

Experimental and Numerical Investigation on the Resistance and Failure Behavior of Ductile Concrete-Filled Double-Skin Tube Columns Subjected to Post-Earthquake Fires

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Abstract

Fire following an earthquake has been a major cause of damage in a number of historic seismic events. Considering the amount of damage and statistics showing a high probability for the occurrence of post-earthquake ignitions, there is a need to study the effects of seismic damage on the fire resistance of structures. This research studies the resistance and failure behavior of Concrete Filled Double-Skin Tube (CFDST) columns with both experimental and numerical methods. CFDSTs are categorized as a special composite structure which has been shown to have satisfactory performance under separate seismic loading and fire conditions. Comparison between the fire resistance of different CFDST columns with various degrees of simulated seismic damage provided evidence for the overall resilient performance of these columns under post-earthquake fire scenarios.

INTRODUCTION

Fire following earthquake has been reported to cause significant damage in addition to the shaking in a number of historic seismic events (Scawthorn et al. 2005). Considering the increasing risk of fire following earthquake and the possibility of the occurrence of conflagrations in the urban areas, the effects of seismic damage on the fire resistance of structural members need to be better understood. This study summarizes key findings from a series of experimental and numerical works on the behavior of ductile concrete filled double-skin tube (CFDST) columns subjected to post-earthquake fires. Past research has shown satisfactory behavior of CFDST columns under separate fire (Yang and Han 2008; Lu et al. 2010) and seismic loading (Zhao and Grzebieta 2002; Han et al. 2004).

EXPERIMENTAL WORK

Three identical CFDST specimens were constructed for testing under simulated fire following earthquake scenarios. The experiments were conducted in two phases. Phase one was completed by subjecting the identical specimens to different levels of simulated seismic damage via cyclic loading. In the second phase, specimens with different levels of seismic damage were tested under Standard ASTM E119 fire (ASTM 2012). Table 1 and Fig. 1 show the geometric properties of specimens.

Table 1. Geometric features of the specimens

Height	Diameter of Outer Tube	Diameter of Inner Tube	Thickness of Outer Tube	Thickness of Inner Tube
H (in.)	D_o (in.)	D_i (in.)	t_o (in.)	t_i (in.)
106.5	8	5	0.11	0.09

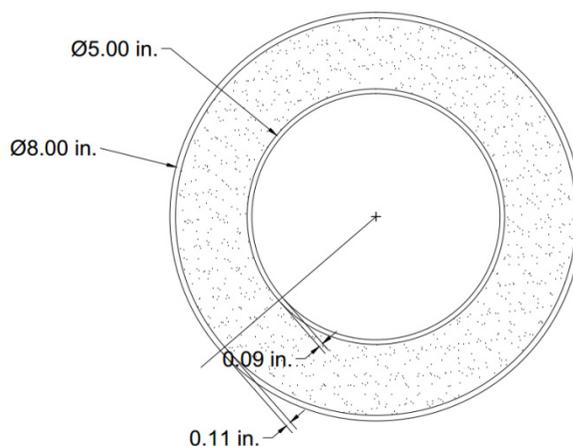


Figure 1. Section of the column specimens

The cyclic loading test setup is shown in Fig. 2. Two of the specimens (namely S1 and S2) were subjected to cyclic loading, keeping the third one (S3) undamaged for the fire test. Specimens S1 and S2 were tested in displacement control mode under a cyclic protocol according to ATC-24 (1992) with increasing displacement amplitudes. Different number of displacement cycles were applied to specimens, resulting in a moderate damage level for S1 (i.e., residual drift of 1.4%) and a high damage level for S2 (i.e., 3.9% residual drift). Outer steel tube for both of specimens had signs of local buckling at the end of the tests. Fig. 3 shows lateral force vs. lateral drift ratio results along with deformed shape of specimen S2.

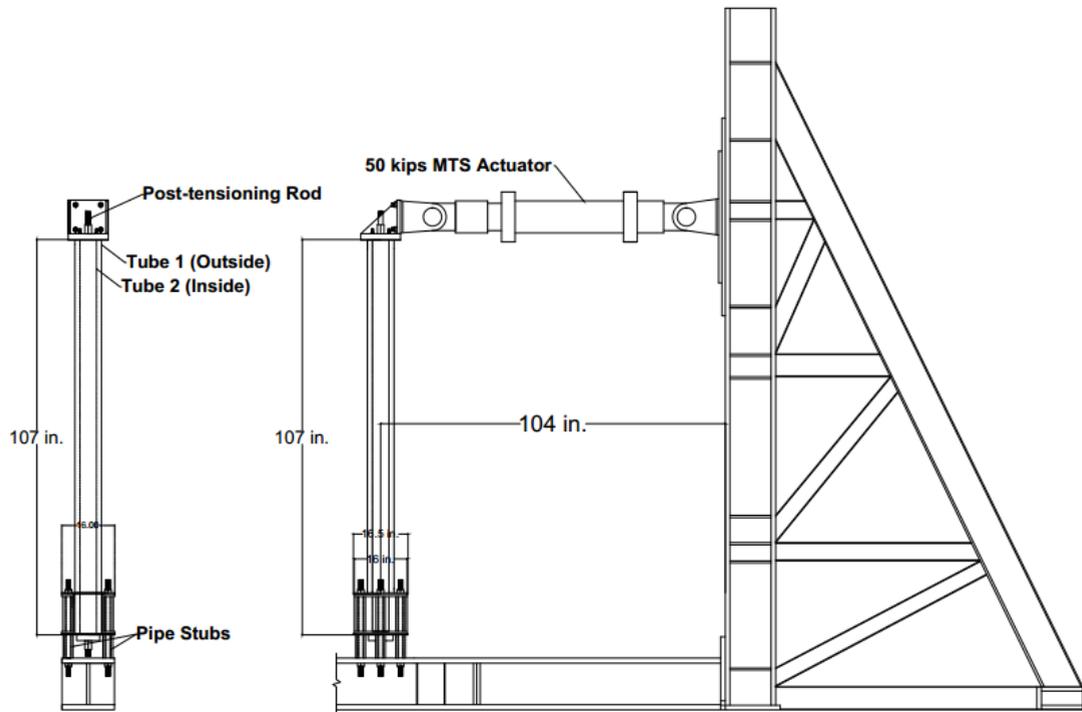


Figure 2. Full view of the experimental setup with dimensions

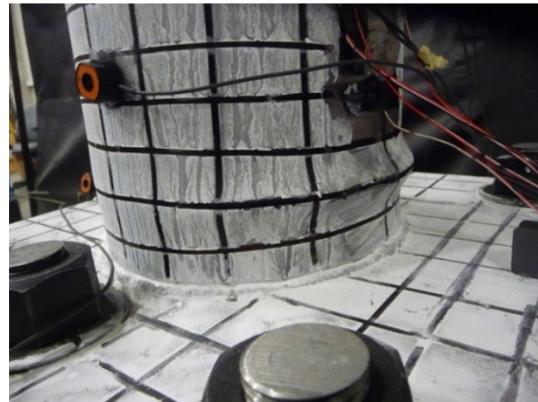
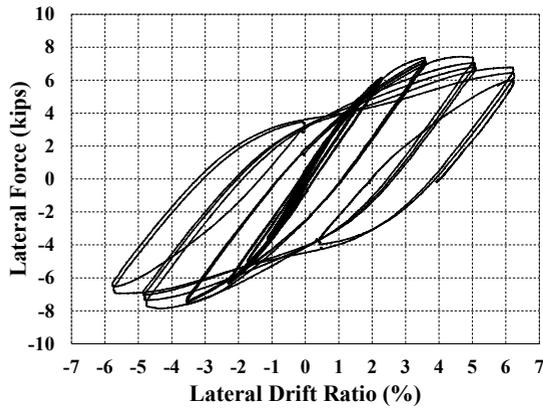


Figure 3. Cyclic testing results for specimen S2

The three specimens were tested under the Standard ASTM E119 fire in a 10 ft tall vertical furnace. An axial load of 70 kips was applied and maintained constant throughout the fire tests. Fig. 4 shows the time history of axial displacement for specimen S3 (i.e., specimen with no seismic damage).

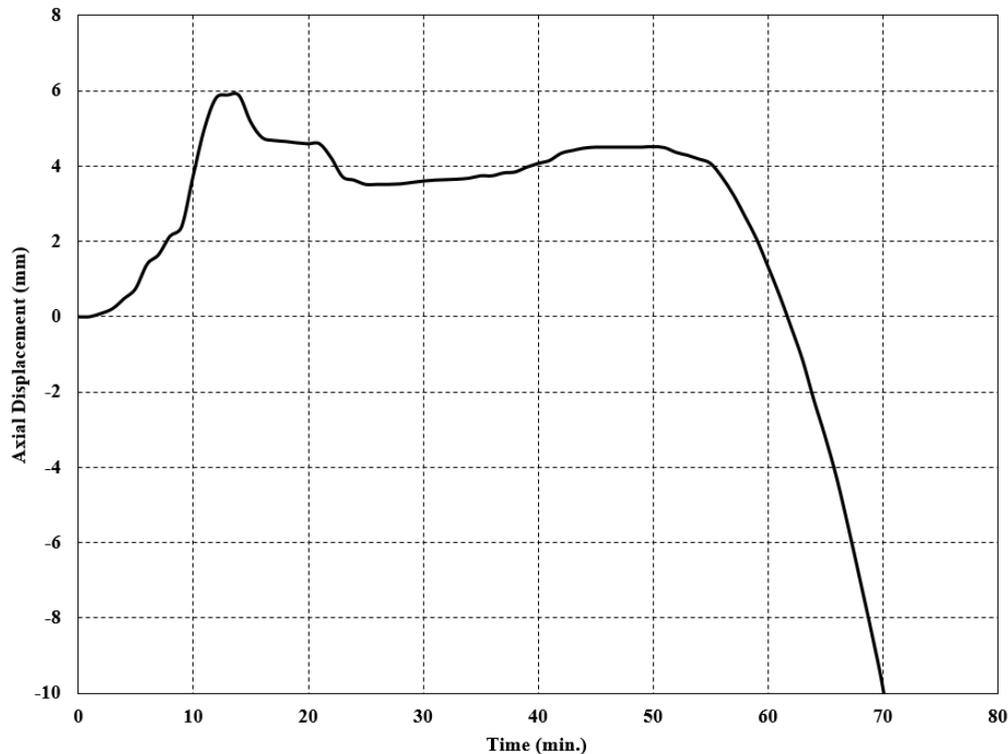


Figure 4. Time history of axial displacement of the moving (bottom) end plate of specimen S3, recorded in the fire test

Specimen S3 failed due to global buckling under the 70 kip axial load after about 65 minutes of fire exposure. Fire resistance time for specimen S1 and S2 with moderate and high seismic damage levels was almost the same as the recorded value for the undamaged specimen (within a 10-minute tolerance). Results indicated that for the particular type of columns built and tested under the mentioned boundary conditions in this study, differences in the initial conditions based on the simulated seismic damage level had insignificant effects on the total fire resistance time of the specimens. More details about the experimental results can be found in the work by Imani et al. (2014).

NUMERICAL ANALYSES

Detailed 3D finite element models of CFDST specimens were built in ABAQUS (Simulia 2012) to parallel the experimental phases presented above. The complete fire following earthquake scenario was simulated using a cyclic loading simulation followed by a sequentially coupled thermal stress analysis to capture the effects of Standard ASTM E119 fire. A bilinear elastic-plastic model with linear kinematic hardening was used for steel material. Concrete was modelled using the Damaged Plasticity material available in ABAQUS with the addition of discrete tensile cracks to capture the effect of crack opening and closing.

Fig. 5 shows the results of cyclic loading simulation for specimen S2 (load-displacement curves along with deformation results). Numerical results are in good

agreement with test data regarding strength, stiffness and local deformations of the specimen. A Similar analysis was conducted for specimen S1.

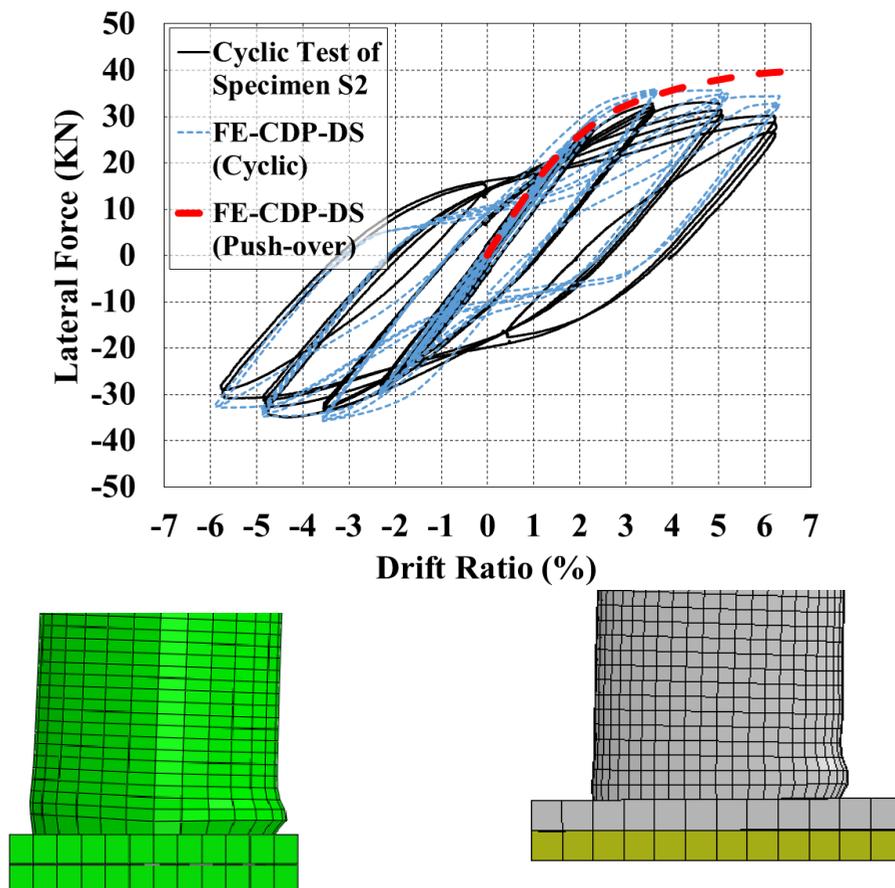


Figure 5. Numerical simulation of the cyclic loading of Specimen S2

Fire simulations were conducted using the Eurocode 4 specifications for thermal and structural properties of steel and concrete for varying temperatures (CEN 2005). Simulation started with a heat transfer analysis using initial and boundary conditions similar to test configuration. Initial conditions included residual displacement from the cyclic loads analyses of specimens S1 and S2. Results of this analysis (i.e., time history of temperature through the cross-section of CFDST column) was used as input for the stress deformation analysis that subjected the column to a constant axial load. The analysis captured local and global buckling of specimens under axial load and fire. Fig. 6 shows fire simulation results for specimen S2 which are in good agreement with test observations. Similar analyses were conducted for specimens S1 and S3 and captured the significant differences in local behavior (deformations and local buckling) for specimens with different levels of seismic damage. Global behavior, on the other hand, was similar for all of the specimens, as the analyses resulted in global buckling of specimens after 60-65 minutes of fire exposure. Additional details on finite element simulations can be found in a study by Imani et al. (2015).

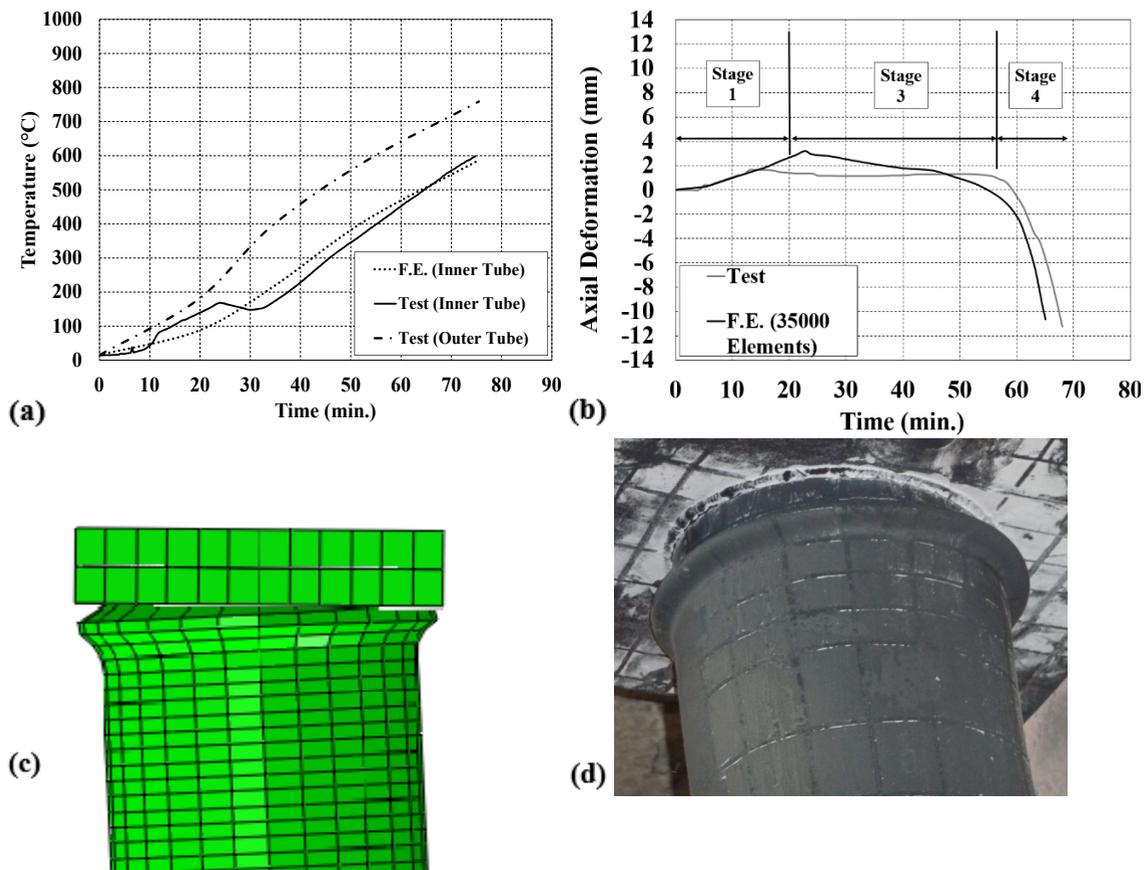


Figure 6. Numerical simulation for fire testing of Specimen S2:

- a) heat transfer analysis b) stress/deformation analysis c) simulated local buckling d) photo of specimen after fire test

CONCLUSIONS

The main goal of this research was to study the behavior of CFDST columns subjected to post-earthquake fire scenarios. CFDST columns with different levels of simulated seismic damage, which were imposed by lateral cyclic loading, were tested in the standard ASTM E119 fire while sustaining a constant axial load.

Results from testing the three CFDST columns subjected to the standard ASTM E119 fire revealed that, for the particular type of columns built and tested under the boundary conditions considered in this study, differences in the initial simulated seismic damage level had insignificant effects on the total fire resistance time of the specimens.

The finite element models were shown to be capable of replicating both the cyclic and fire loading phase of the experiments. Addition of the discrete crack to the Damaged Plasticity model was crucial in capturing the effects of concrete crack opening and closing during cyclic loading. Moreover, thermal and structural material properties adopted from the Eurocode 4 for steel and concrete were shown to be sufficiently

accurate to be used for the numerical simulation of the behavior of CFDST columns subjected to fire.

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