurocode 3. New formulae, for the lateral-torsional buckling, that approximate better the real behaviour of ferritic stainless steel structural elements in case of fire are proposed. These new formulae were based on numerical simulations using the program SAFIR, which was modified to take into account the material properties of the stainless steel.

Keywords: ferritic, stainless steel, Eurocode 3, numerical modelling, lateral-torsional buckling, fire.

1 Introduction

There are five basic groups of stainless steels, classified according to their metallurgical structure: the austenitic, ferritic, martensitic, duplex austenitic-ferritic and precipitation-hardening groups [1]. Austenitic stainless steels provide a good combination of corrosion resistance, forming and fabrication properties. Duplex stainless steels have high strength and wear resistance with very good resistance to stress corrosion cracking. The most commonly used grades, typically referred to as the standard austenitic grades, are 1.4301 (widely known as 304) and 1.4401 (widely known as 316). The austenitic stainless steels are generally the more useful groups for structural applications but increasing interest in ferritic steels for structural purposes has been recently noted due to its low cost. The responsibility of the final cost of the austenitic stainless steel is the price of nickel. Typically they contain 8.0-13.0% of nickel whereas ferritic



stainless steels contain a low nickel level. The ferritic stainless steel 1.4003 studied in this work contains 0.3-1.0%.

The biggest advantage of stainless steel is its higher corrosion resistance. However, its easy maintenance, high durability and reduced life cycle costs are also important properties. It is also known that the fire resistance of stainless steel is higher than the carbon steel usually used in construction.

EN 1993-1-4 "Supplementary rules for stainless steels" [2] gives design rules for stainless steel structural elements at room temperature, only making mention to its fire resistance by doing referring to the fire part of the Eurocode 3, EN 1993-1-2 [3].

Although its use in construction is increasing, it is still necessary to develop the knowledge of its structural behaviour. Stainless steels are known by their non-linear stress-strain relationships with a low proportional stress and an extensive hardening phase. There is not a well defined yield strength, being usually considered for design at room temperature the 0.2% proof strength, $f_y=f_{0.2\text{proof}}$. In a fire situation higher strains than at room temperature are acceptable, so Part 1.2 of Eurocode 3 suggests the use of the stress at 2% total strain as the yield stress at elevated temperature θ , $f_{y,\theta}=f_{2,\theta}$, for Class 1, 2 and 3 cross-sections and $f_{y,\theta}=f_{0.2\text{proof},\theta}$, for Class 4. Comparison of the reduction of strength and elastic stiffness of structural carbon steel and stainless steel at elevated temperature for several grades of stainless steels (as defined in EN 1993-1-2 [3]) is shown in figures 1 and 2, where $k_{y,\theta}=f_{y,\theta}/f_y$ and $k_{E,\theta}=E_\theta/E$, being $f_{y,\theta}$ and f_y the yield strength at elevated temperature and at room temperature respectively, and E_θ and E the modulus of elasticity at elevated temperature and at room temperature.

The stainless steel mechanical and thermal properties at high temperatures, used in this paper, can be found in Part 1-2 of Eurocode 3 [3]. For the evaluation of the yield strength reduction factor, the Eurocode states that the following equation should be used:

$$k_{y,\theta} = \left[f_{0.2p,\theta} + k_{2\%,\theta} (f_{u,\theta} - f_{0.2p,\theta}) \right] \frac{1}{f_y} \quad (1)$$

where

$f_{0.2p,\theta}$ is the proof strength at 0.2% plastic strain, at temperature θ ;

$k_{2\%,\theta}$ is the correction factor for determination of the yield strength $f_{y,\theta}$;

$f_{u,\theta}$ is the ultimate tensile strength, at temperature θ .

Despite both carbon and stainless steel exhibiting different constitutive laws, whereby stainless steel presents a pronounced non-linear behavior even for low stress values, the stainless steel design rules are based on those developed for carbon steel. In a previous paper [4] a new proposal for the lateral-torsional buckling of austenitic grades stainless steel beams was made. In the present paper a similar study is done for the ferritic stainless steel grade 1.4003 (the only ferritic stainless steel presented in Part 1.2 of the Eurocode 3).

Figure 1 shows that the variation of the strength reduction of the stainless steel grade 1.4003 with temperature is different from the other grades, mainly for the temperature range from 500°C to 700°C.



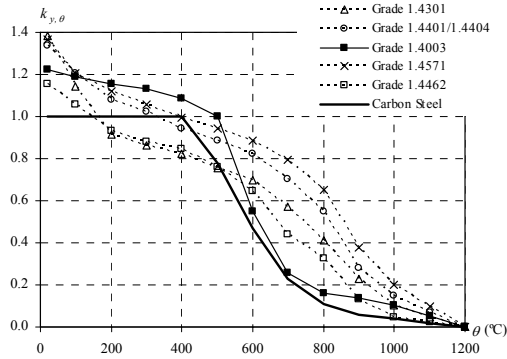


Figure 1: Strength reduction at high temperatures.

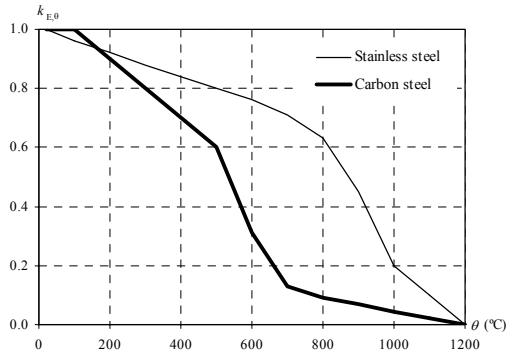


Figure 2: Elastic stiffness reduction at high temperatures.

The reduction of the yield strength and the reduction of the modulus of elasticity are used in the determination of the non-dimensional slenderness at high temperatures, as it will be shown later in this work.

Program SAFIR [5], a geometrical and material non linear finite element code, which has been adapted according to the material properties defined in EN 1993-1-4 [2] and EN 1993-1-2 [3], to model the behaviour of stainless steel structures [6] has been used in the numerical simulations. This program, widely used by several investigators, has been validated against analytical solutions, experimental tests and numerical results from other programs, and has been used in several studies that lead to proposals for safety evaluation of structural elements, already adopted in Eurocode 3. In the numerical simulations, geometrical imperfections and residual stresses were considered [4].

The objective of the study presented in this paper is to evaluate the accuracy of the lateral-torsional buckling design procedures prescribed in Eurocode 3, for I cross-sections in stainless steel grade 1.4003, at high temperatures. This study concluded that the Eurocode 3 formulae need to be improved and that a new proposal should be made for the stainless steel grade 1.4003.



2 Case study

A simply supported beam with fork supports subjected to uniform bending diagram was chosen to explore the validity of the beam safety verifications.

The influence of the cross-sectional shape, assessed using the height/width (h/b) relation, was taken into account in this work. Equivalent welded cross-sections equivalent to an IPE220 (representative of h/b = 2), HE500A (representative of h/b < 2) and IPE500 (representative of h/b > 2) were studied.

A uniform temperature distribution in the cross-section was used so that comparison between the numerical results and the Eurocode could be made. In this paper, the temperatures chosen were 400, 500, 600 and 700 °C, deemed to cover the majority of practical situations.

In the numerical simulations, a lateral geometric imperfection given by the following expression was considered:

$$y(x) = \frac{l}{1000} \sin\left(\frac{\pi x}{l}\right) \tag{2}$$

where *l* is the length of the beam. An initial rotation around the beam axis with a maximum value of *l*/1000 radians at mid span was also considered.

The adopted residual stresses follow the typical patterns for carbon steel welded sections, considered constant across the thickness of the web and flanges. The distribution is shown in Figure 3, and has the maximum value of *f_y* (yield strength) [7–9].

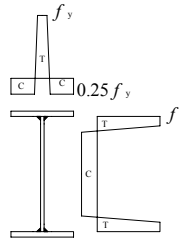


Figure 3: Residual stresses: C – compression; T – tension.

3 Formulae for lateral-torsional buckling

3.1 Eurocode 3 formulae for stainless steel elements

For stainless steel beams subjected to high temperatures, Part 1-4 of Eurocode 3 [2] states that the same formulation prescribed for carbon steel elements should be used, according to the EN 1993-1-2 [3], where the lateral-torsional buckling resistance for class 1 and class 2 cross-sections is given by

$$M_{b,fi,t,Rd} = \chi_{LT,fi} W_{pl,y} k_{y,\theta} f_y \frac{1}{\gamma_{M,fi}} \tag{3}$$

where

$$\chi_{LT,\bar{f}_i} = \frac{1}{\varphi_{LT,\theta} + \sqrt{(\varphi_{LT,\theta})^2 - (\bar{\lambda}_{LT,\theta})^2}} \quad (4)$$

with

$$\varphi_{LT,\theta} = \frac{1}{2} \left[1 + \alpha \bar{\lambda}_{LT,\theta} + (\bar{\lambda}_{LT,\theta})^2 \right] \quad (5)$$

In this expression the imperfection factor α depends on the steel grade and is given by

$$\alpha = \beta \sqrt{235 / f_y} = 0.65 \sqrt{235 / f_y} \quad (6)$$

The non-dimensional slenderness for lateral-torsional buckling at high temperatures is given by

$$\bar{\lambda}_{LT,\theta} = \bar{\lambda}_{LT} \left[\frac{k_{y,\theta}}{k_{E,\theta}} \right]^{0.5} \quad (7)$$

being

$$\bar{\lambda}_{LT} = \sqrt{\frac{W_{pl,y} f_y}{M_{cr}}} \quad (8)$$

where $W_{pl,y}$ is the plastic bending modulus, f_y is the yield strength of steel and M_{cr} is the elastic critical moment for lateral-torsional buckling.

3.2 Proposal for austenitic and duplex stainless steel elements

Figure 4 shows that the stainless steel beam design curve for lateral-torsional buckling from Eurocode 3 is not on the safe side. To improve this curve new severity factors β , given in table 1, different from the one used for carbon steel (see equation 6), were proposed by the authors [4, 6]. The new severity factor takes into account the influence of the shape of the cross-section. In this previous work the authors did not consider the influence of the stainless steel grade.

4 Comparison between the lateral-torsional buckling formulae and the numerical results

Application of eqs. (3) to (8) and Table 1 to ferritic stainless steels leads to the results of Figure 5, that compare the numerical results and the code proposals. It is clear that this proposal, based on austenitic stainless steels, is not accurate for ferritic stainless steels.

In this figure it can be observed that a beam with a length of 5 m exhibits slenderness values for 700°C and 600°C quite different from the corresponding values for 400°C and 500°C. These differences are not so big for the case of austenitic stainless steel as shown in fig. 4. These differences result from the reduction of the yield strength (see fig. 1) is shown in fig. 6. As it can be seen in



equation (7) the slenderness at room temperature is multiplied by the factor $(k_{y,\theta}/k_{E,\theta})^{1/2}$ in order to obtain the slenderness at high temperatures. Figure 6 shows that from 500°C to 700°C there is a great decrease of this factor for the 1.4003 stainless steel, which does not occur with the others stainless steel grades.

Table 1: Values of the severity factor β .

Cross-section	Limits	β
Welded I section	$h/b \leq 2$	0.85
	$h/b > 2$	1.00

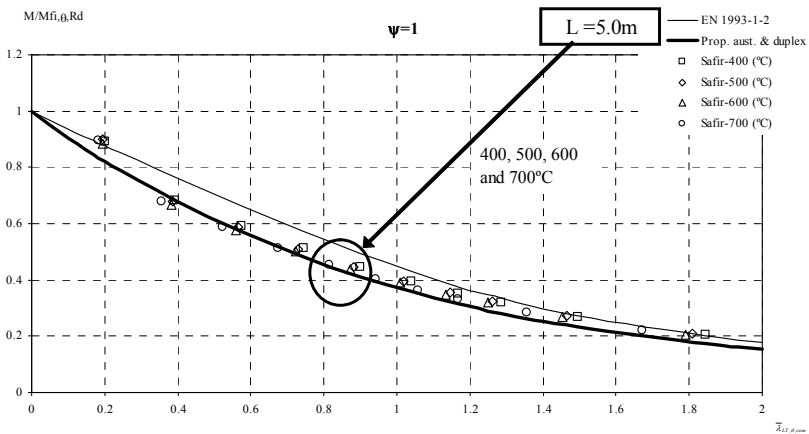


Figure 4: Lateral-torsional buckling in IPE 500 beams of the stainless steel grade 1.4301.

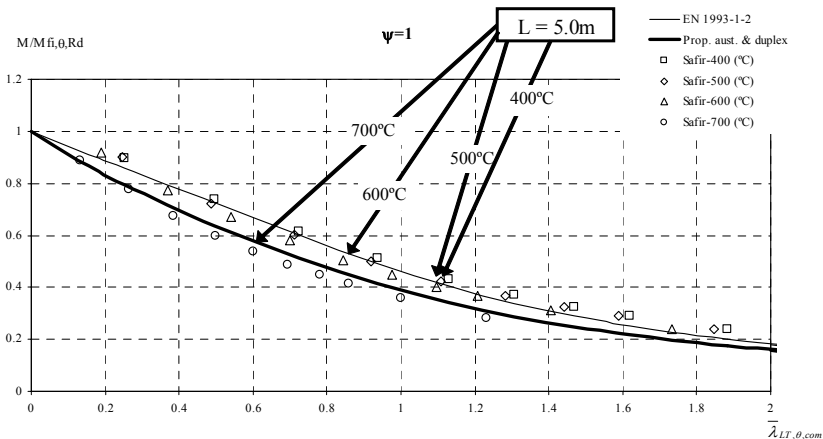


Figure 5: Lateral-torsional buckling for in IPE500 beams of the stainless steel grade 1.4003.

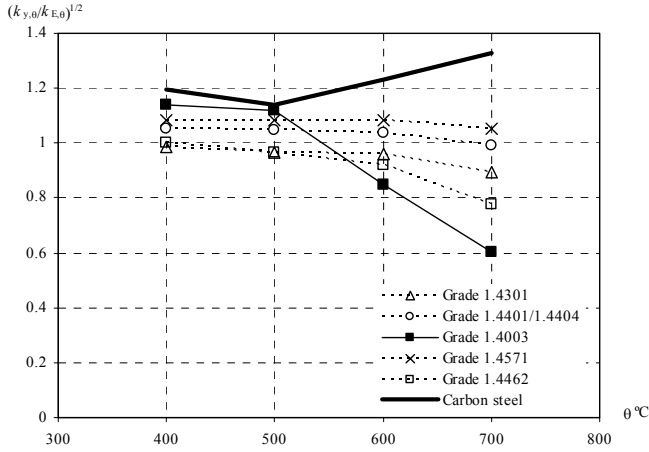


Figure 6: Variation of the square root used in the determination of the slenderness.

From figure 5 it can be concluded that the previous proposal [4] and the Eurocode 3 are not safe for the case of the ferritic stainless steel grade 1.4003. In the next section a new proposal covering ferritic stainless steel grades will be presented.

5 New proposal for the ferritic stainless steel grade 1.4003

Based on a parametric study considering the influence of the shape of the cross-section a new severity factor β , given in table 2, was found for the stainless steel grade 1.403.

Table 2: Values of the severity factor β for the 1.4003.

Cross-section	Limits	β
Welded I section	$h/b \leq 2$	1.00
	$h/b > 2$	1.20

Figures 7 to 9, compare the beam design curves obtained using Part 1-2 of Eurocode 3, described in section 3.1 of this paper (denoted “EN 1993-1-2”), the curve obtained with the new severity factor given in table 2 (denoted “New proposal”), and the numerical results obtained with the program SAFIR.

Table 3 summarizes the new severity factor taking into account the influence of the type of the stainless steel.



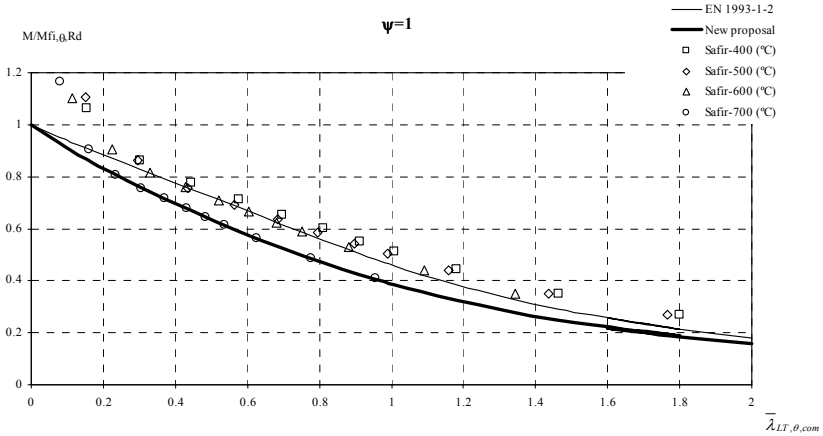


Figure 7: Lateral-torsional buckling in HE500A beams (representative of $h/b < 2$) of the stainless steel grade 1.4003.

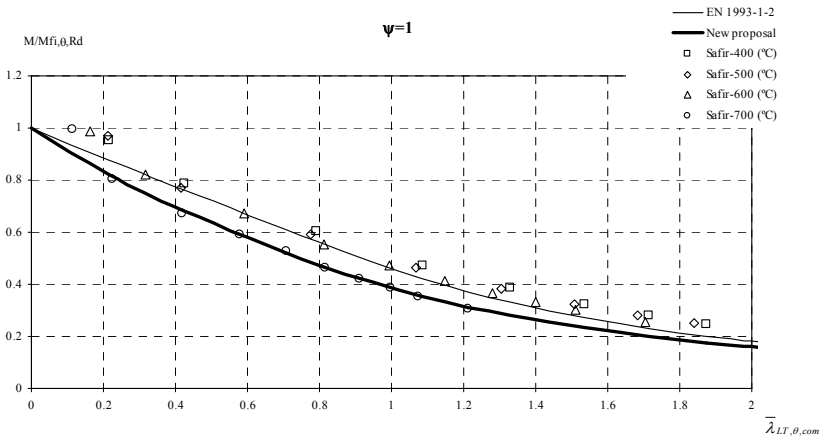


Figure 8: Lateral-torsional buckling in IPE220 beams (representative of $h/b = 2$) of the stainless steel grade 1.4003.

6 Conclusions

This paper has shown that the previous proposal made by the authors [4], for the lateral-torsional buckling resistance of unrestrained stainless steel beams under fire loading, based on the austenitic stainless steel, is not safe for the ferritic stainless steel grade 1.4003. A new severity factor that takes into account the influence of the steel grade, as well as the influence of the slenderness of the cross-section (relation h/b of the cross-section) has been proposed being in good agreement with the numerical results obtained with the program SAFIR. This



study also has shown that the slenderness of the cross-section should be taken into account as it is already proposed in Eurocode 3 for carbon steel elements at room temperature.

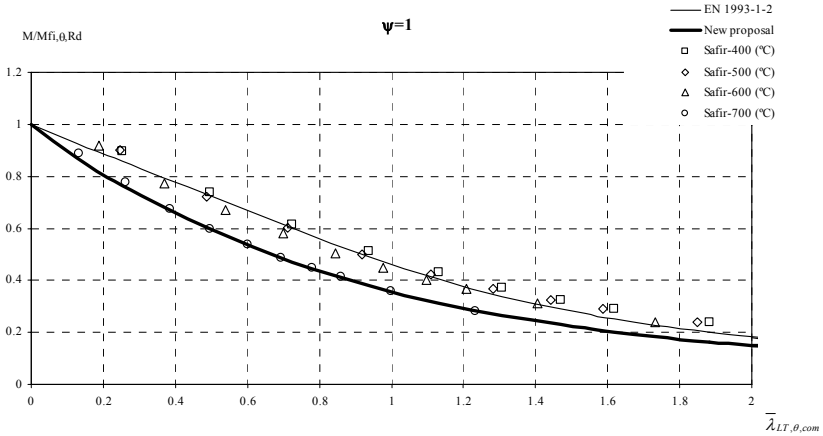


Figure 9: Lateral-torsional buckling in IPE500 beams (representative of $h/b > 2$) of the stainless steel grade 1.4003.

Table 3: New proposal for the severity factor β .

Cross-section	Limits	β	
		Austenitic and Duplex stainless steel	Ferritic stainless steel 1.4003
Welded I section	$h/b \leq 2$	0.85	1.00
	$h/b > 2$	1.00	1.20

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