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The performance of concrete filled steel tube columns under post-earthquake fires

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ABSTRACT

In this study, a nonlinear three-dimensional finite element (FE) model was developed and validated to investigate the response of concrete filled tube (CFT) columns subjected to post-earthquake fires. Three steps were considered successively in the modelling, namely, cyclic, thermal and structural analyses. Outputs from the cyclic loading including residual deformations were imposed as an initial condition to the thermal-stress model, imitating the seismic response of the column. Subsequently, a nonlinear sequentially thermal-stress analysis was conducted to simulate the fire response of column after the earthquake. The proposed FE model was validated by comparing the simulation results with the observations of full-scale fire and cyclic tests available in the literature. The validated numerical model was then used to study the behavior of CFT columns under the combined action of earthquake and fire as a multi-hazard event. Three probable seismic damage scenarios were considered in the column, namely, middle length, bottom and top end region damages. The level of damage was assumed as a high damage level, presuming that the column reached 50% of its lateral resistance while still maintaining its overall stability after the earthquake. The results showed that the top and bottom end region damages have not significantly influence the fire response of the damaged column. Besides, the column with the middle span damage performed a lesser fire resistance time owing to the coincidence of damage location to that of onset of global buckling.

1. Introduction

Concrete filled tube (CFT) columns have been shown to be superior structural members for exhibiting high performance against severe events. High seismic resistance of these systems is reported by several researchers [1–3] and their high fire resistance without external protections are addressed elsewhere [4–7]. CFT columns gain their high fire resistance via two main effects, namely, the shield effect of the steel tube and the heat sink effect of the concrete. The former protects the in-filled concrete from heating directly and maintains its integrity, besides, the later postpones temperature increase in the concrete core. Nonetheless, the degradation of material properties at high temperatures leads to a real nonlinear behavior of these members, which makes it hard to foresee their failure. Although analytical formulations have been developed in this field [8], they are not capable enough to exactly estimate the fire resistance of CFT columns. On the other hand, conducting the full-scale test is expensive and the facilities are not available easily, arising the need for the development of numerical model. Up to now, several studies dedicated on the numerical simulation of CFT columns at fire [9–12] and earthquake [13–15] but none of them considers the behavior of these composite columns under the combination of both incidents as a multi-hazard event.

Ding and Wang [9] developed an advanced model for predicting the fire performance of CFT columns with circular and square cross-sections. Some relevant features, such as the effect of air gap, the slip between the steel tube and the concrete core surfaces, and the influence of concrete tensile strength on the fire resistance of CFT columns were considered explicitly in their study. They showed that the existence of slip at the steel-concrete interface as well as the tensile strength of concrete material has minor effect on the fire resistance of CFT columns. In addition, the failure time of CFT columns could be enhanced slightly by considering the air gap in the modelling. By examining various amount of initial imperfection, they confirmed that the value of $L/1000$ that has been used widely by other researchers is an acceptable quantity as an initial imperfection. Espinos et al., [10] studied numerically the behavior of axially loaded CFT columns with circular cross-sections at fire. They presented that the steel tube-concrete interface in the tangential direction can be modelled as frictionless in fire. This is due to the transversal separation of adjacent surfaces owing to the high thermal expansion of steel material at elevated temperatures. Besides, when the Coulomb friction is modelled in the interface, the value of coefficient friction has not any influence on the fire performance of CFT columns. Moreover, they showed that adopting the constant value of $h_j = 200 W/m^2$ for

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the thermal conductance at the gap existed between the steel tube and in-filled concrete surfaces leads to the accurate results.

Hu et al., [13] evaluated the response of CFT columns under the combination of axial compressive force and bending moment. Three types of cross-sections were examined by them, namely, circular (CU), square (SU) and square sections with stiffening ties (SS). Their study showed that the larger the imposed axial force, the bigger the confining effect provided by the steel tube on the concrete core. In terms of confining effect, the circular columns showed superior performance in comparison with the two other sections. However, the stiffening of square sections with tie elements showed direct relation with the enhancement of confining effect. Due to the weak confining effect in SU sections, severe local buckling exhibited in the tube at the mid-length and top regions, without any sign of tube buckling for CU and SS one. Chang et al., [15] studied the performance of an enhanced type of CFT column, as the steel reinforced-concrete filled-steel tubular column (SRCFST) under cyclic loading. Their study revealed that the insertion of steel section within the concrete core could noticeably enhance both the strength and the stiffness of conventional circular CFT columns. This resulted because the steel section could carry a portion of applied lateral loading, which led to a decrease in the tensile zone of in-filled concrete. Furthermore, by increasing the compressive strength of concrete core and the tube thickness, the columns experienced higher lateral peak load. They also showed that, by increasing the applied axial force the deformability and stiffness of CFT columns remarkably decreased.

A review of historical records prove that the damages generated by post-earthquake fires can be very substantial, often exceeding the damage produced by earthquake itself [16, 17]. Hence, the occurrence of fire ensuing earthquakes is a noteworthy concern to be considered on the resistance of structural members, especially for those are located in the moderate-to-high seismically zones. Although several researchers investigated the resistance of CFT columns under fire and earthquake, there is still a lack of understanding on the response of these composite columns under the fire after earthquake as a multi-hazard incident.

With regards to the lack of studies on the behavior of CFT columns exposed to both events, this work was aimed to explore numerically the actual performance of these columns under post-earthquake fires. In this study, a three-dimensional nonlinear finite element (FE) simulation was developed, using ABAQUS program [18]. Various key variables such as the initial imperfection, the thermal conductance at the air gap, contact model between the in-filled concrete and the steel tube, as well as the degradation of material properties at elevated temperatures were considered in the modelling. Three analysis steps were considered consecutively in the modelling, namely, cyclic, thermal and structural analyses. The effect of earthquake loading on the column was simulated via cyclic loading of the specimen. The outcome of seismic analysis including the residual deformations were applied stress-free as the initial condition to the next analysis step, i.e., sequentially thermal-stress analysis. The accuracy of numerical model developed in this paper was validated by comparing the FE results with the experimental tests available in the literature on the cyclic testing [3] and fire testing of CFT columns [4]. By means of validated model on the cyclic response and fire resistance of CFT columns separately, the performance of these composite columns were then explored under the combination of both events.

2. Numerical model under cyclic loading

2.1. General

A three-dimensional nonlinear FE model was conducted in ABAQUS package [18] to simulate the effect of earthquake loading on composite tubular columns. Eight CFT circular columns were tested by Han and Yang [3] and among them, the specimens labeled as SC2–3 and SC2–4, were chosen for the verification of cyclic analysis in this study. To accurately replicate the test predictions in the FE simulation, the materials, loading and boundary conditions were modelled exactly the same as those used in the reference test [3]. In spite of the existence of symmetry, the whole length and the full cross-section of column was modelled. This was for considering the probability of unsymmetrical deformed shape occurrence, which could be dominated by the shear failure of concrete in the cyclic loading.

Table 1
Detail information on the selected columns for cyclic analysis.

Column	L (mm)	$D \times t$ (mm)	f_{sy} (MPa)	E_s (GPa)	f_{cu} (Mpa)	N_o (kN)	n
SC2–3	1500	114 × 3	308	200	38.9	286	0.4
SC2–4	1500	114 × 3	308	200	38.9	429	0.6

2.2. Geometry, loading and meshing

To study the influence of axial load on the lateral resistance of CFT columns, the samples were chosen such that they were similar in both geometry and material with different amount of applied axial load (Table 1). The axial load level, n, was considered as $n = N_0 / N_u$, where N_0 and N_u are the applied axial load and the compressive capacity of the column, respectively [3].

Two rigid steel plates with the thickness of 16 mm were modelled at the column endings, through which the axial load and the boundary conditions were appended. A rigid steel stub with a length of 150 mm was modelled at the mid-span of the column, through which the cyclic loading was applied (Fig. 1). The pined-pined boundary conditions were modelled at both endings while one end was allowed to move in the longitudinal direction, as was in the test. The loading was applied in consecutive steps as follows. First, the axial load (N_o) was applied to the top plate and kept constant through the whole analysis, simulating the reaction from the upper stories. This load was equal to 286 kN and 429 kN for column SC2–3 and SC2–4, respectively, which was considered as 40% and 60% of the column ultimate axial strength (Table 1). The lateral cyclic load was then applied to the steel stub according to the ATC-24 [19] guidelines to simulate the seismic load. The loading history included elastic cycles and inelastic cycles. The elastic cycles were applied under the load control mode at load levels of $0.25P_u$, $0.5\ P_u$ and $0.7\ P_u$, where P_u was the estimated lateral load capacity. The inelastic cycles were then imposed in levels of Δ_y, $1.5\ \Delta_y$, $2\ \Delta_y$, $3\ \Delta_y$, $5\ \Delta_y$, $7\ \Delta_y$, $8\ \Delta_y$, where Δ_y was the yield displacement of column. Note that in this section, to replicate the test results appropriately, the value of P_u and Δ_y were used as obtained in the test [3].

The steel tube, in-filled concrete and the steel stub were meshed using three-dimensional eight node solid elements with reduced integration (C3D8R) available in ABAQUS [18]. To efficiently capture the occurrence of local buckling, mesh refinement was done in the areas that the local buckling of steel tube was anticipated. From the test, these

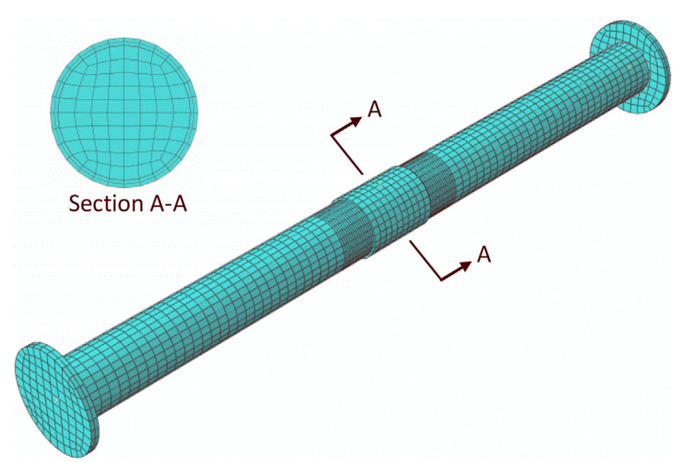

Fig. 1. Meshed model of column SC2-3 and SC2-4 under cyclic loading.