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Effects of axial and rotational restraints on concrete-filled tubular columns under fire

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ABSTRACT

This paper presents a study of the effects of axial and rotational restraints on the fire response of concrete filled tubular (CFT) columns. The fiber model presented by the authors in a previous paper Ibañez et al. (2013) is employed to simulate the fire behavior of CFT columns within non-sway frames. Parametric studies are performed to analyze the influence of the different factors affecting the problem. Consequently, the opposite effects that the restraining frame has on the fire response of CFT columns are corroborated. On one hand, the restrained thermal elongation induces restraining forces which negatively affects the column. However, a beneficial effect is produced by the rotational restraint which positively modifies the boundary conditions of the heated column. Besides, another favorable effect comes from the gradual redistribution of the internal forces as the heated column loses its mechanical capacity, resulting in higher FRR. In a second step, current provisions given by Eurocode 4 Part 1.2 (EC4) are analyzed together with those given in the UK National Annex to Eurocode 4. Finally, these values are also used in the assessment of the simple calculation model presented by the authors in a previous paper Ibañez et al. (2015) and subsequently a proposal is made obtaining reasonably accurate but slightly safe results since the guidelines of CEN-Horizontal Group Fire were followed. As a result, the fire effective length value of 0.5 L given by EC4 is found to lead to unsafe results, being more appropriate to adopt the value of 0.7 L suggested in the UK National Annex.

1. Introduction

Generally, most of the published works on the fire behavior of CFT columns deal with the study of these columns as isolated members. Without restraints, their general fire response can be divided into the four stages displayed in Fig. 1 in terms of column axial displacement along time [1,3]. At the first phase of a fire, the steel tube expands faster than the concrete core due to its higher thermal conductivity and its direct exposure to fire and, as a result, the axial displacement rate of both components is decoupled. Owing to this fact, the axial load ratio of the steel tube progressively increases, up to a point where the whole applied load is supported uniquely by the steel tube (stage 1). When it reaches its critical temperature and the local yielding of the steel section occurs (stage 2), it starts to shorten, allowing the loading plate to contact back the concrete core. At this point, the axial force ratio undergoes an inversion since the load sustained by the steel tube is gradually transferred to the concrete core as the column shortens (stage 3). In previous stages, the steel tube has lost its load-bearing capacity and now the concrete core is the element showing more resistance. The ultimate failure occurs when the concrete core completely loses its strength and stiffness after a significant period of time during which its mechanical properties are completely degraded (stage 4).

However, the behavior of a column within a structure differs from that shown as an isolated member and this is even more noticeable at high temperature, where the increment in the column relative stiffness to the adjacent non-exposed structural members leads to changes not only in its boundary conditions but also in its loading conditions, modifying its response. Therefore, and taking into account the characteristic fire behavior of CFT columns presented above, the study of the effects of axial and rotational restraints becomes crucial to completely understand the response of these composite columns when they are assembled to other structural members.

In this line, some attempts have been done [4,5,6], although the number of studies in the field of CFT columns is still scarce in comparison with the number of publications on steel structures [7,8,9,10,11,12]. Among the most relevant works, the global model presented by Wang [4] can be found to evaluate the effects of structural continuity on the fire resistance of CFT columns by a finite element program developed by the authors. According to Wang [4], given the uniform reduction of the cross-sectional stiffness in steel columns, in fire limit state, the structural continuity should provide built-in conditions and should reduce bending

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Notation

A/V	Section factor
CFT	Concrete filled tube
D	Diameter of the column
EC4	Eurocode 4 Part 1.2
FRR	Fire resistance rating
L	Length of the column
l_θ	Buckling length in the fire situation
P/P_0	Restraining forces
T	Temperature
UK NA	UK National Annex to Eurocode 4
t	Thickness of the steel tube
α	Stiffness ratio $\alpha = K_{beam}/K_{column}$
β	Effective length ratio
$\overline{\lambda}$	Relative slenderness of the column at room temperature
$\overline{\lambda}_\theta$	Relative slenderness of the column in a fire situation
μ	Axial load level $\mu = N / N_{Rd}$
ξ	Relative error

moments to a negligible level since the bending stiffness at elevated temperatures is very low. However, the author pointed out that it may be not the case of CFT columns where the temperature distribution in the composite cross-section is non-uniform. A numerical study was carried out to assess the provision for the effective length of composite columns in the fire limit state given by Eurocode 4 Part 1.2 [13] which currently has a value of 0.5 L for columns placed at an intermediate story. As reported by the author, its applicability for CFT columns was confirmed.

In the same vein, Bailey [5] also presented a fiber beam model for simulating square CFT columns at room and high temperatures. The work focused on the evaluation of the effective length at fire limit state of these composite columns and it was concluded that for columns continuous at both ends the adoption of an effective length of 0.75 L was recommended to obtain safe predictions.

The two works mentioned above employed fiber beam models since they are the most efficient from the computational point of view when part of a structure, and not only a single element, is modeled. Although using fiber beam models may imply assuming some simplifications, the improvement in the response given by more realistic models usually does not compensate the increase in the computational cost associated.

However, some studies can be found where three-dimensional finite element models have been employed despite their elevated computing time. Thus, Yu et al. [6] developed a three-dimensional model in ABAQUS for circular CFT columns but, in order to maximize the

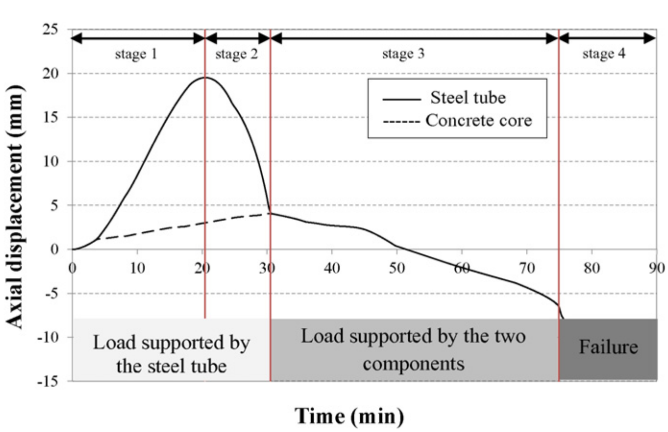

Fig. 1. Typical behavior of a CFT column subjected to elevated temperatures.

efficiency of the numerical procedure with acceptable loss of accuracy, simplifications such as neglecting the slip and separation between the steel tube and the concrete core were adopted. Only the CFT column was heated and the rest of the structural elements were not exposed to fire. The authors highlighted two aspects to be considered in fire design: due to the redistribution of internal forces, the bending moment in the heated column was significantly reduced and the FRR of the column within a frame was improved.

Hence, given the limited number of research studies dealing with the fire behavior of CFT columns within frames, this paper presents a new model for the study of the effects of axial and rotational restraints on the fire response of columns with continuity at both ends.

In this work, an extensive parametric analysis of the fire response of CFT columns within frames and continuous at their both ends is carried out. For that purpose, a validated fiber beam model previously developed by the authors [1] is employed. The subsequent study of the results is presented jointly with the evaluation of the provisions given by Eurocode 4 Part 1.2 [13]. Finally, the assessment of a simple calculation method proposed by the authors in a previous publication [2] is included and the corresponding proposal for the effective length in fire is given.

2. Description of the numerical model

A previously validated fiber beam numerical model developed by the authors [1] is available. For the sake of simplicity, just a brief description of the model is given hereafter since it is not the purpose of this paper.

The finite element model takes as a basis the FedeasLab [14] platform, a Matlab toolbox for the nonlinear analysis of structures. This model is capable of simulating with enough accuracy the fire behavior of concentric axially loaded concrete filled tubular columns. The details of the model are described in [1] jointly with its validation against results from own experiments and from tests found in literature. The validity of the model covers a wide range of concrete infill: plain, bar reinforced and steel fiber reinforced concrete of both normal and high strength.

By means of the numerical model, a sequentially coupled thermal-stress analysis can be performed where two analysis steps are differenced: a thermal analysis and a mechanical analysis. First, a sectional thermal analysis is carried out to compute the temperature field of the columns and subsequently, a mechanical problem is solved to obtain the structural response.

For the main heat transfer parameters, the values recommended in EN 1991-1-2 [15] are used. The standard ISO-834 [16] fire curve is applied to the exposed surface of the CFT column along its whole length as a thermal load, through the convection and radiation heat transfer mechanisms. The thermal resistance at the steel–concrete interface is taken into account through a gap conductance value of 200 W/m^2 K, as recommended by other authors [3,17]. The effect of concrete moisture is considered assuming that during the process of water evaporation, which starts when the temperature reaches 100 °C, the concrete temperature does not increase since all the heat provided is employed in this process until the moisture has evaporated completely.

The fiber beam model consists of three parts: the concrete core, the steel tube and the link elements, which connect the former two. It is based on the clear differentiation of phases discussed in the previous section and in the simulation of the existing relative sliding between the steel tube and the concrete core, since this interaction mechanism is the main phenomenon responsible for the bearing capacity of the column.

Therefore, in the model, a complete circular CFT column is formed by assembling in parallel two simple columns: a steel hollow section column and a concrete column. These columns are modeled with fiber finite elements connected at their nodes by link elements both longitudinally and transversely as shown in Fig. 2. Transversal link elements have a high stiffness to assure identical deformed shapes. However, the longitudinal link elements are designed in such a way that the top