BASELINE STUDY ON THE BEHAVIOUR OF COLD-FORMED STEEL COLUMNS SUBJECTED TO FIRE

Hélder David S. Craveiro [a], João Paulo C. Rodrigues [a], Luís Laím [a]

[a] University of Coimbra, Portugal

Abstract

In this paper is presented a state-of-the-art and future research pathways on cold-formed steel (CFS) columns subjected to fire, the experimental set-up built at the University of Coimbra for testing CFS columns and some preliminary results obtained in the tests, comparing them with the ones existing in the literature. The main objective of the experimental research already carried out is to assess the fire resistance, mechanical behaviour and characterize the failure modes of cold-formed steel columns with restraining thermal elongation in case of fire, develop simplified calculation methods and provide experimental data for future numerical studies.

Keywords: cold-formed steel, columns, fire resistance, restraining forces, state-of-the-art

INTRODUCTION

Recently the demand of cold-formed steel structures (CFS) has increased significantly, especially for residential, commercial and industrial buildings due to a high strength to weight ratio and an ease to erect when compared to hot rolled-steel structures. In some cases, CFS structures are required to be fire resistant however they present poor fire behaviour because of a combination of the high thermal conductivity of steel and the elevated section factor of the structural member. Despite increasing use there is a lack of research on their behaviour under fire situation. Therefore it is extremely important to investigate and assess the behaviour of cold-formed steel columns subjected to fire.

Due to experimental limitations, so far, most of the experimental studies were performed on stub columns, resulting in a lack of knowledge on the behaviour of CFS slender columns subjected to fire.

A state-of-the-art review is presented in this paper as well as the experimental set-up developed at University of Coimbra for testing of CFS slender columns with restrained thermal elongation subjected to fire and some preliminary experimental results obtained, comparing them with some existing ones in the literature.

1 STATE-OF-THE-ART REVIEW

As mentioned there has been little research on the behaviour of CFS slender columns subjected to fire being most of the studies on stub columns. However these studies are very important and are here presented as baseline studies for future investigations.

A study performed at the Swedish Institute of Steel Construction (Ranby, 1998),for developing structural fire design of thin-walled cold-formed steel sections, was presented in order to find out the steel temperature, how it varies across the steel cross-section and the effect on the load bearing resistance. It was intended to develop a method for designing thin walled cold formed steel sections and to show that limiting the maximum temperature to 350ºC for class 4 cross sections, as mentioned in the EN 1993-1.2 (2005), is too restrictive. Results showed that initial deflections have the same influence on the load bearing resistance at ambient temperature and in case of fire and that the calculation of the plate buckling resistance according to EN1993-1.3 (2005) considering the reduced yield strength and elastic modulus is accurate at elevated temperatures. Results also showed that the 350ºC limitation for class 4 cross section is too restrictive.

Feng et al. (2003) performed a total of 52 load-bearing capacity tests at ambient and elevated temperature on compressed short CFS lipped channels, with and without service holes and unlipped channels to assess the physical behaviour and failure modes of this type of structures. The column was heated in an electric kiln and longitudinal distribution of temperature and displacements were measured. Elevated temperatures tests, without thermal restraint, were carried out under steady state condition for four temperature levels (250, 400, 550 and 700ºC). When the temperature reached the desired level the axial compression loading was applied until failure. This experimental study showed that depending on the initial imperfections the failure mode of nominally identical columns can be different at both ambient and elevated temperatures. Despite the difference in failure modes the failure loads of nominally identical columns were very close. A numerical analysis was also performed (Feng et al., 2003) based on the experimental work using the design methods presented in some international standards such as the EN 1993-1.3(2006), and a finite element analysis (FEA) using the commercial software ABAQUS (2004) considering geometrical and material non-linearities. Stress-strain relationship of steel at high temperature was determined according to EN 1993-1.2(2005), with a suitable modification in order to use the mathematical equations for the stress-strain relationships at elevated temperatures, or the ones proposed by Outinen et al. (1999). It was found that ambient temperature design guidelines can be used at elevated temperatures providing the reduced yield strength based on 0,2% proof stress and the reduced elastic modulus.

Heva and Mahendran (2008) performed a series of local buckling tests of CFS compression members at elevated temperatures. The tests were carried out at predefined temperatures up to 700ºC (100, 200, 300, 400, 500, 600 and 700ºC) using a small electric furnace and a special loading set-up made to fit the furnace using 253MA stainless steel and a Tinius Olsen Testing Machine. Ultimate loads were calculated using the available design rules, emphasizing the EN 1992-1.2 (2005)using the effective width method for the local buckling capacity of compression members at elevated temperatures. The yield stress reduction factors at elevated temperatures determined by Ranawaka (2009) and Dolamune Kankanamge (2011) were used since the recommended yield stress reduction factors for both cold-formed and hot-rolled steels were identical in this standard. It was found that using the reduced mechanical properties at elevated temperatures with ambient temperature design guidelines is possible to predict approximately the axial compression capacity of CFS short columns. This study showed once again that limiting the temperature to 350ºC as in EN 1993-1.2 (2005) is too restrictive since the CFS columns presented significant capacities beyond this limiting temperature.

Ranawaka and Mahendran (2009) carried out a research based on experimental studies to investigate the distortional buckling behaviour of CFS short compression members under fire conditions. Two types of cross section were tested with different nominal thicknesses, both with low and high strength steels, G250 and G550. Steady state tests were carried out and three types of distortional buckling failure modes were observed at elevated temperature tests, namely by both flanges moving inwards or outwards and by one flange moving outward while the other moving inward. Comparing the ultimate load results with the ones obtained using the direct strength method it was found that they are reasonably accurate when the appropriate reduced mechanical properties are used. Based on this experimental research a numerical study on CFS compression members subjected to distortional buckling at elevated temperatures was developed, considering geometric imperfections, residual stresses and the reduced mechanical properties at elevated temperatures (Ranawaka and Mahendran, 2010). Comparing numerical and experimental results it was found out that the developed finite element models considering accurate mechanical properties and stress-strain characteristics of steels, initial geometric imperfections and residual stresses as a function of temperatures were able to simulate the failure modes, load deflection and ultimate loads.

Ju Chen and Ben Young (2007) developed a numerical study on CFS lipped channel stub and slender columns at elevated temperatures using a finite element software ABAQUS (2004) to investigate the behaviour and design of CFS lipped channel columns at elevated temperatures considering the effects of initial local and overall geometrical imperfections. The nonlinear model was verified against experimental results obtained in the research performed by Young and Rasmussen (1998) at ambient temperature and in the research performed by Feng et al. (2003) at ambient and elevated temperatures, and then the strength prediction of columns was compared with the design strengths using the effective width and direct strength method. It was found that the estimated column strengths using FEA is in good agreement with experimental results both at ambient and elevated temperatures and that the effective width and direct strength method using the reduced material properties conservatively predicted the columns strength.

Almeida et al. (2012) performed some experimental tests on CFS slender columns at elevated temperatures in order to investigate de behaviour of compressed CFS columns considering the influence of the restraining to thermal elongation. Single sections (C), open built-up (I) and closed built-up (2R) sections were tested. Single sections were 1.5 mm thickness and pin ended and semi-rigid boundary conditions were adopted. The applied load corresponds to 30% of the design buckling resistance of a compression member ($N_{b,Rd}$) determined according to the Eurocode 3 Part 1.1 (2005) and Part 1.3 (2006). Some of the results obtained are presented in Fig. 1.

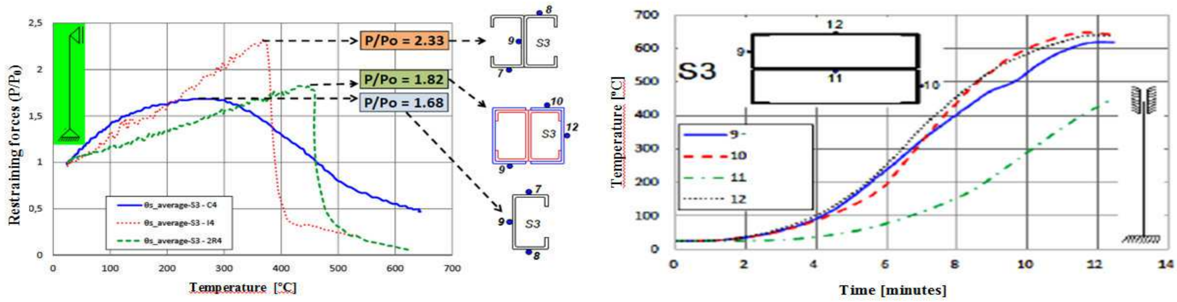

Fig.1 Evolution of restraining forces (a) and temperatures in the column's mid-section in height (b).

So far the absence of experimental fire resistance studies in slender CFS columns is clear. Establishing the presented studies as a starting point and aiming to respond to the existing challenges in this research field a new experimental set-up was developed in order to perform fire resistance tests on cold-formed steel slender columns with restrained thermal elongation.

2 FIRE RESISTANCE TESTS ON CFS COLUMNS WITH RESTRAINED THERMAL ELONGATION

The main objective of this experimental research is to assess the influence of the cross section shape, load level ratio, end-support conditions on the fire resistance and structural behaviour of CFS slender columns with restrained thermal elongation in case of fire. Restraining forces, critical times and temperatures, vertical and horizontal displacements were measured and the predominant failure modes characterized. The experimental programme was carried out on CFS slender columns with different types of cross sections, namely single sections, C, open built-up cross sections, I, and closed built-up cross sections, R and 2R (see Fig. 2) with pin-ended support conditions and 3 kN.mm of axial restraining provided by the surrounding structure. In Fig. 2 it is possible to see the locations for the thermocouples in the specimens. Longitudinally the thermocouples will be placed in five different sections, in order to evaluate the longitudinal temperature distribution. Columns were 2950 mm long and the cross section 2.5 mm thick and presenting the steel grade S280GD (EN 10147:2000).

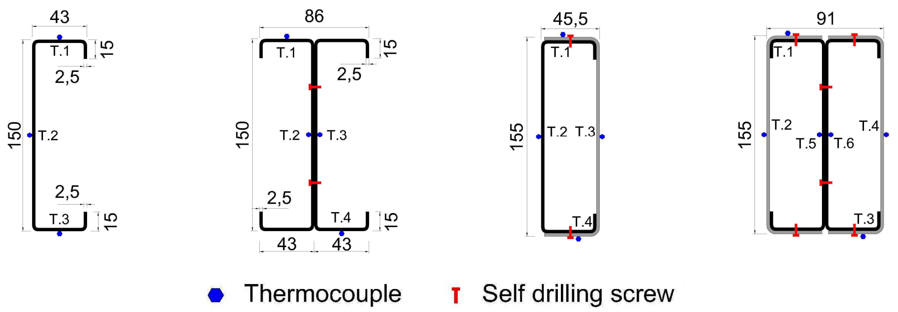

Fig. 2 CFS cross sections tested. Thermocouple's position in each cross section.

2.1 Experimental set-up

The experimental set-up system developed at the University of Coimbra (Fig. 3) comprises a 2D reaction frame and a 3D restraining steel frame of variable stiffness in order to simulate the axial stiffness of a surrounding structure to the CFS column subjected to fire. The restraining frame was composed by four columns and two beams placed orthogonally. The connections between columns and top beams were made using threaded rods M24 in order to allow the vertical adjustment of the position of the top beams. The hydraulic jack used to apply the load was placed in the 2D reaction frame. The thermal action was applied using a vertical modular electric furnace programmed to follow the standard fire curve ISO 834. To measure the restraining forces generated during the heating process a special device was built consisting on a hollow steel cylinder with a load cell inside where a Teflon lined solid steel cylinder that was connected to the top of the column, slides through it. The temperatures in each specimen were measured using type K thermocouples placed in the cross section and throughout the length of the column. Vertical displacements were measured using Linear Variable Displacement Transducers (LVDT) placed on top and bottom of the column and the lateral displacements were measured using Wire Displacement Transducers placed throughout the column's length.

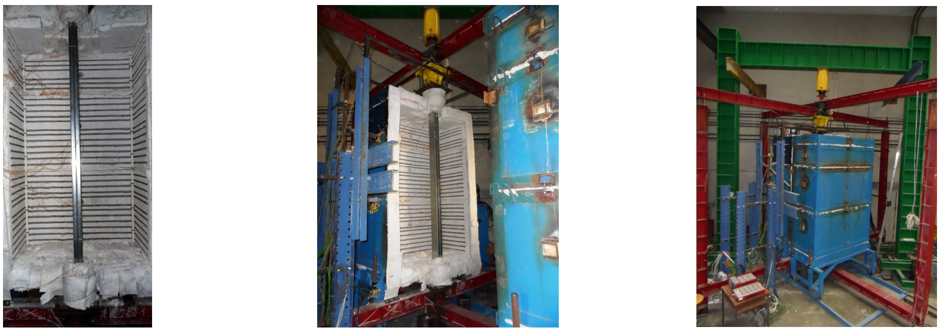

Fig. 3 Experimental set-up for CFS slender columns with thermal restrained elongation subjected to fire.

2.2 Test procedure

Test specimens were placed in the centre of the restraining structure in the built end-support system that provided pin-ended conditions. All measuring devices were installed in the defined positions. Then the vertical electrical furnace was closed and using a hydraulic jack the correspondent service load was applied. The top beams were connected to the steel columns with M24 grade 8.8 threaded rods. However, during the initial applied load, the vertical displacements of the top beams were allowed, as a slide, in order to guarantee that this load was directly applied to the CFS column. The applied load corresponded to 30% and

50% of the design buckling resistance of a compression member ($N_{b,Rd}$) determined according to the EN 1993-1.1 (2005) and EN 1993-1.3(2006). In Tab. 1 the correspondent loads to the 30% of load level to each cross section considering the pin-ended situation are presented.

Tab. 1 Load values applied.

	C [kN]	I [kN]	R [kN]	2R [kN]
30% $N_{b,Rd}$	8,010	27,200	24,400	95,100

Reaching the established load, vertical displacements of the top beams were blocked, using nuts, and then the electrical furnace, programmed to reproduce ISO 834 fire curve, was turned on. The load applied using the hydraulic jack was kept constant throughout the test and the restraining forces developed by thermal elongation were measured with the load cell placed inside the built device. The test ended when the column no longer supported the applied load and the initial load was reached. Three tests for each type of cross section were carried out.

3 RESULTS AND CONCLUSIONS

Since all fire resistance tests were performed inside the vertical furnace, only the final shape of the column could be observed. It was observed that the failure mode involved global buckling and more or less visible local buckling, and that identical columns presented identical deformed shapes.

Some preliminary results for the 50% load level concerning the evolution of temperatures in the mid-section of the column, for each cross section, and the evolution of the restraining forces are presented (Fig. 3 and 4).

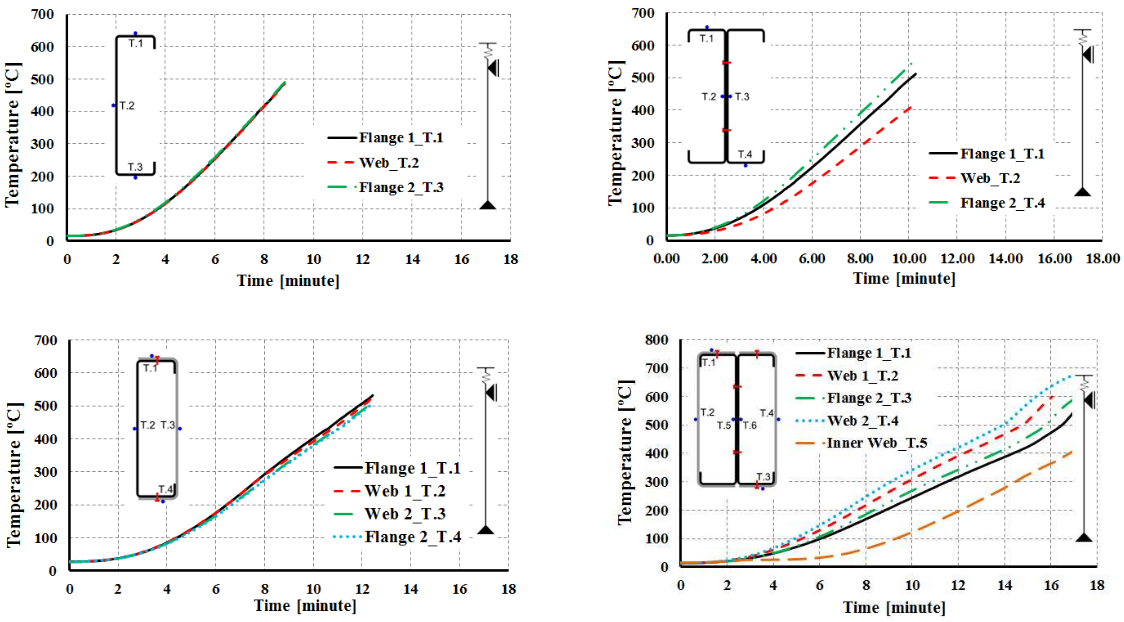

Fig. 3 Evolution of temperatures in each cross section in the mid-section of the column

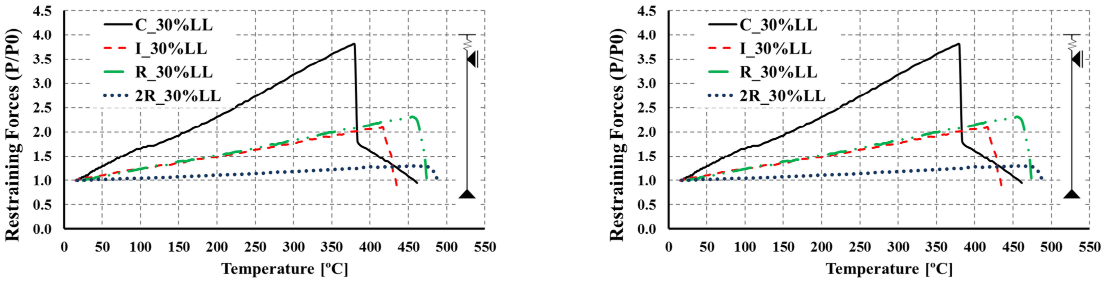

Fig. 4 Evolution of restraining forces *vs* time and temperature in CFS columns with a 30% load level

It was found that the temperature in each cross section was relatively uniform, except for the closed built-up cross section, 2R, where it was found that the temperature in the inner web is significantly lower. It was observed that for the C cross section the restraining forces increased up to 3.8 times while for I, R and 2R increased up to 2.09, 2.31 and 1.29, respectively and that closed built-up cross sections showed a greater fire resistance. Also it could be observed that the failure temperature was relatively similar for the tested cross sections. Post-critical behaviour at high temperatures was not significant. It was clear that 350 º C limitation indicated in the Eurocode 3 Part 1.2 is too restrictive since that for temperatures higher than this one the columns still showed load bearing capacity. Comparing these results with the ones presented by Almeida et al. (2012) it was found some similarities between them, both in terms of temperature and restraining forces despite the different thicknesses adopted.
Further experimental and future numerical studies will be performed in CFS slender columns in the scope of this research project.

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