FLEXURAL BUCKLING OF AXIALLY LOADED FERRITIC STAINLESS STEEL COLUMNS IN CASE OF FIRE

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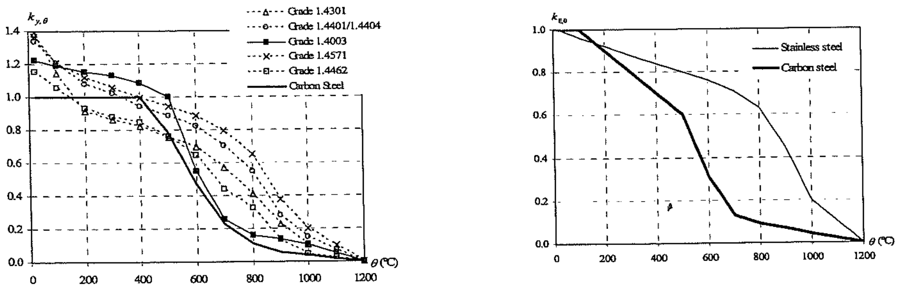
INTRODUCTION

The stainless steels can be subdivided in five basic groups, according to their metallurgical structure: the austenitic, ferritic, martensitic, duplex austenitic-ferritic and precipitation-hardening groups [1]. The austenitic stainless steels give good combination of corrosion resistance, forming and fabrication properties. The duplex stainless steels have high strength and wear resistance with very good resistance to stress corrosion cracking. The most commonly used grades, for structural applications, are the austenitics 1.4301 (widely known as 304) and 1.4401 (widely known as 316). However increasing interest in ferritic steels has been recently noticed due to its low cost. The high final cost of the austenitic stainless steel is due to the price of nickel. Typically they contain 8.0-13.0% of nickel whereas ferritic stainless steels contain a lower nickel level. The ferritic stainless steel 1.4003 studied in this work contains 0.3-1.0%.
The use of stainless steel is increasing however 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, $f_y=f_{0.2proof}$.
The EN 1993-1-4 "Supplementary rules for stainless steels" [2] gives design rules for stainless steel structural elements at room temperature, and only makes mention to its fire resistance by referring to the fire part of the Eurocode 3, EN 1993-1-2 [3]. 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 $f_{y,\theta}=f_{0.2proof,\theta}$, 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 figure 1, 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:

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

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 $f_{y,\theta}$ and $f_{u,\theta}$ 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 behaviour 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 flexural buckling of austenitic grades stainless steel columns 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 a) 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.



a) Strength reduction b) Elastic stiffness reduction

Fig. 1. Mechanical properties 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 flexural buckling design procedures prescribed in Eurocode 3, for welded 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.

1 CASE STUDY

An axially loaded column, was chosen to explore the validity of the column safety verifications of the Eurocode 3 in case of fire.

The following welded cross-sections were used: equivalent HEB 200 section and equivalent HEB 280 section. The ferritic stainless steel grade 1.4003 was studied for each cross-section. 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 with maximum amplitude of $l/1000$ [6], was adopted.

The adopted residual stresses follows the typical pattern for carbon steel welded sections, considered constant across the thickness of the web and flanges [7].

2 FORMULAE FROM EUROCODE 3 FOR THE FLEXURAL BUCKLING OF STAINLESS STEEL COLUMNS IN CASE OF FIRE

For stainless steel columns subjected to high temperatures, Part 1.4 of Eurocode 3, refers that the same formulation prescribed for carbon steel elements should be used, following EN 1993-1-2 [1], where the flexural buckling resistance for class 1, 2 and 3 sections, is

$$N_{b,fi,t,Rd} = \chi_{fi} A k_{y,\theta} f_y \frac{1}{\gamma_{M,fi}} \tag{2}$$

where χ_{fi} is given by

$$\chi_{fi} = \frac{1}{\phi_\theta + \sqrt{\phi_\theta^{\,2} - \bar{\lambda}_\theta^{\,2}}} \tag{3}$$

with

$$\phi_\theta = \frac{1}{2}\left[1 + \alpha\bar{\lambda}_\theta + \bar{\lambda}_\theta^{\,2}\right] \tag{4}$$

In this expression the imperfection factor α is a function of the steel grade and is given by

$$\alpha = 0.65\sqrt{235/f_y} \tag{5}$$

The normalized slenderness for flexural buckling at high temperatures is given by

$$\bar{\lambda}_\theta = \bar{\lambda}\left[\frac{k_{y,\theta}}{k_{E,\theta}}\right]^{0.5} \tag{6}$$

3 PROPOSAL FOR AUSTENITIC STAINLESS STEEL ELEMENTS

As it can be observed in figure 2, the curve resulting from the application of part 1.2 of Eurocode 3 is not on the safe side. To improve these results, a new imperfection factor α, different from the one defined for carbon steel, and given in equation (7), is proposed for the flexural buckling of austenitic stainless steel columns [4].

$$\alpha = \beta\varepsilon \tag{7}$$

with ε given in the part 1.1 of Eurocode 3 [8]

$$\varepsilon = \sqrt{235/f_y} \tag{8}$$

where a value of 1.4 is proposed for the severity factor β.
The reduction factor χ_{fi} is also changed according to

$$\chi_{fi} = \frac{1}{\phi_\theta + \sqrt{\phi_\theta^{\,2} - \gamma\bar{\lambda}_\theta^{\,2}}} \tag{9}$$

with

$$\phi_\theta = \frac{1}{2}\left[1 + \alpha\bar{\lambda}_\theta + \gamma\bar{\lambda}_\theta^{\,2}\right] \tag{10}$$

where the factor γ should take the value 1.5.

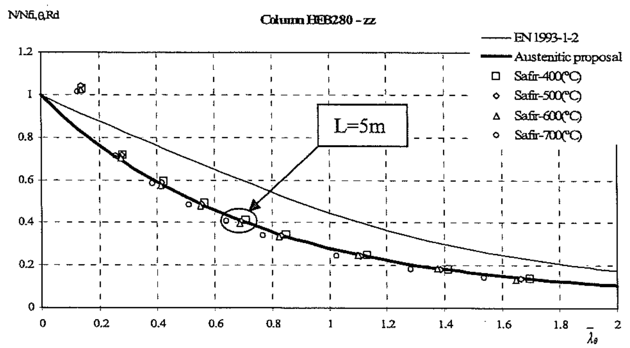


Fig. 2. Flexural buckling in stainless steel grade 1.4301 columns at high temperatures

4 COMPARISON BETWEEN THE FLEXURAL BUCKLING FORMULAE AND THE NUMERICAL RESULTS FOR FERRITIC GRADE

Application of equations (2) to (10) to ferritic stainless steels leads to the results of Figure 3, which compares the numerical results and the code proposals. It is clear that the austenitic proposal is not accurate for ferritic stainless steels.

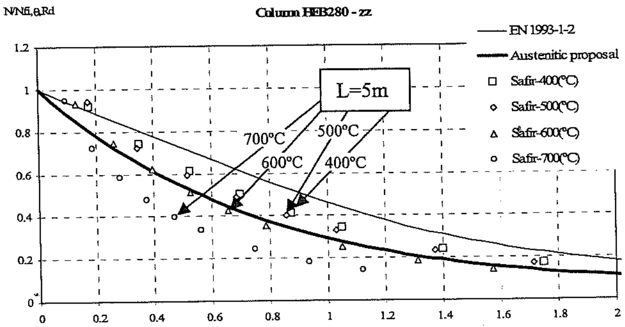


Fig. 3. Flexural buckling in stainless steel grade 1.4003 columns at high temperatures

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. 2. These differences result from the reduction of the yield strength (see figure 1). As it can be seen in equation (6) 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 4 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.

From figure 3 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.

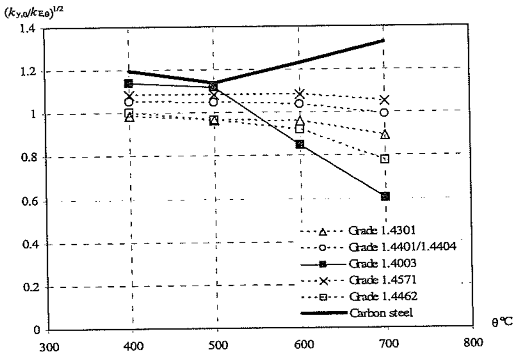


Fig. 4. Variation of the square root used in the determination of the slenderness

5 NEW PROPOSAL FOR THE FERRITIC STAINLESS STEEL GRADE 1.4003

Based on the proposal made for austenitic stainless steel (see section 2) a new imperfection factor α, was found for the stainless steel grade 1.4003 (equation (11)), using equation (7) and ε given in part 1.4 of the Eurocode 3 [2]

$$\alpha = \beta\sqrt{\frac{235}{f_y}\frac{E}{210000}}\sqrt{\frac{k_{E,\theta}}{k_{y,\theta}}} \tag{11}$$

where the severity factor β takes the value of 1.5, the young modulus of the ferritic stainless steel grades is 220000MPa and the yield strength of the 1.4003 grade is 250MPa.
This imperfection factor takes in to account the reduction of the yield strength shown in figure 1 in the stainless steel grade 1.4003.
Figures 5 to 8, compare the beam design curves obtained using Part 1.2 of Eurocode 3, described in section 3 of this paper (denoted "EN 1993-1-2"), the curve obtained with the new imperfection factor given in equation (11) (denoted "New proposal"), and the numerical results obtained with the program SAFIR.

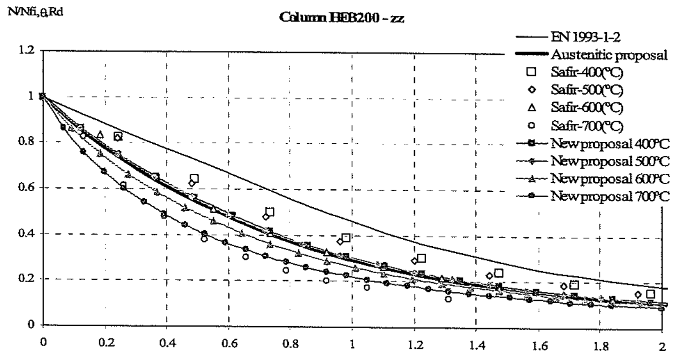


Fig. 5. Flexural buckling around the zz-axis in stainless steel HEB200 column at high temperatures

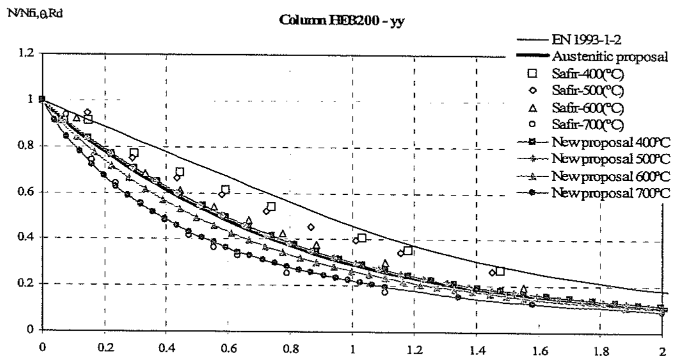


Fig. 6. Flexural buckling around the yy-axis in stainless steel HEB200 column at high temperatures

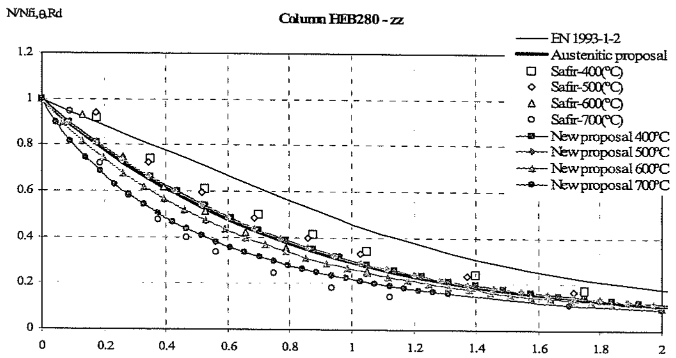


Fig. 7. Flexural buckling around the zz-axis in stainless steel HEB280 column at high temperatures

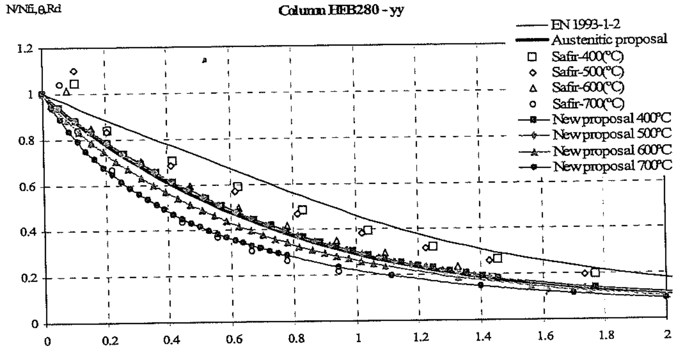


Fig. 8. Flexural buckling around the yy-axis in stainless steel HEB280 column at high temperatures

7 CONCLUSIONS

This paper has shown that the previous proposal made by the authors [4], for the flexural buckling resistance of stainless steel columns under fire loading, based on the austenitic stainless steel, and the Eurocode prescriptions are not safe for the ferritic stainless steel grade 1.4003.

A new imperfection factor that takes into account the influence of the steel grade, and the reduction of the yield strength with the temperature increase, has been proposed being in a better agreement with the numerical results obtained with the program SAFIR.

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