NUMERICAL MODELLING OF THIN-WALLED STAINLESS STEEL STRUCTURAL ELEMENTS IN CASE OF FIRE

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ABSTRACT

In this paper, numerical tests made in stainless steel thin-walled elements, using the program SAFIR, will be presented.

In order to make these simulations, two main changes in SAFIR were made: i) the program was changed in order to deal with the stainless steel 2D material properties to be used with shell elements and ii) the possibility of the program to take into account residual stresses in shell elements was introduced.

The stainless steel stress-strain relationship at high temperatures, was based on the one presented in part 1.2 of Eurocode 3 [1], which has no initial linear branch as the case of carbon steel.

The hardening rule to be used on the shell element formulation could not be exactly established without an approximation of the Eurocode 3 constitutive law [1].

Due to the fact that the SAFIR procedure to take into account the residual stresses consists in transforming them first into residual strains and adding them after to the other initial strains [2], it was necessary to implement a procedure that took in consideration the non-linearity of the material stress-strain relationship.

The paper shows the influence of the residual stresses on the ultimate load bearing resistance of thin-walled stainless steel structural elements in case of fire.

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1. INTRODUTION

Stainless steel has countless desirable characteristics for a structural material [3, 4, 5]. Even though 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. A well defined yield strength does not exist, the conventional limit of elasticity at 0.2% is usually considered.

The EN 1993-1-4 "Supplementary rules for stainless steels" [6] gives design rules for stainless steel structural members at room temperature, mentioning fire resistance making reference to the fire part of the Eurocode 3, EN 1993-1-2 [1], see figure 1.

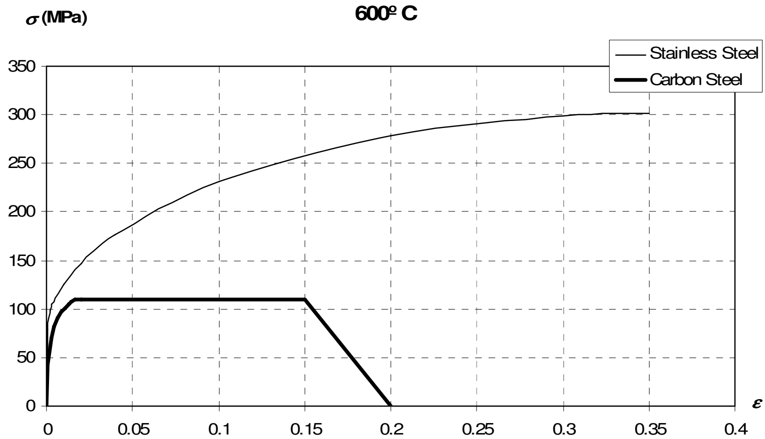

Fig. 1 – Stress-strain relationships of carbon steel S 235 and stainless steel 1.4301 at 600 ºC.

Program SAFIR [7], a geometrical and material non linear finite element code, which has been adapted according to the material properties defined in EN 1993-1-4 [6] and EN 1993-1-2 [1], to model the behaviour of stainless steel structures 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.

The stainless steel stress-strain relationship at high temperatures has no initial linear branch as for carbon steel, and the hardening rule to be used on the shell element formulation could not be exactly established without an approximation of the Eurocode 3 constitutive law [1].

Due to the fact that the SAFIR procedure to take into account the residual stresses consists in transforming them first into residual strains and adding them after to the other initial strains [2], it was necessary to implement a procedure that took in consideration the non-linearity of the material stress-strain relationship.

The objective of the study presented in this paper is to evaluate the accuracy of the hardening law introduced for the shell elements in SAFIR, and with these introduced 2D material properties of stainless steel it is evaluated the influence of the residual stresses in thin-walled stainless steel cross-section. Thus this paper shows the influence of the residual stresses on the ultimate load bearing resistance of Class 4 stainless steel structural elements, in case of fire.

2. SOFTWARE DEVELOPMENT

In order to make this study it were introduced some modifications in the program SAFIR. The two main changes were:

- changing the program SAFIR in order to deal with the stainless steel 2D material properties, with the purpose of using shell elements in the numerical simulations of thin walled stainless steel structural elements.
- introducing the possibility of the program SAFIR accounts with residual stresses in shell elements in elastic materials and in stainless steel.

2.1 Stainless steel 2D material properties introduced in SAFIR

The modelling of the material stainless steel was made by a non-elastic plane stress based on the von Mises surface and on isotropic hardening. The constitutive law of the stainless steel has a permanent non-linear behaviour.

The Shell element from SAFIR is programmed to be used in large displacements in the plane stress state. This finite element was first introduced for elastic materials and then for bi-dimensional elastic-plastic material law [8].

For the stainless steel it was used the same formulation used in the carbon steel [8], but, due to the different stress-strain relationship (see figure 1) it was necessary to achieve a different hardening rule for the stainless steel.

The stainless steel stress-strain relationship at high temperatures used in this work was the one prescribed in part 1.2 of Eurocode 3 [1] and is described in Table 1 and in Figure 2.

Table 1 – Expressions of the constitutive law of the stainless steel at high temperatures

Strain range	Stress σ	Tangent modulus
$\varepsilon \le \varepsilon_{c,\theta}$	$\dfrac{E \cdot \varepsilon}{1 + a \cdot \varepsilon^b}$	$\dfrac{E\left(1 + a \cdot \varepsilon^b - a \cdot b \cdot \varepsilon^b\right)}{\left(1 + a \cdot \varepsilon^b\right)^2}$
$\varepsilon_{c,\theta} < \varepsilon < \varepsilon_{u,\theta}$	$f_{0.2p,\theta} - e + (d/c)\sqrt{c^2 - (\varepsilon_{u,\theta} - \varepsilon)^2}$	$\dfrac{d\left(\varepsilon_{u,\theta} - \varepsilon\right)}{c\sqrt{c^2 - \left(\varepsilon_{u,\theta} - \varepsilon\right)^2}}$
Parameters	$\varepsilon_{c,\theta} = f_{0.2p,\theta} / E_{a,\theta} + 0.002$	
Functions	$a = \dfrac{E_{a,\theta}\,\varepsilon_{c,\theta} - f_{0.2p,\theta}}{f_{0.2p,\theta}\,\varepsilon_{c,\theta}^{\;b}}$ $\quad b = \dfrac{(1 - \varepsilon_{c,\theta}\,E_{ct,\theta} / f_{0.2p,\theta})\,E_{a,\theta}\,\varepsilon_{c,\theta}}{(E_{a,\theta}\,\varepsilon_{c,\theta} / f_{0.2p,\theta} - 1)\,f_{0.2p,\theta}}$ $c^2 = (\varepsilon_{u,\theta} - \varepsilon_{c,\theta})\left(\varepsilon_{u,\theta} - \varepsilon_{c,\theta} + \dfrac{e}{E_{ct,\theta}}\right)$ $\quad d^2 = e\,(\varepsilon_{u,\theta} - \varepsilon_{c,\theta})\,E_{ct,\theta} + e^2$ $e = \dfrac{(f_{u,\theta} - f_{0.2p,\theta})^2}{(\varepsilon_{u,\theta} - \varepsilon_{c,\theta})E_{ct,\theta} - 2\,(f_{u,\theta} - f_{0.2p,\theta})}$	

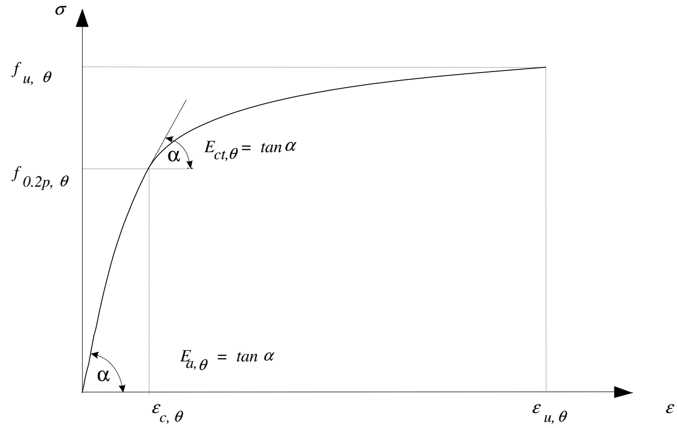

Fig. 2 –Stress-strain relationship of the stainless steel at elevated temperatures

In table 1 it can be found the constitutive law given by the function $\sigma = f(\varepsilon)$. The hardening rule used in SAFIR, $\tau = g(k)$, can be obtained using $\varepsilon = k + \dfrac{\sigma}{E}$ and making $\tau = \sigma$.

For the second branch ($\varepsilon_{c,\theta} < \varepsilon < \varepsilon_{u,\theta}$) it was possible to use this process to achieve the hardening rule, but for $\varepsilon < \varepsilon_{c,\theta}$ the equation $\sigma = E \cdot \varepsilon /(1 + a \cdot \varepsilon^b)$ did not allow this conversion. Therefore it was developed the equation (1) that approximates the hardening function for the first branch of the stainless steel constitutive law.

$$\tau = b \cdot k^2 + c \cdot k + d + a \cdot \sqrt{k} \tag{1}$$

The parameters *a*, *b*, *c* and *d* were obtained imposing that equation (1) should satisfy the boundary conditions, resulting in

$$\begin{cases} a = 56.0362 \cdot f_{0.2p,\theta} - 0.112 \cdot h \\ b = 63501.9 \cdot f_{0.2p,\theta} - 127.1 \cdot h \\ c = -880.512 \cdot f_{0.2p,\theta} + 2.763 \cdot h \\ d = 0.001 \cdot f_{0.2p,\theta} \end{cases} \tag{2}$$

where *h* is the value of $\dfrac{\partial \tau}{\partial k}(0.002)$ in the second branch.

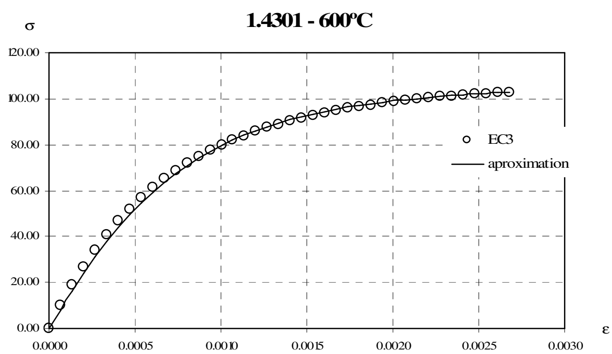

Fig. 3 – Stainless steel constitutive law: comparison between the approximation used for 2D analysis and the Eurocode 3 at 600ºC, for the 1.4301.

Figure 3 shows a comparison between the stress-strain relationship obtained with Eurocode 3 and with the approximation given by equation (1).

2.2 Shell elements residual stresses introduced in SAFIR

In order to introduce the possibility of the SAFIR accounts with residual stresses it is first necessary to transform them into residual strains and then to add them to the other initial strains. This was the formulation adopted in SAFIR for the others finite elements [2].

Due to this procedure the methodology to be adopted for the consideration of the residual stresses, depends on the linearity or non-linearity of the material stress-strain relationship. Therefore the introduction of this consideration was made for all the materials, that have a first elastic phase in its material behaviour and provided that the residual stresses are always in that elastic phase, which is not the case for stainless steel.

As the stainless steel has a non-linear stress-strain relationship, another procedure was used. This procedure begins with the determination of a "comparison stress" of von Mises (see equation 3) of the residual stresses introduced.

$$\sigma_{c,res} = \sqrt{\sigma_{x,res}^2 - \sigma_{x,res} \cdot \sigma_{y,res} + \sigma_{y,res}^2 + 3 \cdot \tau_{xy,res}} \tag{3}$$

With this "comparison stress" and with the constitutive law it is possible using the Newton-Raphson method to achieve a residual "comparison strain". Due to the fact that it was used in SAFIR an approximation to the hardening law of the stainless steel, as explained in the section 2.1 of this paper, this approximation of the hardening law was also used to determine the residual "comparison strain".

With the comparison residual strain and with the comparison residual stress it is possible to determine a secant modulus $E_{\sec} = \dfrac{\sigma_{c,res}}{\varepsilon_{c,res}}$. This modulus is used in the elasticity matrix [D] necessary to evaluate the residual strains

$$\{\varepsilon_{res}\} = [D]^{-1} \cdot \{\sigma_{res}\} \tag{4}$$

3. VALIDATION OF THE SOFTWARE DEVELOPMENT

These developments in the Shell finite elements of the program SAFIR are analysed in this section, being the results obtained with them, compared with the 3D Beam finite element of SAFIR, with the 3D Beam finite element of the commercial software ANSYS and with some experimental tests made by Ala-Outinen et al [9].

Here, the approximation to the stainless steel hardening law described in section 2.1 is tested. These comparisons are made for elements with Class 1 sections. The flexural buckling of a square hollow section and the lateral-torsional buckling of an I-cross section are analysed with shell and beam finite elements, and the results compared between them.

3.1 Flexural buckling in a Class 1 stainless steel square hollow section

The same Class 1 hollow section SHS40x40x4 used in reference [9] to make experimental test on stainless steel columns in case of fire, has been adopted. The round corners were not considered in the finite element mesh used to discretize the cross-section.

In the numerical simulations, a lateral geometric imperfection given by the following expression was considered [10]:

$$y(x) = \frac{l}{1000}\sin\left(\frac{\pi x}{l}\right) \tag{5}$$

where l is the length of the column.

No residual stresses were introduced in these first simulations. The yield strength and the ultimate strength considered were, according to the Eurocode 3, 210MPa and 520MPa respectively. It wasn't considered the increasing of the yield strength in the corner regions [11]. The comparisons were made with uniform temperature in the cross-section.

In figure 4 it is shown the results obtained for different temperatures using the beam-finite elements from SAFIR and from ANSYS. These results are compared with the Eurocode 3 (denoted "EN 1993-1-2").

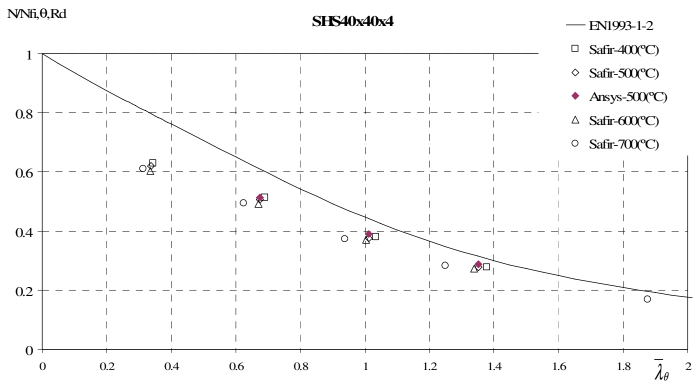

Fig. 4 – SHS40x40x4 numerical results using 3D beam finite elements.

The yield strength and the ultimate strength measured in the experimental tests in reference [9] had the value of 595MPa and 736MPa respectively, therefore these were the values considered in the results presented in figure 5. The load level, the length and the support conditions of the simulations with SAFIR are the same used in the experimental tests. In the graphic "Outinen tests" correspond to the experimental tests, "Outinen tests SAFIR B" are the simulations of the experimental tests with the beam elements from SAFIR and "Outinen tests SAFIR S" are the simulations of the experimental test with the shell elements from SAFIR (see figure 6).

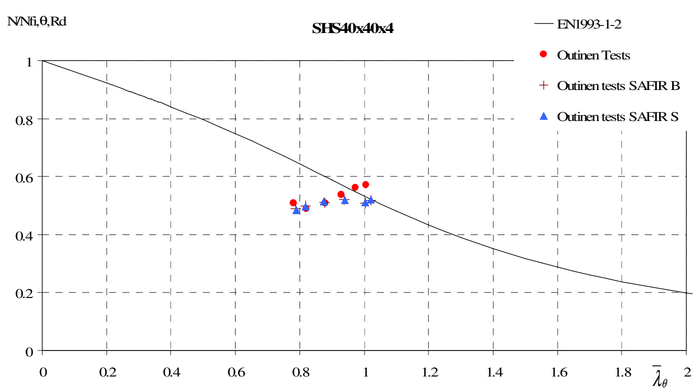

Fig. 5 – SHS40x40x4 numerical results with SAFIR using beam and shell finite elements compared with the experimental tests [9].

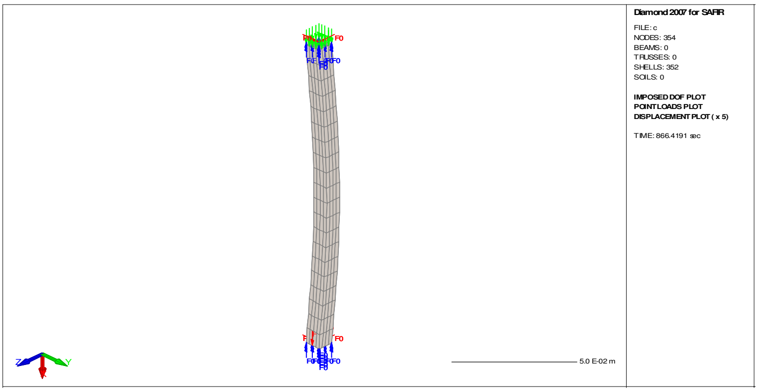

Fig. 6 – SHS40x40x4 column simulated with shell elements.

From figure 4 and 5 it can be concluded that the approximation used for the stainless steel hardening rule used in SAFIR gives a good approximation when compared with the results from others softwares and with experimental results.

3.2 Lateral-torsional buckling of a Class 1 stainless steel IPE welded section

In this section a comparison between the results obtained using the 2D material properties introduced in SAFIR for shell elements with the results obtained using 3D beam elements from SAFIR, with and without residual stresses, is presented.

It was chosen to test simply supported beams subjected to uniform bending with Class 1 welded IPE220 cross-section (see figure 7). In the numerical simulations, a lateral geometric imperfection given by expression (5) was considered. The yield strength and the ultimate strength considered were, according to the Eurocode 3, 210MPa and 520MPa respectively. The comparisons were made with uniform temperature of 600ºC in the cross-section.

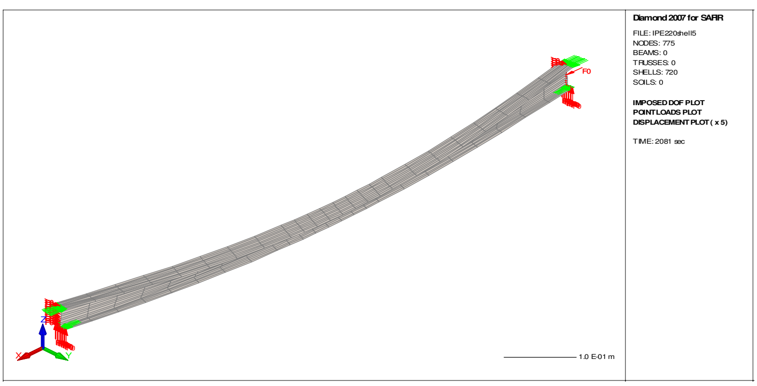

Fig. 7 – Simply supported stainless steel beam subjected to uniform bending.

The adopted residual stresses are considered as constant across the thickness of the webs and flanges. For the welded IPE section, the distribution shown in figure 8, that has the maximum value of f_y (yield strength) [12] was used.

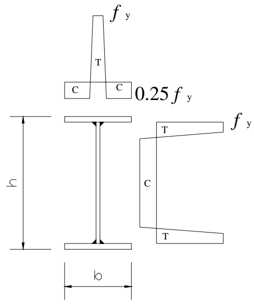

Fig. 8 – Residual stresses in an IPE welded section: C – compression; T – tension.

Table 2 – Results

		Without residual stresses	With residual stresses	Eurocode 3
L=3m	3D-Beam	20.6 kNm	19.9 kNm	20.3 kNm
	Shell	19.3 kNm	19.2 kNm	
L=5m	3D-Beam	15.7 kNm	15.0 kNm	14.1 kNm
	Shell	14.3 kNm	14.0 kNm	

From table 2 it can be concluded that the introduction of the residual stresses in shell elements, gives results that are in good agreement with the results obtained with the 3D beam elements.

4 RESIDUAL STRESSES IN CLASS 4 STAINLESS STEEL SQUARE HOLLOW SECTIONS

In order to study the influence of the residual stresses in Class 4 sections it is presented here a study.

It is compared the numerical results obtained for columns with the square hollow sections SHS150x150x3 and SHS200x200x5 of the stainless steel grade 1.4301. The yield strength and the ultimate strength considered were, according to the Eurocode 3, 210MPa and 520MPa respectively. The comparisons were made with uniform temperature of 600ºC in the cross-section. The tested columns had lengths of 0.9m with fixed ends and were subjected to centric axial compression (see figure 9). This length was chosen so that the collapse would be by local buckling instead of global buckling. In these numerical tests the curvature of the corners was considered.

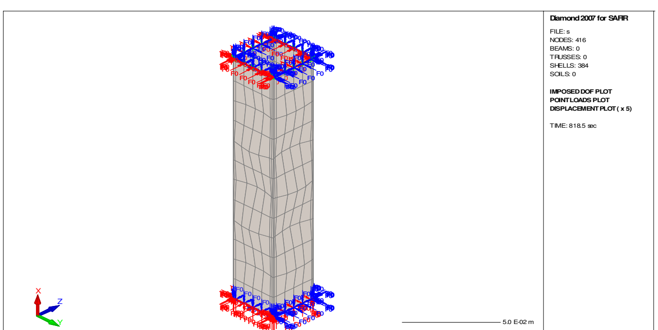

Fig. 9 – Stainless steel beam analysed with shell elements with residual stresses.

For the tested columns without residual stresses it was considered the following possibilities:

a) not having geometric imperfections and not introducing higher corners yield strength according to [11];
b) not having geometric imperfections but introducing higher corners yield strength;
c) having only global imperfections given by expression (5) and introducing higher corners yield strength;
d) having only local imperfections with a maximum value of b/200 [13] and introducing higher corners yield strength;
e) having global imperfections given by expression (5), local imperfections with a maximum value of b/200 and introducing higher corners yield strength;

Table 3 – Ultimate axial compression effort without residual stresses

Case	SHS150x150x3	SHS200x200x5
a)	160.5 kN	423.8 kN
b)	175.5 kN	473.6 kN
c)	174.5 kN	465.6 kN
d)	149.5 kN	387.9 kN
e)	149.5 kN	387.9 kN

From table 3 it can be concluded that no global imperfections are needed to be considered. Therefore it were introduced the residual stresses only in the case d).

The adopted residual stresses are considered as constant across the thickness of the internal section members. For the square hollow section, the distribution shown in figures 10, which has the maximum value of half of f_y [14] was used.

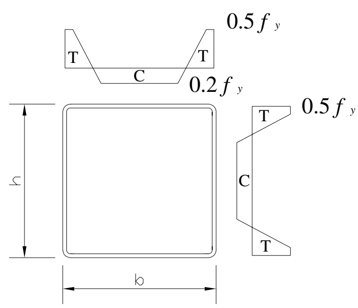

Fig. 10 – Residual stresses in a hollow section: C – compression; T – tension.

Table 4 shows the obtained results for columns with local imperfections with and without residual stresses

Table 4 – Ultimate axial compression effort with local imperfections

	SHS150x150x3	SHS200x200x5
Without residual stresses	149.5 kN	387.9 kN
With residual stresses	139.5 kN	376.5 kN
With/Without residual stresses	0.93	0.97
EN 1993-1-2 [1, 6, 13]	136.9 kN	356.8 kN

From these results it can be concluded that the influence of the residual stresses is low. However this influence is of the same magnitude of the one observed in table 2 for a Class 1 section.

The comparison with EC3 appears to show a good approximation to the numerical results.

4. CONCLUSIONS

This paper has shown that the approximation made for the stainless steel hardening law at high temperatures, to be used in the SAFIR shell elements, gives good results.

The influence of the residual stresses in the resistance of stainless steel Class 4 sections is low. However this influence is of the same magnitude to the one observed in table 2 for a Class 1 section, which leads to think that they should be also taken into consideration.

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