Fourth International Workshop «*Structures in Fire*» - Aveiro, Portugal - May of 2006

SiF'06

NUMERICAL MODELING OF THE BEHAVIOUR OF A STAINLESS STEEL PORTAL FRAME SUBJECTED TO FIRE

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ABSTRACT

It is known that stainless steel has a better fire performance than carbon steel, which can lead to a growing utilization of this kind of steel in structures. In fact, although more expensive than the carbon steel, structures in stainless steel can be competitive because of its smaller thermal protection need.

With the purpose of modelling by Finite Element Method the behaviour of a stainless steel framed structure, without any protection, submitted to fire, has been introduced in the SAFIR program, the material properties of the stainless steel. SAFIR is a finite element program with geometrical and material non-linear analysis, specially developed in the University of Liège for studying structures subjected to fire. The thermal and mechanical properties of the stainless steel, introduced in the SAFIR program are temperature dependent, according to the Eurocode 3. The stress strain relationship, the thermal conductivity and the specific heat are the most important material properties for the structure analysis at high temperatures. These properties in stainless steel are considerable different from carbon steel.

The behaviour of the structure will be compared in the two different materials: stainless steel 1.4301 (also known as 304) and carbon steel S235. The benefits of using stainless steel in the fire resistance of the structure, which is 3 times higher than the one

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obtained with carbon steel, avoiding any fire protection material needed to fulfil the necessary fire requirements will be shown.

1. INTRODUTION

The use of stainless steel for structural purposes has been limited to projects with high architectural value, where the innovative character of the adopted solutions is a valorisation factor for the structure. The high initial cost of stainless steel, coupled with, limited design rules, reduced number of available sections and lack of knowledge of the additional benefits of its use as a structural material, are some of the reasons that lead the designers to a smaller use of the stainless steel in structures [1]. However, a more accurate analysis shows a good performance of the stainless steel when compared with the conventional carbon steel.

The biggest advantage of stainless steel is its higher corrosion resistance. However, its aesthetic appearance, easy maintenance, high durability and reduced life cycle costs are also important properties. It is known that the fire resistance of stainless steel is bigger than the carbon steel usually used in construction. The question of knowing if stainless steel structural elements can be used in buildings, without any fire protection, is very important, because the use of stainless steel in structures is usually due to aesthetic considerations. Eliminating the fire protection in structures will result in smaller construction costs, lower construction periods, more efficient use of interior spaces, healthier work environment and a better aesthetic appearance of the building. On the other hand, the life cycle costs of unprotected stainless steel structures are smaller than protected carbon steel structures.

Thinking in economic terms, it would be improbable that the stainless steel could be chosen instead of carbon steel, due to its higher fire resistance. However, for designers that value the appearance and the durability of stainless steel, the additional benefit of having a significant fire resistance without any protection, can reverse the choice in favour of this material. In fact the stainless steel can be an excellent solution, in application where corrosion resistance and fire resistance are demanded at the same time.

Although the use of stainless steel in construction is increasing, it is still necessary to develop the knowledge of its structural behaviour.

The high corrosion resistance of the stainless steel in most of the aggressive environments has been the reason for its use in structures located near the sea, and also in oil-producing, chemical, nuclear, residual waters and food storage facilities. Its corrosion resistance results in a well adherent and transparent layer of oxide rich in chromium that forms itself spontaneous on the surface in the presence of air or of any other oxidant environment. In case it is crossed, or has some cut damage, the superficial layer regenerates itself immediately in the presence of oxygen.

The stainless steel has, at room temperature, unlike carbon steel, a non-linear behaviour, even for small stresses values. On the other hand, it doesn't have a clearly defined yield strength. A conventional elasticity limit to a strain of 0,2%, is usually adopted. Table 1 compares the mechanical properties of the stainless steel 1.4301 (also known as 304), used in the structure studied in this paper, with the carbon steel S235, at room temperature.

Table 1 – Steel mechanical properties at room temperature.

Mechanical properties	Carbon steel S235	Stainless steel 1.4301
Ultimate strength (MPa)	360	520
Yield strength (MPa)	235	210
Ultimate strain	> 15%	40%

In figure 1 the stress-strain relationships of carbon steel S235 and stainless steel 1.4301 at room temperature and at 600 ºC [2, 3], are represented.

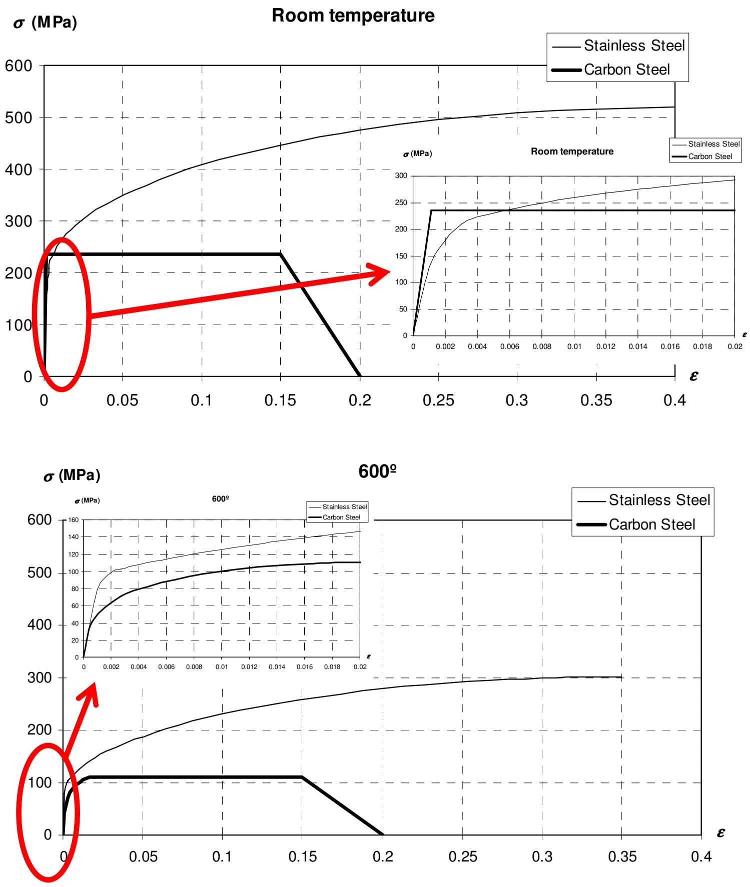
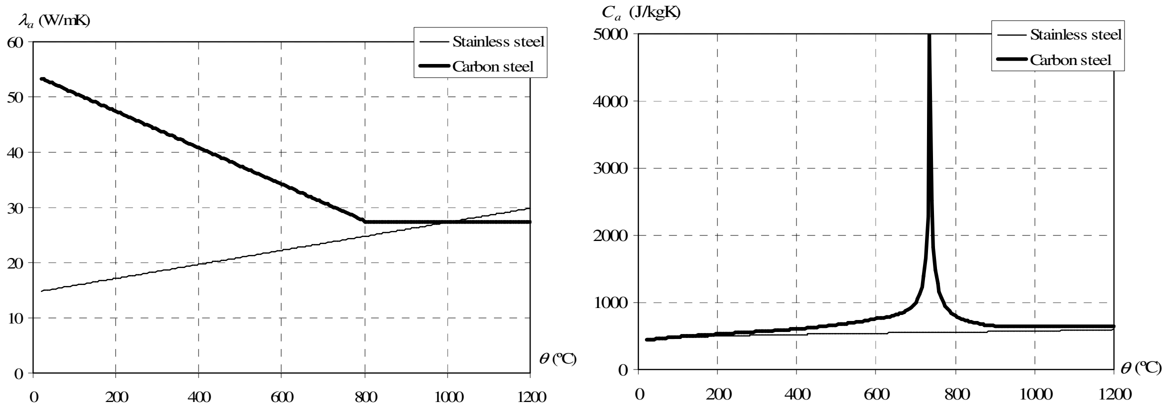


Fig. 1 – Stress-strain relationships of carbon steel S 235 and stainless steel 1.4301 at room temperature and at 600 ºC.

The carbon steel S235 was chosen due to its value of the yield strength, similar to the nominal stress (0,2% proof stress) of the stainless steel 1.4301. For design purposes according to the Eurocode 3, these are the values used to check the resistance of the structural elements.

Figure 2 shows the existing differences between the thermal conductivity and the specific heat of carbon steel and stainless steel. Although the stainless steel has a thermal conductivity lower than the carbon steel, which would make one suppose slower heating speed in stainless steel, the specific heat of the carbon steel is superior, therefore there isn't a big difference between the temperature evolution of the two materials, as it can be observed in figure 7.



a) b)

Fig. 2 – Carbon steel and stainless steel: a) thermal conductivity b) specific heat.

The fire resistance of a steel framed structure, with two spans and three stories as it is shown in figure 3, is determined in this paper. As it will be seen, the fire resistance of this structure in S235 carbon steel is lower to the expected standard resistance R30, and the 1.4301 stainless steel structure will widely exceed that resistance.

This structure simulates an office building in an altitude of 700m, analysed in a previous reference. In order to account for the effects of the assembly imperfections, possible eccentricities and geometrical imperfections, it has been introduced, according to part 1.1[4] of Eurocode 3, an initial imperfection, that corresponds to an rotation angle of 0.0033 rad.

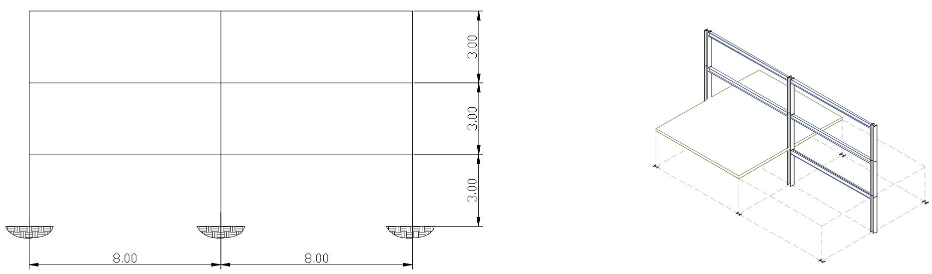


Fig. 3 – Schematic representation of the two-dimensional framed structure studied, with 5m of length between frames.

2. NUMERICAL MODELLING

There are several numerical programs for structural fire resistance analysis, which can be programs based on simplified calculation methods of the Eurocodes, or more complex programs for non-linear analysis, based in the finite element method, that are included in the advanced calculation methods of the Eurocodes. The program SAFIR [5] used in this work is a finite element code for non-linear geometrical and material analysis, specially developed in the University of Liege for the analysis of structures subjected to fire.

The program SAFIR has two distinct calculation modules, one for the thermal analysis of the structure and the other for his mechanical behaviour analysis. So, first it is calculated the evolution of the non-uniform temperature field, for each existing section type in the structure, and in a subsequent phase the mechanical module of the program reads these temperatures and determines the mechanical behaviour of the structure in a transient analysis.

2.1 Thermal analysis

The thermal analysis of the program SAFIR can be made using three-dimensional solid elements (3D), or two-dimensional plane elements (2D). The solid elements are linear and have eight nodes, and the also linear, plane elements, can be triangulate with 3 nodes or quadrilateral with 4 nodes.

2.2 Mechanical analysis

The transient analysis of the mechanical behaviour of the structure uses, as it was early said, the results of the previous thermal analysis.
Beyond the shell element, are also available in SAFIR, truss elements and beam elements, being possible with these last two, to modulate three-dimensional framed structures.
The beam element is based in the Bernoulli hypothesis, where plane sections before deformation remains plane after deformation and the effect of the shear effort is not considered. On the other hand this element does not contemplate local buckling, therefore it should only be used Class 1 and Class 2 sections profiles, as defined in Eurocode 3[4].
The cross-section of the elements is simulated using a fiber model finite element, being the temperature, the stress, the strain and the other material properties considered constant in each fibre. The beam element with the fibre model, allows the consideration of residual stresses [6].
The collapse criterion of the structure is defined as being the instant that his stiffness matrix becomes non positive defined, being not possible to establish the equilibrium of the structure.
The program permits the use of the "arc-length" method, to solve the local ruins problems that sometimes appear. In fact in hiperstatic structures ruin in one of their elements does not correspond to global collapse of the structure. It is possible that, after the instant in which local ruin occurs, part of the efforts that can not be supported by the element in question, be redistributed by the others elements of the structure, finding a new equilibrium.

3. ACTIONS IN STRUCTURES SUBJECTED TO FIRE

3.1 Mechanical actions

The design value of the actions effects in case of fire, should be obtained using the following accident combination as defined in the EN 1990[7]:

$$\sum \gamma_{GA} G_k + \psi_{1,1} \cdot Q_{k,1} + \sum \psi_{2,i} \cdot Q_{k,i} + \sum A_d(t) \quad (2)$$

where

γ_{GA} – is the partial safety factor of the permanent actions in case of accident, which should take the unit value;

G_k - is the characteristic value of the permanent actions;

$Q_{k,1}$ - is the characteristic value of the main or dominant variable action;

$\psi_{1,1}$ - is the combination coefficient associated to the main or dominant variable action [7];

$\psi_{2,i}$ - is the combination coefficient associated to the remaining variable actions [7];

$A_d(t)$ - is the calculation value of the action resulted from the fire exposition and that is represented by the temperature effect in the material properties and from the indirect fire actions that results from the efforts due to the restraints to thermal elongation.

The live action consider was obtained trough the part 1-1 of Eurocode 1 [8]. The wind and snow action were quantified having in attention the location and implantation of the building according to part 1-4 [9] and part 1-3 [10] of Eurocode 1.
In this work it will be only presented the structural analysis corresponding to the actions combination that has for the main variable the wind action. Figure 4 shows the corresponding loads to this actions combination.

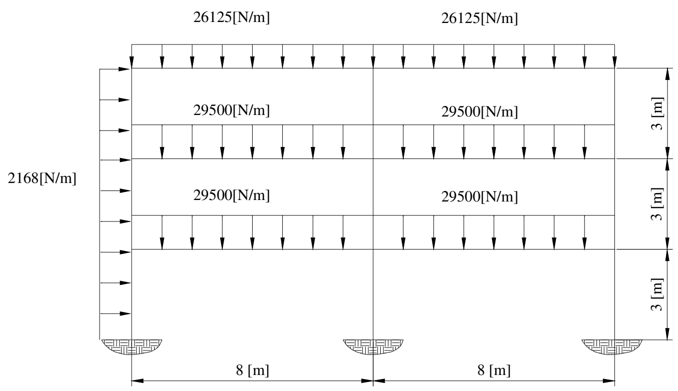


Fig. 4 – Corresponding loads to the actions combination that has the wind as the dominant variable action.

3.2 Thermal actions

In this work, the standard fire curve ISO 834, was used, which has the following analytic expression is [11]:

$$\theta_g = 20 + 345\log_{10}(8t+1) \tag{3}$$

Where

θ_g is the gas temperature in the room subjected to fire in °C;
t is the time in min.

4. CASE STUDY

The fire resistance will be determined in the steel structure already presented in figure 3, when subject to fire in compartment C4 as shown in figure 5.

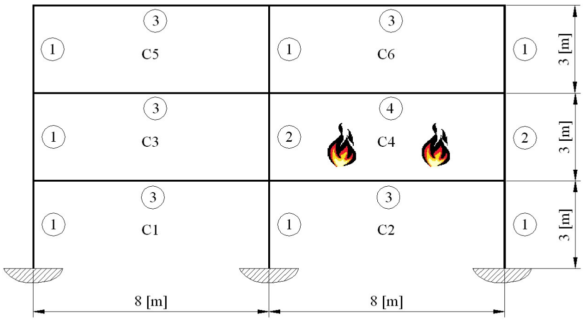


Fig. 5 – Structure with fire only in room 4.

For the structure in carbon steel it was used the S235, the structure design was made at room temperature leading to IPE 450 section for the beams and HEA 300 section for the columns. In the stainless steel structure it was used the class 1.4301 that has a proportional elastic limit stress of 210 MPa, near to the yield stress of the chosen carbon steel. The sections used of the beams and columns were the same of the structure in carbon steel.
In figure 5, the various types of structural elements are numbered according to the thermal loading. For example, the type 2 elements correspond to columns heated only in one flange. The type 4 section corresponds to a beam heated in three sides. Figure 6 illustrates these two cases.
The thermal modulus of the program SAFIR determinesthe evolution of the temperature field trough time, doing a non-linear analysis, since the material thermal properties depends on the temperature and the boundary conditions are also non-linear.

a) b)

Fig. 6 – a) Beam subjected to fire in three sides; b) Column subjected to fire in one side.

The temperature field in the cross-section of the profiles is not uniform, as it would be obtained using the simplified heat conduction equation, prescribed in Eurocode 3, where is assumed that the temperature field is uniform in the cross section of the profiles, due to the elevated thermal conductivity of steel. As it can be easily understood, it is possible to appear elevated thermal gradients in the analysed sections, which can origin significant changes in the structure efforts.
Figure 7 shows the temperature evolution of a point of the beam cross section. It can be verified that the heating curve of the stainless steel is very similar to the heating curve of carbon steel with the exception of temperatures between 600 ºC and 900 ºC. In this part of the curves it can be observed a delay in the curve of the carbon steel due to the change of metallurgic phase that is taken into account due to the peak in the specific heat value of this steel and that does not exists in the stainless steel, as it can be seen in figure 2.

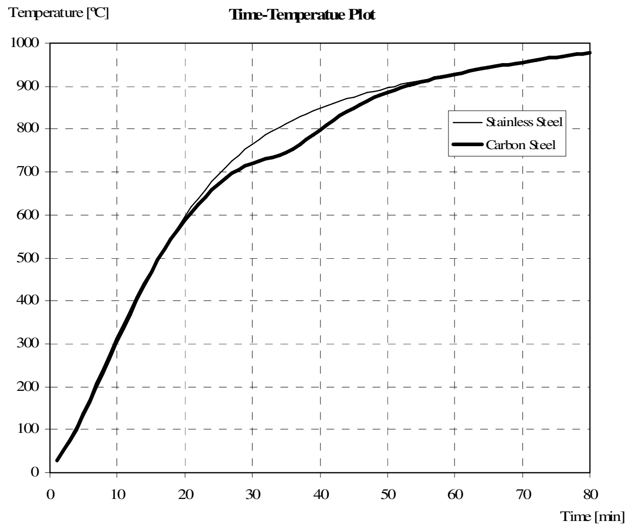


Fig. 7 – Temperature evolution in a node of the beam 4 cross section.

The beam elements used in the structure mesh are represented in figure 8. The obtained temperatures, in the elements sections, are in a second phase used in the structural analysis of the program SAFIR. The deformed shape and the internal forces are determined trough an incremental process, during the fire, until the instant in which it is not possible to establish the equilibrium. This instant corresponds to the structure fire resistance.
The finite elements used are based on the Euler Bernoulli beams, presenting 3 nodes, with a central node that considers the non-linear axial displacement [12]. The nd nodes have three degrees of freedom (two translations and one rotation) and the third node of the beam element one degree of freedom (the axial displacement), in a total of 7 degrees of freedom.

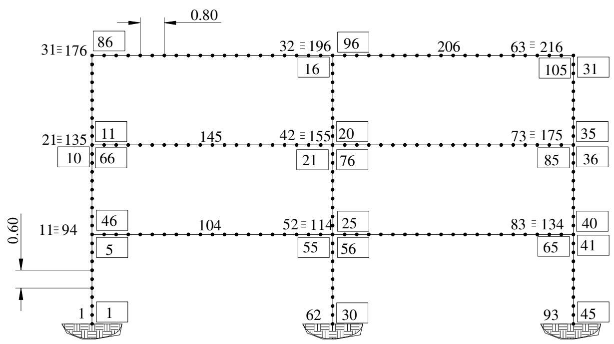
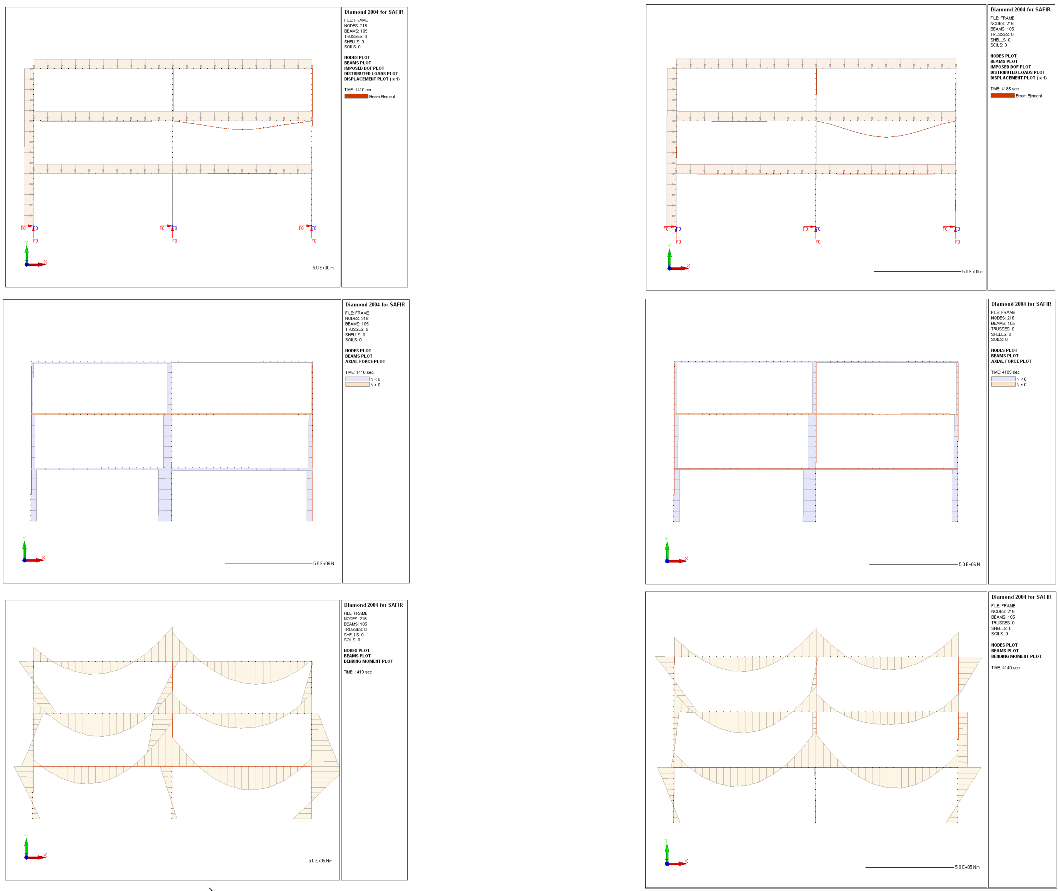


Fig. 8 – Beam elements used in the structure mesh. Nodes and elements (in box) numbering.

The deformed shape of the structure and the force diagrams can be obtained with pos-processor Diamond 2004. Figure 9 presents the deformed shape, axial forces diagrams and bending diagrams at the instant of collapse, for the carbon steel and for the stainless steel structure. In this figures it can be observed that instant of collapse the deformed shape of the stainless steel structure is bigger than in the carbon steel structure, which can be justified by the fact that the stainless steel stress-strain relationship has an ultimate strain bigger than in the carbon steel, as illustrated in figure 1. It also can be observed that the bending diagrams have some differences in the two structures.



a) b)

Fig. 9 – Obtained results in the failure instant; a) Carbon steel structure; b) Stainless steel structure (displacements scale factor of 1).

The failure in the carbon steel structure occurred after 1410 seconds (23,5 minutes) while the stainless steel structure only collapses after 4140 seconds (about 1 hour and 9 minutes), which corresponds to a fire resistance of about 3 times bigger than the fire resistance of the carbon steel structure.

The fire resistance of the carbon steel structure, is clearly below the standard fire resistance defined as R30, being necessary to use fire protection to fulfil the required fire resistance, which is not the case when stainless steel is used.

5. CONCLUSIONS

It has been determined the fire resistance of a structure in carbon steel and in stainless steel. In both cases it has been considered that the structure was not fire protected.

The analysis was made with the program SAFIR developed, in the University of Liege, especially for the study of the behaviour of structures subjected to fire. In order to use this program in the analysis of stainless steel structures, it was introduced in the code the necessary changes to considerer the stress strain relationship of this material, as well as its thermal properties, in function of the temperature.

It was concluded that the studied structure in stainless steel 1.4301 has a fire resistance 3 times bigger than the fire resistance of the same structure in carbon steel S235. Concerning the standard qualification, the carbon steel structure is R15, while the structure in stainless steel is R60. This resistance allows for the utilization of the stainless steel structure without any fire protection, which increases the economic advantage of the stainless steel as a structural

material, allowing for the structure to be showed, which is often, decisive in the choice of this kind of steel in construction. The results of the practical case presented in this paper should be seen as preliminary study. In fact, it should be determined the behaviour of the structure in carbon steel considering the stress-strain relationship allowing for strain hardening, prescribed in the Annex A of part 1-2 of the Eurocode 3.
The steel grade S235 was chosen because its yield strength is similar to the nominal stress (0,2% proof stress) of the stainless steel 1.4301.

6. REFERENCES

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