Fire Resistance of Axially Loaded Slender Concrete Filled Steel Tubular Columns

Development of a Three-Dimensional Numerical Model and Comparison with Eurocode 4

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In recent years, concrete filled tubular (CFT) columns have become popular among designers and structural engineers, due to a series of highly appreciated advantages: high load-bearing capacity, high seismic resistance, attractive appearance, reduced column footing, fast construction technology and high fire resistance without external protection. In a fire, the degradation of the material properties will cause CFT columns to become highly nonlinear and inelastic, which makes it quite difficult to predict their failure. In fact, it is still not possible for analytical methods to predict with enough accuracy the behaviour of columns of this kind when exposed to fire. Numerical models are therefore widely sought. Many numerical simulations have been carried out worldwide, without obtaining satisfactory results. This work proposes a three-dimensional numerical model for studying the actual fire behaviour of columns of this kind. This model was validated by comparing the simulation results with fire resistance tests carried out by other researchers, as well as with the predictions of the Eurocode 4 simplified calculation model.

Keywords: Fire resistance, concrete filled steel tubular columns, finite element analysis.

1 Introduction

Filling hollow steel columns with concrete is an interesting way to improve their fire resistance [7]. The temperature at the surface of a hollow structural section without external protection increases quickly during the development of a fire. However, if the steel tube is filled with concrete, while the steel section gradually loses its resistance and rigidity, the load is transferred to the concrete core. The concrete core heats up more slowly, thus increasing the fire resistance of the column. Besides its structural function, the steel tube acts as a radiation shield to the concrete core. This, combined with a steam layer in the steel-concrete boundary, leads to a lower temperature rise in the concrete core when compared to exposed reinforced concrete structures [7].

During a fire, the temperature distribution in the cross-section of a CFT column is not uniform: steel and concrete have very different thermal conductivities, which generates a behaviour characterized by noticeable heating transients and high temperature differentials across the cross-section. Due to these differentials, CFT columns can achieve high fire resistance times without external fire protection [7]. However, it is necessary to resort to numerical models in order to make an accurate prediction of these temperature profiles along the fire exposure time [8], [9].

In this work, the ABAQUS finite element analysis package [1] was employed to model the behaviour of slender axially loaded CFT columns exposed to fire. With this software, a sequentially coupled nonlinear thermal-stress analysis was conducted. The results of the simulations were compared with a series of fire resistance tests available in the literature [11], as well as with the predictions of the Eurocode 4 [6] simplified calculation model.

2 Development of the numerical model

2.1 Finite element mesh

A three-dimensional numerical model was developed in ABAQUS [1], with variable parameters such as the length of the column (L), the external diameter (D), the thickness of the steel tube (t) and the thermal and mechanical material properties. It consisted of two parts: the concrete core and the steel tube. Due to symmetry on the geometry and boundary conditions, only a quarter of the column was modelled.

The three-dimensional eight-node solid element C3D8RT was used to mesh the model. It is an eight-node thermally coupled brick, with trilinear displacement and temperature, reduced integration and hourglass control. The mesh density was controlled to have a maximum element size of 2 cm, which proved to be sufficient to predict with enough accuracy the thermal and mechanical behaviour of the CFT columns under fire.

2.2 Material properties

The numerical model took into account the temperature dependent thermal and mechanical properties of the materials. For concrete, Lie's model [12] was employed, as it proved to be the one that best predicted the behaviour of the concrete infill in CFT columns, according to Hong & Varma [9]. The mechanical model implemented in ABAQUS employed the hyperbolic Drucker-Prager yield surface. The thermal properties for concrete at elevated temperatures were extracted from EN 1992-1-2 [4]. For steel, the temperature dependent thermal and mechanical properties recommended in EN 1993-1-2 [5] were adopted. The isotropic multiaxial plasticity model with the Von Mises yield surface was employed.

The values of the thermal expansion coefficient for concrete and steel recommended by Hong and Varma [9] were employed: $\alpha_s = 12 \times 10^{-6}\ ^\circ\mathrm{C}^{-1}$, $\alpha_c = 6 \times 10^{-6}\ ^\circ\mathrm{C}^{-1}$. The moisture content of the concrete infill was not modelled in this research, which lies on the safe side.

2.3 Thermal analysis

For conducting the thermal analysis, the standard ISO-834 [10] fire curve was applied to the exposed surface of the CFT column model as a thermal load. The thermal contact in the steel-concrete boundary was modelled by employing the "gap conductance" and "gap radiation" options. For the governing parameters of the heat transfer problem, the values recommended in EN 1991-1-2 [3] were adopted.

3 Validation of the numerical model

The three-dimensional numerical model was validated by comparing the simulations with experimental fire resistance tests [11] and with the EC4 simplified calculation model [6].

3.1 Comparison with experimental results

The numerical model was employed to predict the standard fire behaviour of a series of CFT column specimens listed in Table 1. These specimens were tested at the NRCC, and their results were published by Lie & Caron [11]. All the specimens tested were circular, filled with siliceous aggregate concrete and subjected to a concentric compression load. Their total length was 3810 mm, although only the central 3048 mm were directly exposed to fire. Because of the loading conditions, all the tests were assumed as fix-ended.

Table 1: List of CFT columns analyzed, from the NRCC research report [11]

Column specimen	D (mm)	t (mm)	f_y (N/mm^2)	f_{ck} (N/mm^2)	N (kN)	$\mu = N/N_{pl,Rd}$	FRR (min)
1	141	6.5	401.93	28.62	131	8.90 %	57
2	168	4.8	346.98	28.62	218	15.37 %	56
3	219	4.8	322.06	24.34	492	26.19 %	80
4	219	4.8	322.06	24.34	384	20.44 %	102
5	219	8.2	367.43	24.34	525	18.88 %	82
6	273	5.6	412.79	26.34	574	17.08 %	112
7	273	5.6	412.79	26.34	525	15.63 %	133
8	273	5.6	412.79	26.34	1000	29.76 %	70

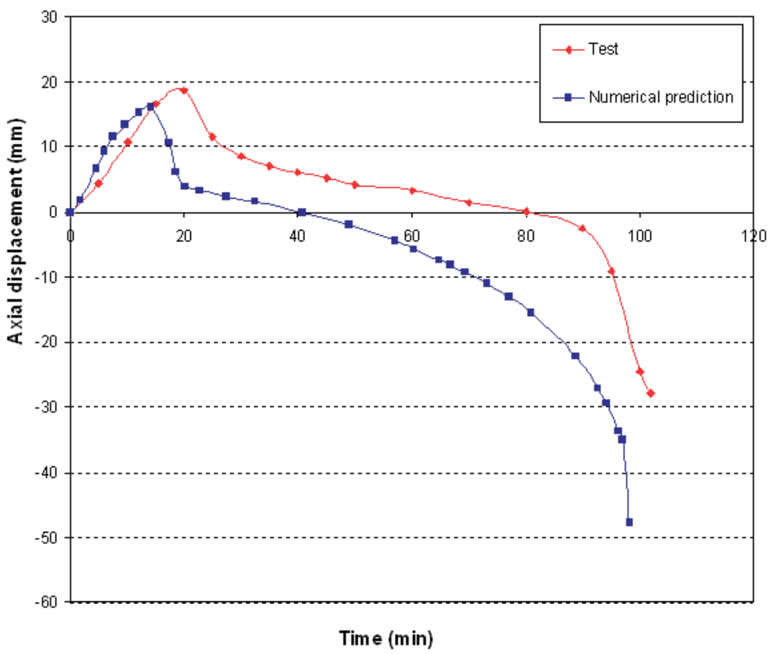

Fig. 1: Comparison between calculated and measured axial displacement, for test no. 4

Table 2: Predicted and measured FRR and maximum axial displacement (δ_{max})

Column specimen	FRR (min)		$\xi_{FRR} = \dfrac{FRR_{test}}{FRR_{NS}}$	δ_{max} (mm)		$\xi\,\delta_{max} = \dfrac{\delta_{max,\ test}}{\delta_{max,\ NS}}$
	Test	**Simulation**		**Test**	**Simulation**	
1	57	72	0.79	24.09	24.35	0.99
2	56	75	0.75	20.48	19.25	1.06
3	80	74	1.08	18.13	12.36	1.47
4	102	97	1.05	18.77	16.23	1.16
5	82	68	1.21	20.36	19.30	1.05
6	112	126	0.89	16.40	17.71	0.93
7	133	137	0.97	19.67	18.61	1.06
8	70	70	1.00	5.51	10.35	0.53
		Average	**0.97**		**Average**	**1.03**
		Standard deviation	**0.15**		**Standard deviation**	**0.26**

For each simulation, the axial displacement at the top of the column versus the fire exposure time was registered, comparing this curve with the curve obtained in the fire resistance test [11]. Fig. 1 shows an example of the comparison of the two curves for one of the specimens studied.

From these curves, the fire resistance rating (FRR) was obtained for each of the specimens under study. The failure criteria from EN 1363-1 [2] were adopted. This standard establishes that the failure time is given by the more restrictive of the following two limits: maximum axial displacement, and maximum axial displacement velocity. By applying these criteria, the values in Table 2 were obtained. As shown in Fig. 2, most of the values obtained lie in the region of 15 % error, apart from two values, corresponding to column specimens no. 1 and no. 2, which have the smallest diameters.

The maximum axial displacement (δ_{max}) was also obtained for each of the column specimens studied here. Table 2 shows the calculated and measured values, which are plotted in Fig. 3, where it can again be seen that most of the cases lie in the region of 15 % error, apart from specimens no. 3 and no. 8, corresponding to those with a higher loading level, over 20 % of the maximum load-bearing capacity of the column at room temperature.

3.2 Comparison with the Eurocode 4 simplified calculation model

In this section, the numerical model is compared with the predictions of the EC4 simplified calculation model [6], obtaining the results shown in Table 3. It is seen in Fig. 4 that the proposed numerical model gives a better prediction of the

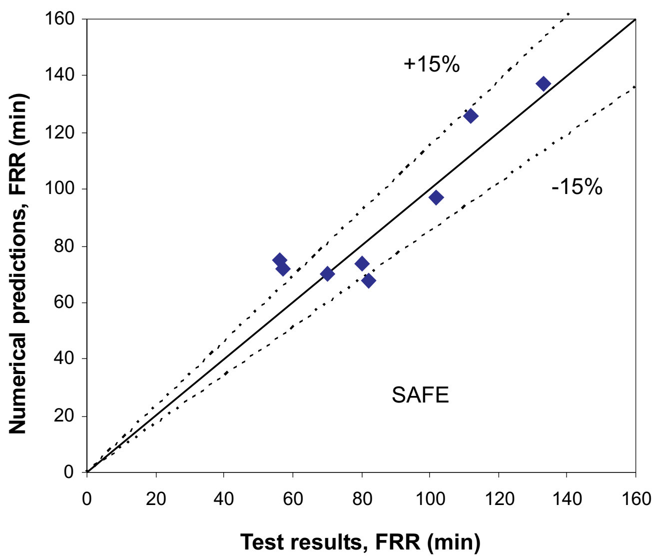

Fig. 2: Comparison of the fire resistance ratings, calculated versus test results

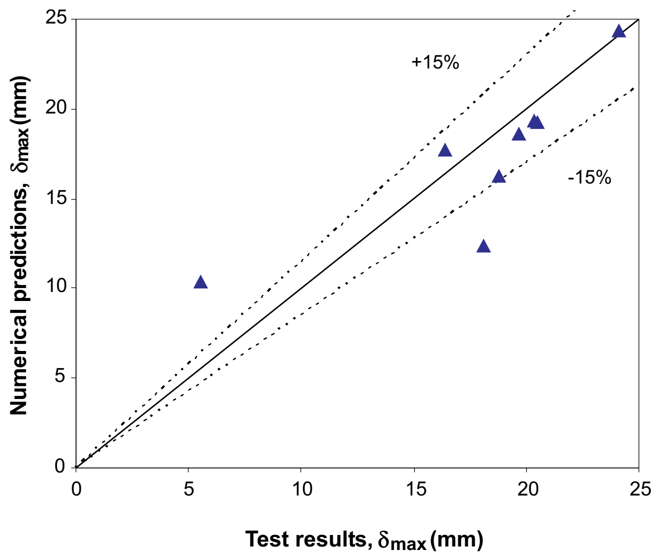

Fig. 3: Comparison of the maximum axial displacement, calculated versus test results

Table 3: Comparison of the numerical model and EC4 predictions with the tests

Column specimen	FRR (min)				$\xi_{FRR} = \frac{FRR_{test}}{FRR_{calc}}$		
	Test	Simulation	Simulation (no expansion)	EC4	Simulation	Simulation (no expansion)	EC4
1	57	72	49	49	0.79	1.16	1.16
2	56	75	46	46	0.75	1.22	1.22
3	80	74	52	49	1.08	1.54	1.63
4	102	97	63	61	1.05	1.62	1.67
5	82	68	52	51	1.21	1.58	1.61
6	112	126	118	91	0.89	0.95	1.23
7	133	137	126	96	0.97	1.06	1.39
8	70	70	58	56	1.00	1.21	1.25
				Average	**0.97**	**1.29**	**1.39**
				Standard deviation	**0.15**	**0.25**	**0.21**

fire resistance rating, showing a very accurate trend. However, the EC4 simplified model turns out to be excessively conservative, as shown in the figure. We must note that the EC4 simplified model does not take into account the thermal expansion of the materials, nor the air gap at the steel-concrete boundary, which lies on the safe side and gives a very conservative prediction. If we apply these simplifications to our numerical model, smaller values of the fire resistance ratings are obtained, very similar to those predicted by EC4, as shown in Table 3. As can be seen in Fig. 5, our predicted values reproduce quite well the results of EC4, except for those tests with fire resistance ratings around 120 minutes, where our numerical model provides more accurate results, producing a trend that is closer to reality.

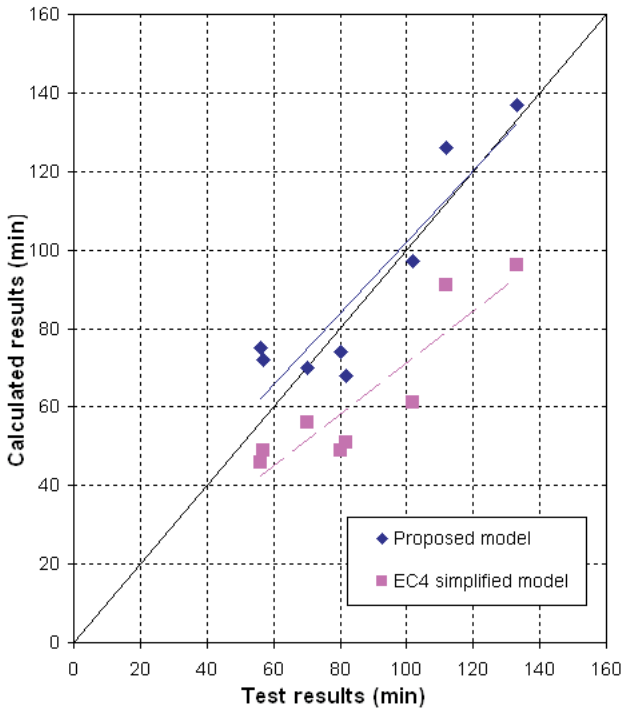

Fig. 4: Comparison of FRR, proposed numerical model, and EC4 model

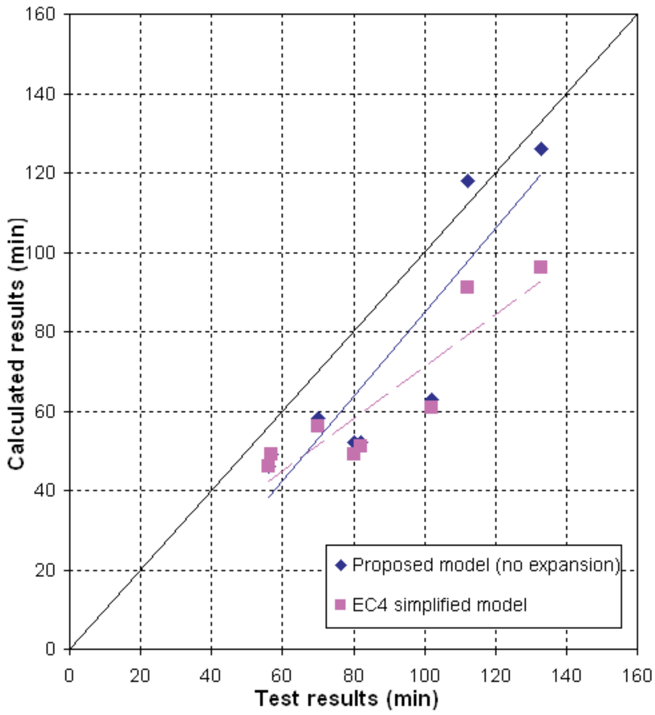

Fig. 5: Comparison of FRR, proposed model (without expansion), and EC4 model

4 Summary and conclusions

A three-dimensional numerical model for axially loaded slender CFT columns under fire has been presented. By means of this model, a prediction was made of the behaviour under standard fire conditions of eight column specimens previously tested by the NRCC research group [11]. The proposed numerical model showed better behaviour for columns with low slenderness and loading levels under 20 %. Despite these two aspects, the model showed an accurate response when contrasted with the fire tests.

The study has also proved that the predictions of the EC4 simplified calculation model [6] can be reproduced with the proposed numerical model by eliminating the thermal expansion of the materials, which lies on the safe side. However, if the real behaviour of CFT columns under fire is to be predicted, this factor must be taken into account, extending the failure time. The expansion of the steel tube produces an opposed axial strain in the early stages of heating, as well as an opening of the gap in the steel-concrete interface, which delays the heating of the concrete core and thus increases the fire resistance rating.

The proposed numerical model proved to give better predictions than the EC4 simplified model, which turned out to be excessively conservative.

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