CERIS Civil Engineering Research and Innovation for Sustainability

STASTEFI – Fire Design of Stainless Steel Members

Summary

The risk of fire in a building is high, as it may have several ignition causes (chemical, mechanical, thermal or even electrical). Also, catastrophic events, such as impact, explosions and earthquakes, are commonly associated with the occurrence of fires. Fires in buildings may have very severe consequences (human life losses), which provides the reason for the growing attention paid by society to this accidental action.

The collapse of buildings structures due to fire is highly undesirable. The elevated temperatures inflict important changes on the material mechanical properties, which can decisively influence their structural behaviour – metals such as stainless steel are very susceptible to this influence. Due to their high mechanical resistance at normal temperature, stainless steel members usually have very slender cross-sections, which, together their high thermal conductivity, may lead to a severe mechanical property degradation.

This project is aimed at acquiring knowledge on the behaviour of stainless steel members under fire conditions. It is known that stainless steel performs better under fire than the conventional carbon steel, which can foster an increase in its usage for structural applications. In fact, despite an initial cost higher than carbon steel, stainless steel can be competitive because of the higher fire and corrosion resistances, lower maintenance costs, lower life-cycle cost and superior aesthetic appearance.

Regarding the fire resistance of stainless steel members, the existence of simplified design rules, provided by codes of practice, are of the utmost importance to designers who do not always have access to advanced calculation methods. Part 1-4 of Eurocode 3 (EC3) includes provides design rules for stainless steel members at normal temperature and refers to Part 1-2 of the same EC3 for their fire resistance. In this document, it is stated that the resistance of stainless steel members must be checked using the same design formulae developed for carbon steel ones, an approach that has been found to lead to inaccurate and often unsafe ultimate strength predictions. In fact, as it is also displayed in Part 1-2 of EC3, the two materials have different constitutive laws under fire conditions, which influences the members load-bearing capacity. Moreover, several international codes of practice use the Direct Strength Method (DSM), which is yet to be applied to the design of stainless steel members under fire conditions.

For that reason, different studies have been reported in recent years concerning the behaviour and design of stainless steel members under fire conditions, including their material properties. However, in order to have more accurate, safe and reliable design approaches include in the upcoming Eurocode 3 new generation version, further studies are still required. For instance, there are still open questions concerning the fire design of members with Class 3 or 4 cross sections (highly susceptible to local buckling).

In this project, the focus is on members (columns, beams and beam-columns) with slender cross-sections (I or hollow) and made of the most commonly used stainless steel grades. These members are susceptible to several instability phenomena, such as local, flexural or lateral-torsional buckling, which, add further complexity to their analysis (recall also the non-linear stress-strain relationship at elevated temperatures. The performance of experimental and numerical studies on stainless steel members under fire conditions plays an important role in the assessment and improvement of the existing design rules. The experimental results concern fire resistance tests on stainless steel columns, beams and beam-columns, carried out at the Fire Resistance Laboratory of the University of Aveiro. The numerical (shell finite element) studies are carried out using the programs SAFIR (developed at the University of Liège specifically to analyse structures under fire conditions) and ABAQUS (a worldwide know commercial software package), and consisted of performing geometrically and materially non-linear analyses with imperfections (GMNIA). At elevated temperatures, caused by fire, the degradation of the stainless steel mechanical properties leads to a decrease of the member critical buckling loads associated with various buckling modes – these critical buckling loads are determined by means of a program based on Generalised Beam Theory (GBT).

The overall objective of this project is to develop more rational, safer and more economic guidance on the design of stainless steel members when exposed to fire, which will be achieved through the following specific objectives:

- Generate experimental and numerical fire resistance test data on stainless steel members, making sure that they are presented in a format that is easily disseminated.
- Develop methods to design stainless steel members at elevated temperatures, validated against the experimental and numerical ultimate strength values, suitable for incorporation in standards, namely in Eurocode 3.

The experimental results make it possible to carry out a preliminary assessment of the design rules included in Part 1-2 of the current EC3 version, which were originally developed for carbon steel members, as well as the calibration of shell finite element (SFE) numerical models to be used in the performance of extensive parametric studies.

In the experimental test campaigns carried out in the context of this project, the influence of the various parameters affecting the fire resistance of stainless steel members is investigated. Parameters such as the steel grade, restraint conditions, loading conditions (e.g., the bending moment diagram shape in beams and beam-columns), cross-section dimensions (wall width and thickness), span lengths are considered. The tests are carefully planned, through preliminary

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CERIS

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numerical analyses aimed at identifying the key behavioural features to be evidenced in the fire resistance experimental tests, performed with the equipment available at the Fire Resistance Laboratory of the University of Aveiro, namely a gas furnace enabling fast heating conditions (e.g., the ISO 834 fire curve – most common heating curve used for standard fire resistance evaluation), a flexible steel frame, adaptable to different test set-ups, a force application system, jacking up to 500 kN, and a data acquisition system reading temperatures, strains and displacements.

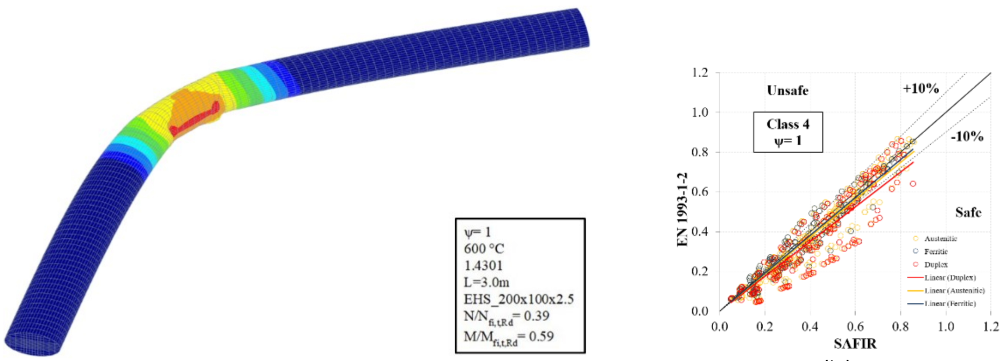
The test results obtained are used to validate the SAFIR and ABAQUS SFE models developed, which are subsequently used to perform the parametric studies, namely the member GMNIAs intended to gather ultimate strength data – it is worth noting that SAFIR and ABAQUS SFE models have already been widely used by several researchers in studies aimed at developing methodologies for the design of both carbon and stainless steel members at normal temperature and under fire conditions (a number of them have already been incorporated in EC3). The GMNISs performed include initial geometrical imperfections, exhibiting suitably chosen critical-mode shapes and amplitudes, and residual stresses with commonly used patterns.

On the basis of the experimental and numerical ultimate strength gathered and collected from the literature, results, the merits (accuracy, safety and reliability) of the existing design rules for stainless steel members under fire conditions are assessed. Special attention is paid to the design rules prescribed in EC3, and it is expected that the findings reported in the project will contribute towards improving and widening the scope of these design rules, with the final goal of inclusion in future versions of EC3. However, existing alternative design approaches are also addressed, since they bring accumulated scientific knowledge important for the success of the project. For instance, the use of the Direct Strength Method, to determine the fire resistance of the stainless steel members is being investigated – the GBT-based buckling results are used in this context.

The first task of the project consists of establishing the methodology, comprising the definition of the members to be analyse and the preparation of the fire resistance tests. Then, the second task deals with the fire resistance of axially compressed cross-sections and laterally restrained beams. The local buckling of thin walled sections and the non-linear nature of the stainless steel stress-strain relationship influence the cross-section fire resistance. Thin stainless steel plates, with different restraint and loading conditions, are analysed at elevated temperatures, with the purpose of developing a design method based on the Effective Width concept, as prescribed by EC3. Experimental and numerical fire resistance studies on restrained columns and beams with I-sections and various hollow sections belonging to different Classes are performed. The results obtained are compared with the EC3 design provisions and, if necessary, new proposals will be developed. The results obtained in this task will be directly used when investigating the fire resistance of unrestrained members, in tasks 4, 5 and 6. Next, the third task is devoted to the performance of GBT-based numerical buckling analyses, whose results are needed to predict the member fire resistance by means of the Direct Strength Method.

The remaining three project tasks are concern the fire resistance of each of the unrestrained members considered in this project, made of various stainless steel grades and exhibiting I-sections and various hollow sections: columns, in task 4, beams, in task 5, and beam-columns, in task 6. Naturally, these tasks use the experimental and numerical results obtained previously.

It is expected that a complete set of fire design rules for stainless steel members, cast in a format suitable for codes of practice (such as EC3) will be delivered at the end of the project.



(a) (b)

Figure 1. Numerical modelling of stainless steel beam-columns with elliptical hollow section under fire conditions: (a) beam-column deformed configuration and (b) assessment of the Eurocode 3 design rules.