FIRE RESISTANCE OF COLD-FORMED C STEEL COLUMNS

N. Lopes [a], F. Arrais [a], Paulo Vila Real [a]

[a] LABEST — Civil Engineering Department, University of Aveiro, Portugal

Abstract

Steel structural elements composed of cold-formed thin walled sections, are common in buildings due to their lightness and ability to support large spans, however they are more susceptible to the occurrence of local buckling. Additionally, in these members, when subjected to axial compression, the flexural buckling, torsional-flexural buckling and distortional buckling are also common failure modes. These instability phenomena are intensified at high temperatures. This work has the main objective of presenting a numerical study on the fire behaviour of cold-formed thin walled C sections when subjected to compression and high temperatures. The influence of different geometrical imperfections shapes and residual stresses on the ultimate load are evaluated. Comparisons between the finite element numerical results, obtained with geometric and material non-linear analysis, and the Eurocode 3 Parts 1-2 and 1-3 rules are also made.

Keywords: steel, cold-formed, columns, buckling, residual stresses.

INTRODUCTION

The cold-formed steel profiles can be applied to almost all existing buildings typologies. The use of these profiles in construction began around 1850 in the United States and United Kingdom, however, they were not widely used in buildings until 1940. In recent years, it has been recognized that the cold-formed steel profiles can be effectively used as primary structural elements (ASRO, 2008).The cold-formed profiles are commonly used in buildings due to its lightness and ability to overcome large spans, being quite common as roof or walls support elements (Silvestre and Camotim, 2010a).

The structural steel elements with thin walled cold-formed sections, subjected to axial compression, are characterized by being able to have the possibility of failure modes occurrence such as local, distortional and global flexural buckling. These instability phenomena and its influence on the ultimate strength at room temperature have been widely studied in recent years (Gonçalves and Camotim, 2007; Silvestre and Camotim, 2010b). However, its behaviour in fire has not received the same attention. In fact, the fire resistance evaluation of cold-formed profiles has a major role in the design of these elements. The thin walls of these profiles, together with the steel high thermal conductivity, provide a great loss of strength and stiffness on these structural elements (Laim and Rodrigues, 2011; Landesmann and Camotim, 2011; Vila Real and Lopes, 2010).

The manufacturing process of thin cold-formed steel members introduces residual stresses and increases the yield strength in the folding regions. Consideration of residual stresses may be complicated on numerical modelling. It can be idealized as a summation of two types: flexural and membrane. But on cold-formed elements, membrane residual stresses are lower than flexural residual stresses. This variation of residual stresses causes the early yielding of cold-formed steel plate surfaces (Schafer and Peköz, 1998).

This paper presents a numerical study on the behaviour of columns in cold formed C sections in case of fire when subjected to simple axial compression. In this study, the influence of geometrical imperfections and residual stresses on their ultimate load bearing capacity is evaluated.

The programs CUFSM (developed at Johns Hopkins university in the United States) (Schafer and Ádány, 2006), and SAFIR (developed at the University of Liege in Belgium) (Franssen, 2005) were used. The program CUFSM performs elastic buckling analysis of thin-walled elements. The thin-walled elements, by their very nature, tend to suffer several instability problems. The CUFSM analysis uses the finite strip method (FSM). In this work, the program CUFSM was used for the purpose of obtaining the local, global and distortional instability modes, comparing these results with the ones from SAFIR. Additionally, the local, distortional and lateral instability modes obtained in CUFSM were used to define the local geometrical imperfections. The program SAFIR uses the finite element method (FEM) for geometric and material non-linear analysis, and was especially developed for the study of structures in fire.

1 NUMERICAL MODELLING

Simply supported columns with C cross section were analysed (with height of 155 mm, width of 77 mm, length of the outstand element 31 mm and thickness of 2 mm). An yield strength of 360 MPa was considered, example from Veríssimo (2008). It was not considered increased yield strength, due to the cold formed process, in the corners.
The steel constitutive law used for the ultimate load bearing capacity determination with the FEM simulations (sections 3 and 4) was the one prescribed in Part 1-2 of Eurocode 3 (EC3) (CEN, 2005). In section 2 a linear elastic constitutive model, with the young modulus given in this Eurocode in function of the temperature, was used.
In the finite element model, shell finite elements were used due to the walls high slenderness. Concentrated loads were applied, in the parallel directions to the columns axis, along the whole section. The restrictions were imposed in order to reproduce two end pinned supports. The thickness of the shell elements was increased at the column ends to consider a rigid body when loads and restrictions are applied. The mesh was refined to obtain the smaller elements in the positions of maximum deflection and on the supports (see Fig. 1). The temperatures of 350 ºC, 500 °C and 600 ºC were adopted, they were considered uniform throughout the cross section. In this paper, due to space limitation, only results at 500 ºC are shown.

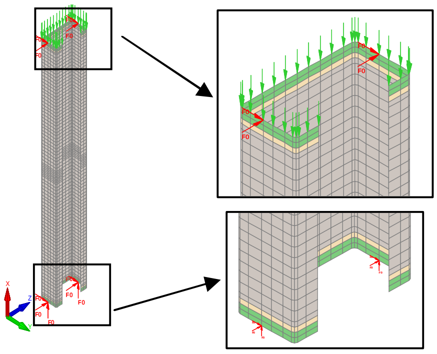


Fig. 1 Adopted numerical model for the C section

2 INSTABILITY MODES

With regard to the stability behaviour, a bar with thin wall section can be classified according to their length:

- Short bar - if instability occurs with a local mode;
- Long Bar - if instability occurs with a global mode;
- Intermediate Bar - if instability occurs in a combination of local and global modes (distortional mode).

This section presents the determined critical loads of elastic instability and corresponded modes, through numerical analysis carried out at the columns subjected to high temperatures. Initial geometric imperfections and residual stresses were not introduced and in the finite element analysis it was adopted a linear elastic constitutive law for the material model. Only the reduction factor for elastic modulus at high temperatures has been applied.
In Fig. 2 the comparisons, between the numerical results obtained with SAFIR and the curve corresponded to elastic instability modes obtained with CUFSM, are presented.

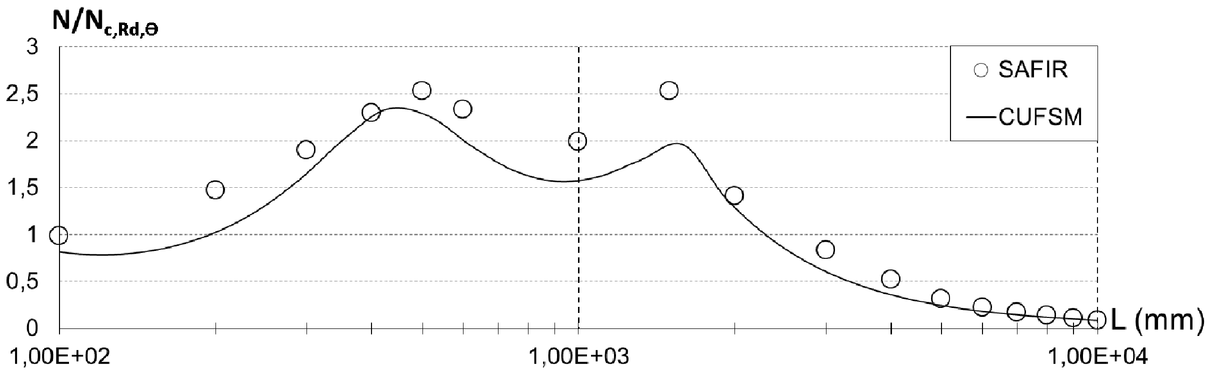


Fig. 2 Comparison between the SAFIR and CUFSM results at 500 ºC

The chosen lengths in this study reach local, distortional, global instability modes.
For a better understanding of the existing instability modes, it is presented in Fig. 3, a comparative analysis between the instability modes that the profile can suffer, when subjected to simple axial compression.

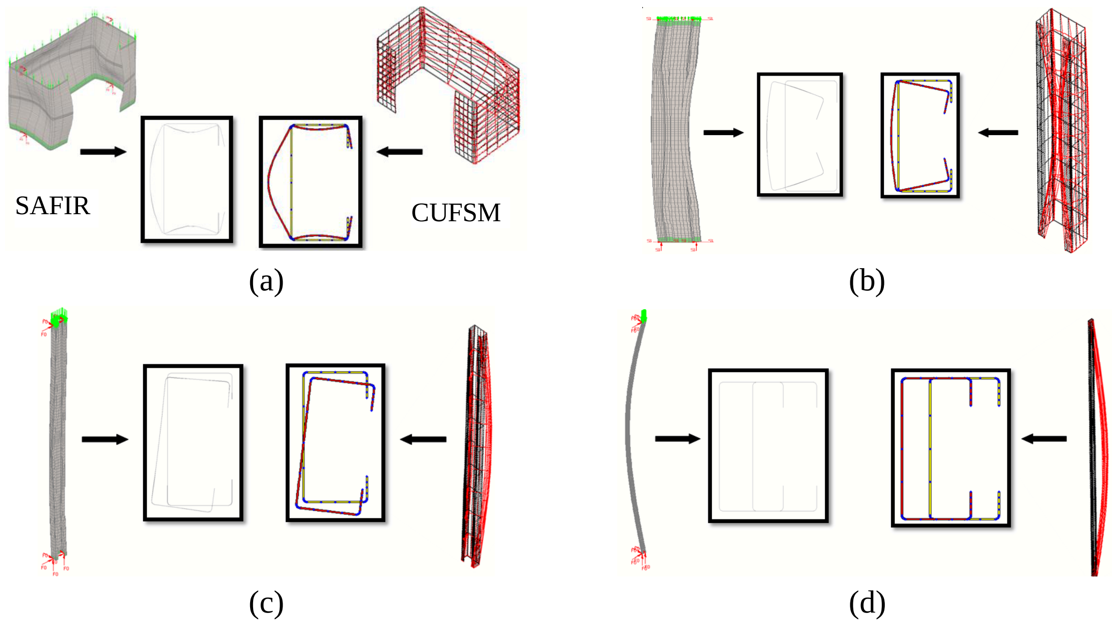


Fig. 3 Instability modes of columns with length of a) 100 mm b) 1000 mm c) 3000 mm and d) 10000 mm

It can be observed the predominance of local buckling on small lengths columns, distortional buckling on intermediate lengths columns and global buckling on long lengths columns.
From the graph in Fig. 2 and from the elastic instability modes shown in Fig. 3, it can observe a good agreement between the results obtained with the SAFIR and CUFSM.

3 INFLUENCE OF THE INITIAL GEOMETRIC IMPERFECTIONS ON THE FIRE RESISTANCE

In this section, it is presented a study of the influence of initial imperfections on the ultimate load bearing capacity of cold formed C columns, in fire situation. It were also analyzed the simple calculation rules in Part 1-2 of EC3, when compared to the numerical results.
The geometry of the C section was addressed by the method mentioned in Annex C of EC3 Part 1-3 (CEN, 2004), in the calculation of the resistance. In these prescribed approaches, the calculation methodology for the effective section for the local instability mode differs from the calculation methodology for the distortional mode instability. The local instability mode effective section was based on the concept of effective width, while in the distortional mode instability it was based on the concept of reduced thickness.

3.1 Isolated influence of the geometrical imperfections

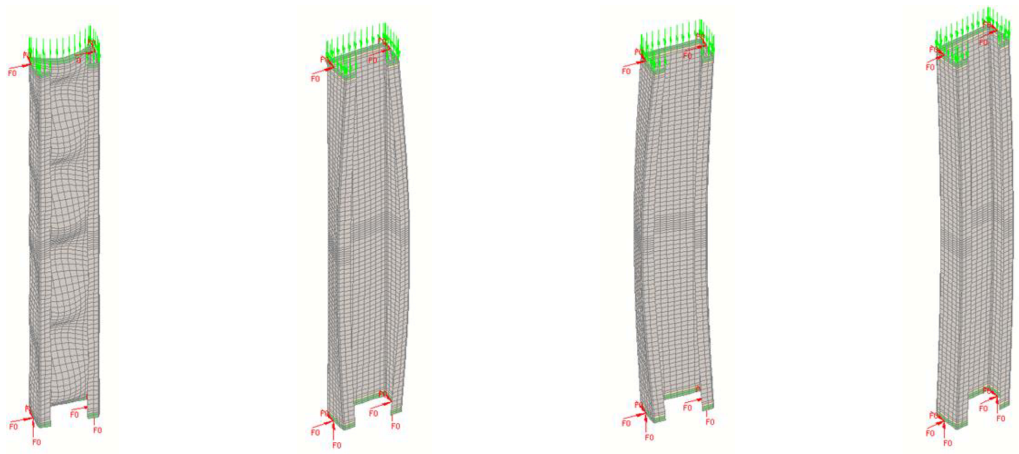
To determine the shape of all the imperfections, the analysis performed with CUFSM considering the applied elastic stresses diagram corresponded to axial compression was used. The local, distortional and global instability modes shape obtained in CUFSM were used to define the geometrical imperfections. The following situations were considered:

- without geometrical imperfections;
- with geometrical imperfections corresponded to the local buckling mode;
- with geometrical imperfections corresponded to the distortional buckling mode;
- with geometrical imperfections corresponded to the global (flexural/torsional) buckling mode;
- with geometrical imperfections corresponded to the global (flexural) buckling mode.

The global imperfections were considered with a sinusoidal shape given by the expression

$$y = \frac{L}{1000}\sin\left(\frac{\pi x}{L}\right) \tag{1}$$

The maximum value for the local was of b/200, being b the profile height, and for distortional imperfections was of b/200, being b the profile width (CEN, 2006).
Fig. 4 shows a column with the different introduced geometrical imperfections.



(a) (b) (c) (d)

Fig. 4 Geometric imperfections (×50): a) local; b) distortional; c) global (flexural/torsional); d) global (flexural)

The influence of the introduction of the different geometrical imperfections is presented in Fig. 5. As effective widths were considered for the calculation of the effective section, leading to the appearance of an eccentricity on the load application, instead of a buckling curve a direct comparison between resistances is presented. It is observed that the columns without any imperfections reach higher resistances compared to the ones which take into account initial imperfections. For all slenderness the analysis with local imperfections are the ones that reduce the obtained ultimate loads.

3.2 Influence of combined geometrical imperfections

Following Part 1-5 of EC3 a combination of the previous enunciated geometrical imperfections is introduced on the numerical model. According to this norm, in combining imperfections, a leading imperfection should be chosen and the accompanying imperfections may have their values reduced to 70%. As the local imperfections gave the lowest axial compression resistance, they were considered as leading imperfections. Two possible combinations were tested:

- local and global imperfections (being these two the most relevant): columns have local imperfections plus 70% of the global imperfections;
- local, global and distortional imperfections: columns have local imperfections plus 70% of the global imperfections plus 70% of distortional imperfections.

3.3 Discussion of the results

From the graph in Fig. 5 it can be observed that the combinations give lower resistances than the ones obtained with the separate imperfections. The observed differences between the two set of combinations are very small, they give almost the same values. Also, for intermediate columns slenderness the design curve proposed by EC3 is too conservative.

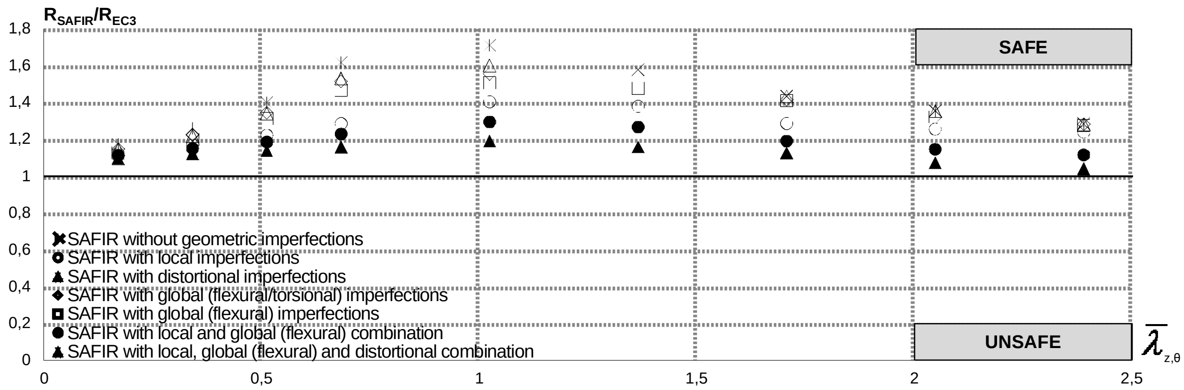


Fig. 5 Comparison of the numerical results at 500 ºC

4 INFLUENCE OF RESIDUAL STRESSES ON THE FIRE RESISTANCE

In this section, it is presented the influence of the residual stresses on the ultimate load bearing capacity. Fig. 6 shows the considered residual stresses pattern.

Fig. 7 presents the results obtained with and without residual stresses. They were considered on columns with and without geometrical imperfections.

It is observed that the resistance of columns, with intermediate lengths, without any imperfections is affected by residual stresses. In the other hand, considering the geometric imperfections, the residual stresses do not affect the resistance values.

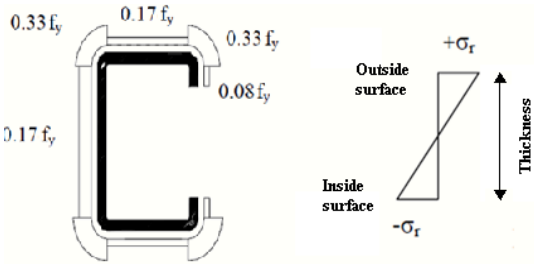


Fig. 6 Definition of residual stresses on cold-formed steel C section (Adapted from (Schafer and Peköz, 1998))

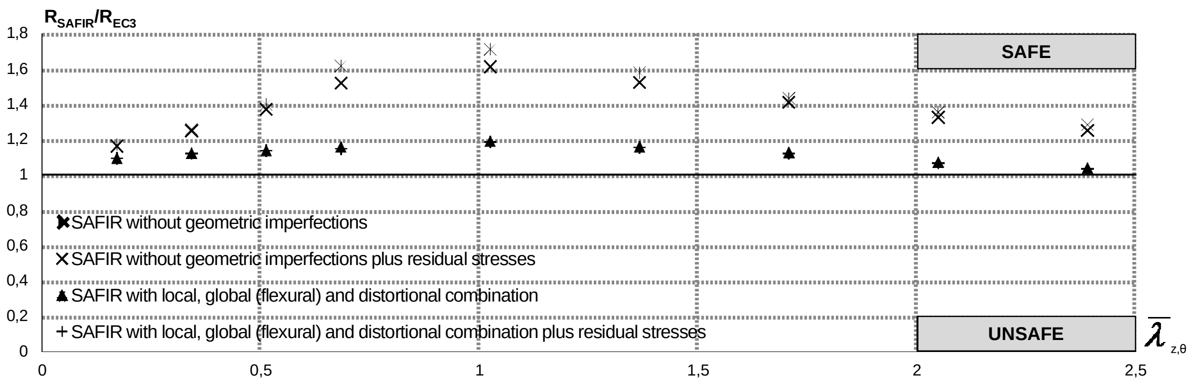


Fig. 7 Comparison of the numerical results with residual stresses at 500 ºC

5 CONCLUSIONS

In this work it was presented a numerical study on the behaviour of cold formed columns with C cross section in case of fire.

The numerical results obtained at high temperature, for the determination of elastic instability critical loads and buckling modes, were compared using finite element method (FEM) analysis with the program SAFIR with those obtained by finite strips method (FSM) through CUFSM program. It was observed a good agreement between the results obtained with these two programs.

The influence of initial geometrical imperfections (local, distortional, global, and their combination) on the determination of the ultimate loads of these elements at high temperature was analysed, it was concluded that these imperfections are relevant to the determination of those ultimate loads, and that they should be considered.

Considering the residual stresses with the worst initial geometric imperfections combinations was not important, because the ultimate load is extremely affected by all the geometric imperfections and the residual stresses did not have any impact on the resistance values.

Finally, it also performed a comparison between the obtained ultimate loads results and the formulae prescribed in Parts 1-2 and 1-3 of EC3, concluding that the simple calculation rules are on the safe side and sometimes too conservative.

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