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POST-EARTHQUAKE FIRE RESISTANCE OF DUCTILE CONCRETE FILLED DOUBLE-SKIN TUBE COLUMNS

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ABSTRACT

Experimental studies were conducted to examine the behavior of concrete filled double-skin tube (CFDST) columns exposed to fire after being subjected to cyclic loads. The experiments were conducted in two separate phases, consisting of the quasi-static cyclic tests followed by fire tests. Three nominally identical column specimens were constructed for these studies. The first specimen was directly tested under fire to quantify its resistance in an undamaged condition. The second and third specimens were first subjected to quasi-static cyclic lateral loads, imposing varying degrees of drift to simulate two different seismic events with moderate and high damage levels before being exposed to fire. Both of the specimens were pushed to the maximum drift of 6-6.5% with different residual drifts of 1.8% and 3.9% for low and high damage levels, respectively. The undamaged and damaged columns were then subjected to the same fire tests following the standard ASTM E119 temperature-time curve while sustaining an axial load until the column failed due to global buckling. Local buckling of the tubes was also observed in the specimens due to the thermal expansion and separation from the concrete. Overall, the results showed marginal differences in the fire resistance of the three specimens, providing evidence for the resilient performance of these columns under post-earthquake fire scenarios.

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ABSTRACT

Experimental studies were conducted to examine the behavior of concrete filled double-skin tube (CFDST) columns exposed to fire after being subjected to cyclic loads. The experiments were conducted in two separate phases, consisting of the quasi-static cyclic tests followed by fire tests. Three nominally identical column specimens were constructed for these studies. The first specimen was directly tested under fire to quantify its resistance in an undamaged condition. The second and third specimens were first subjected to quasi-static cyclic lateral loads, imposing varying degrees of drift to simulate two different seismic events with moderate and high damage levels before being exposed to fire. Both of the specimens were pushed to the maximum drift of 6-6.5% with different residual drifts of 1.8% and 3.94% for low and high damage levels, respectively. The undamaged and damaged columns were then subjected to the same fire tests following the standard ASTM E119 temperature-time curve while sustaining an axial load until the column failed due to global buckling. Local buckling of the tubes was also observed in the specimens due to the thermal expansion and separation from the concrete. Overall, the results showed marginal differences in the fire resistance of the three specimens, providing evidence for the 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 [1]. 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. The objective of this study is to investigate the behavior of ductile concrete filled double-skin tube (CFDST) columns under fire loading with different initial conditions regarding the level of simulated seismic damage imposed on them prior to the fire tests. The CFDST columns, shown to provide acceptable performances under combined seismic and blast loadings [2] were studied in a series of experiments that were designed to simulate fire-following-earthquake scenarios.

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Specimens

Three nominally identical CFDST column specimens were designed and constructed for testing under simulated post-earthquake fire scenarios. A single design approach was chosen to limit the differences in the initial conditions of fire tests to the level of simulated seismic damage imposed on the specimens in the cyclic tests. The main geometric features of the single design for all three column specimens are summarized in Table 1. Note that the inner tube satisfies the criteria of compactness and high ductility based on the limiting values of AISC specifications for steel structures and AISC seismic provisions. The outer tube is classified as a compact and moderately ductile round filled composite member [3, 4].

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

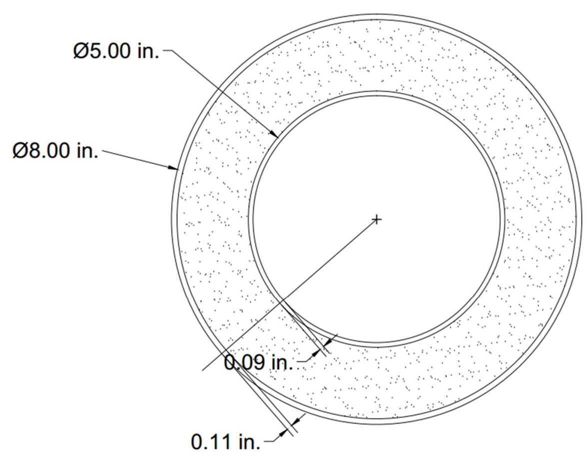


Figure 1. Section of the column specimens

Fig. 1 shows the section of the specimen. The tubes used in the specimen construction were electric resistance welded tubes with nominal yield and tensile strength of 32ksi (220.6 MPa) and 45ksi (310.3 MPa), respectively. Self-compacting concrete with maximum aggregate size of ½” and a spread of 18”-30”during the slump test was used to fill the space between the inner and outer tubes. Two of the specimens (labeled S1 and S2) were used in cyclic testing and the third column (specimen S3) was kept undamaged for the fire test. Cylinders casted on the construction day showed average compression strength values of 8.0ksi (55.8 MPa), 8.7ksi (60.0 MPa), and 9.7ksi (66.9 MPa) on the testing days for specimens S1 (first cyclic test), S2 (second cyclic test), and S3 (first fire test), respectively.

Cyclic Tests

Cyclic tests were first conducted on two of the columns to simulate seismic damage. The specimens were fixed on a lateral foundation beam at the base to form a vertical cantilever condition. The base beam was attached to the strong floor of the lab and an A-shaped reaction frame. A 50kip MTS actuator, connected to the A-frame at the same elevation as the top of the column, was used to apply the lateral cyclic load to the specimens. Fig. 2 shows a full view of the experimental setup with dimensions.

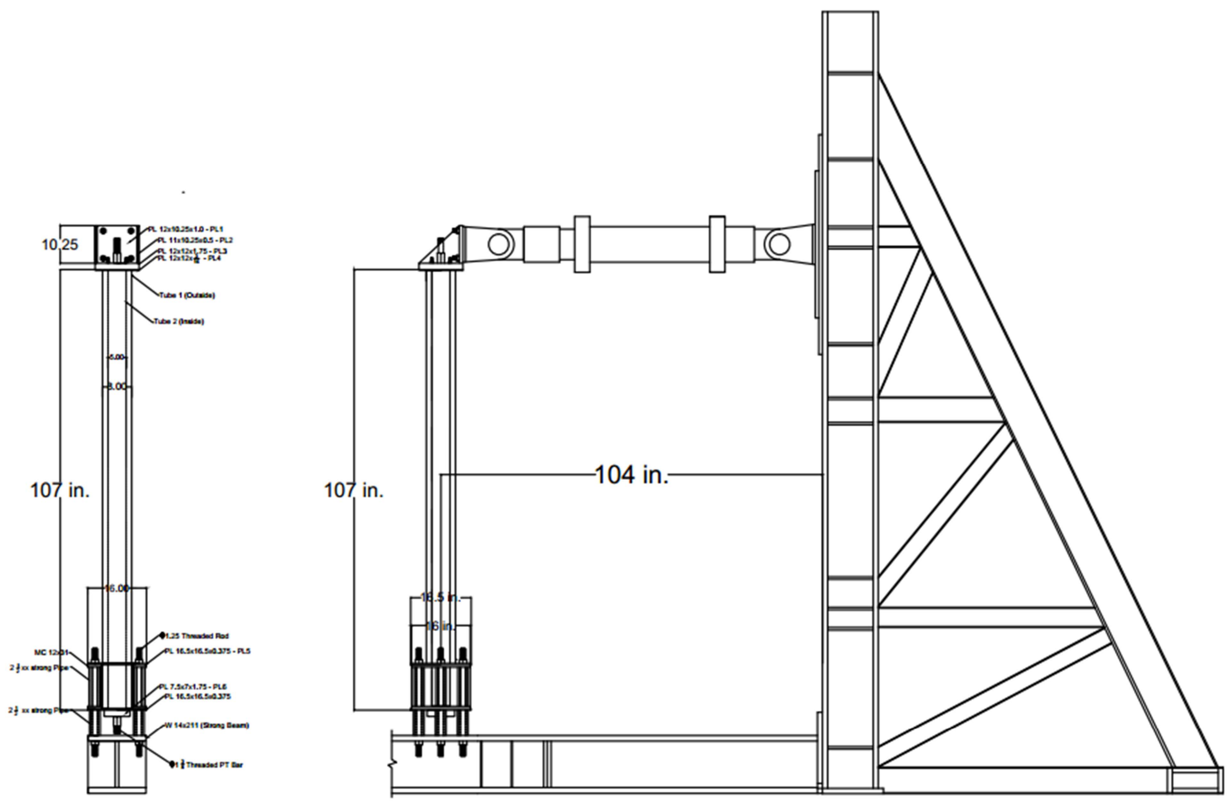
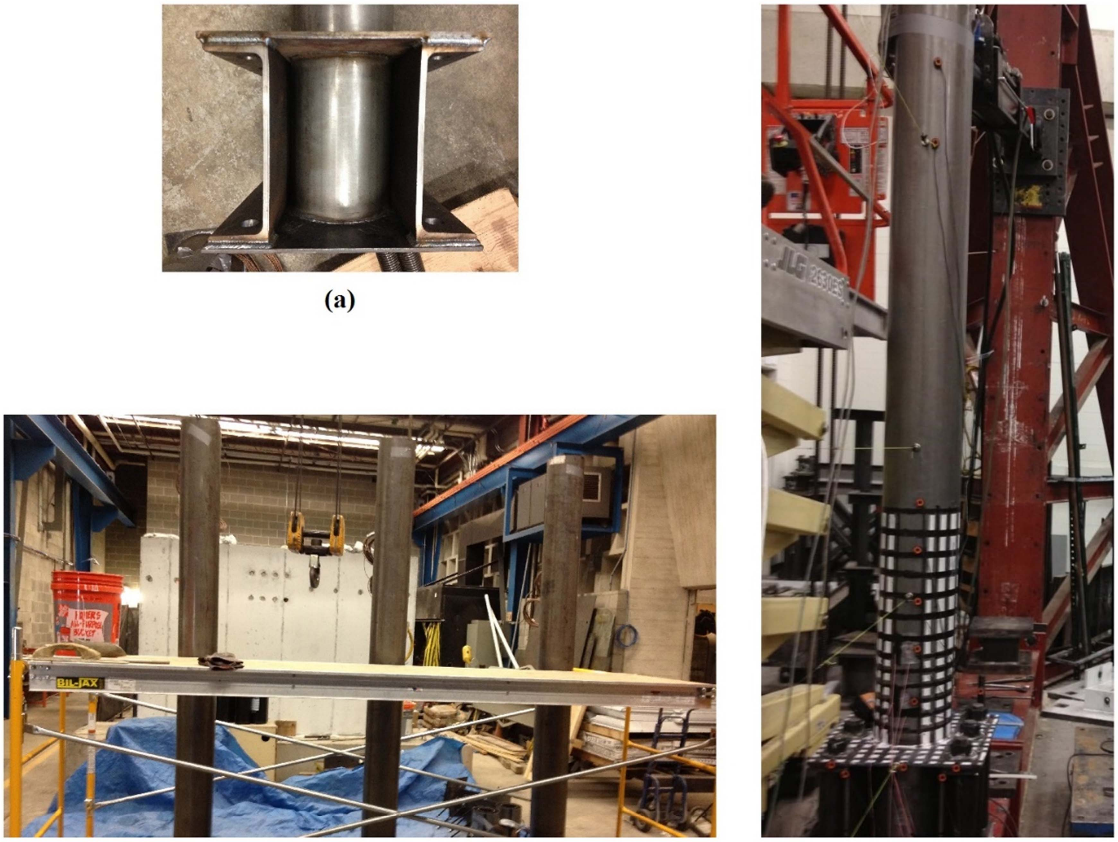


Figure 2. Full view of the experimental setup with dimensions

Each of the three specimens was built with an additional part at the base, built with two channels (one at each side of the outer tube) that were connected to the column using two plates welded to their top and bottom ends. The top plate was built with a circular opening at the center to allow for the passage of the outer tube. The additional part was designed to protect the base beam from possible damage in the cyclic loading process. An axial load of 71kips (about 30% of the column's axial strength) was applied on the columns during cyclic testing by a single post-tensioning threaded rod running through the hollow space inside the inner tube of the specimen. Fig. 3 shows photos of specimens during construction and in the experimental setup with instrumentation. The instrumentation consisted of linear potentiometers (string pots) and LEDs for a krypton camera for recording the displacement response, strain gauges to capture the location of the maximum moment and first yielding of the outer tube, and load cells to record and monitor the amounts of axial and lateral loads applied to the specimen.



(a)

(b)

(c)

Figure 3. Photos of the specimens: a) construction of the additional part at the bottom of the columns, b) before concrete pouring, and c) in the experimental setup with instrumentation

Two of the three main specimens were subjected to the cyclic testing program, keeping the third one undamaged for the fire test. The specimens were tested in displacement controlled mode using the protocol shown in Fig. 4, which is based on ATC-24 recommendations [5]. Maximum displacements for different cycles of the test were defined as multiples of the estimated yield displacement. The target damage level was different for the two specimens. The first specimen (S1) was subjected to cyclic displacements until the first visual signs of local buckling appeared on the outer tube (low damage). The second specimen was pushed further in the last cycles to get to a higher damage level while trying to prevent fractures in the outer tube. The residual drift ratio of the specimens was used as a damage index to distinguish between the damage levels of the two specimens.

Fig. 5 shows the lateral force vs. lateral drift curve recorded for specimens S1. The specimen did not lose much strength until the last cycle where a strength degradation of approximately 5% can be seen. Maximum and residual drift ratios of specimen S1 were calculated to be about 6.2% and 1.4%, respectively. Fig. 6 shows different views of the local buckling of the outer tube for S1. Grid lines were painted on the specimen to provide better visuals of the deformations imposed on the structure as a result of the simulated seismic loading. A similar test was conducted on specimens S2, reaching maximum and residual drifts of 6.3% and 3.9% to impose a higher damage level to the column.

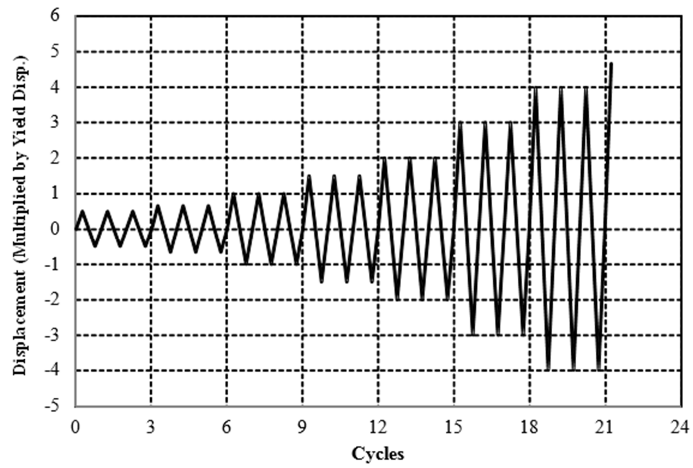


Figure 4. Displacement protocol applied to the specimens in cyclic tests

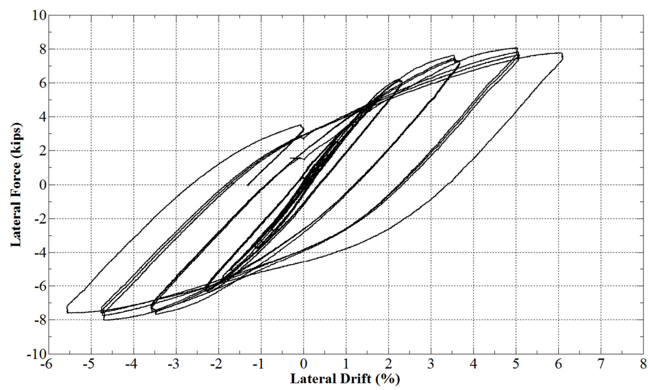


Figure 5. Lateral force vs. lateral drift ratio results for cyclic testing of specimen S1

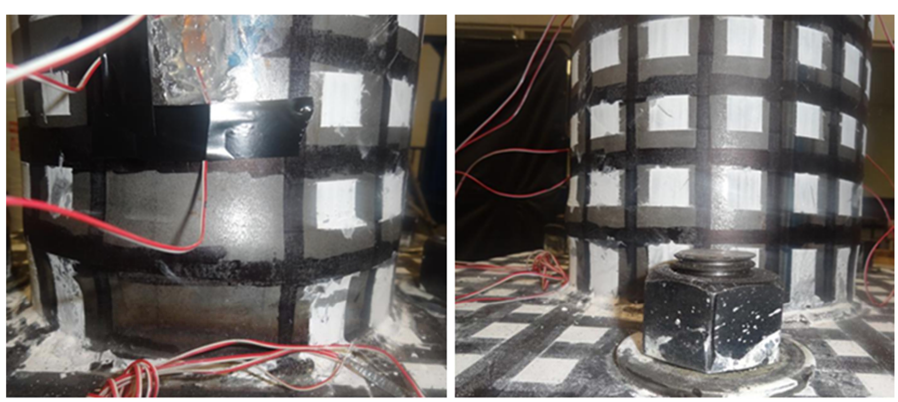


Figure 6. Local buckling of specimen S1 under cyclic loading

Fire Tests

A vertical 10’x10’ furnace available at the fire testing lab of the NGC Testing Services, an independent testing facility that performs fire, acoustic, and structural testing services, was used for the fire tests. The furnace is capable of accommodating members with the maximum height of 10’ and applying a maximum axial load of 120 kips. The boundaries of the furnace were defined by two concrete beams at the top and bottom, a moving/replaceable wall on one side and a fixed wall that was built on the other side of the furnace for each specific test. The top beam was fixed in place working as a reacting member to the applied vertical loads. The bottom beam was attached to a railing that could move up or down with a total travel distance of 4” (±2"). The bottom beam was supported from below by four hydraulic actuators used for applying vertical loads to the test specimens. Fig. 7 shows a photo of the vertical furnace with the specimen between the top and bottom beams.

Two sets of thermocouples were used to monitor and record the temperature distribution around and within the structure during the tests. The first set was used for a control system to keep the average temperature of the furnace as close as possible to the predetermined temperature curve. The second set of thermocouples were placed in the specimens during the construction process and embedded in concrete to record the temperature distribution within the specimen for quantification of the thermal response of the specimen subjected to fire loading.

All of the tests were started by applying the axial load, which was kept constant by maintaining the pressure in the hydraulic pumps, followed by the application of the standard ASTM E119 fire load defined by the temperature curve shown in Fig. 8 [6].The standard curve reaches a temperature of 537°C (1000°F) in 5 minutes and increases up to the temperature of 1050°C (1925°F) at the end of 180-minute period. The fire tests were planned to be terminated at the point that the column could no longer sustain the axial load. This failure criterion could be confirmed by observation of the global buckling of the specimen or detecting the relatively fast movement of the bottom beam under the axial load (close to 1”/min.).

Test 1: Specimen S3 (Undamaged specimen)

Fig. 9 shows the time history of axial displacement recorded for the moving (bottom) end plate of specimen S3 during the fire test. Specimen S3 goes through four stages during the fire test. The first stage is related to the faster expansion of the outer tube compared to the concrete core. As a result, there is a section of the column in which the outer tube carries all the axial load. The second stage corresponds to local buckling of the outer tube that carries the total axial load as it loses strength from heating. The third stage occurs when both steel and concrete again support the axial load. As the furnace temperature gets to higher levels, strength and stiffness degradations of both materials lead to the failure of the column at stage four. Fig. 10 shows the final state of the specimen at the end of the test. The specimen failed with an out of plane global buckling mechanism.

Figure 7.   Specimen S3 installed in the vertical furnace

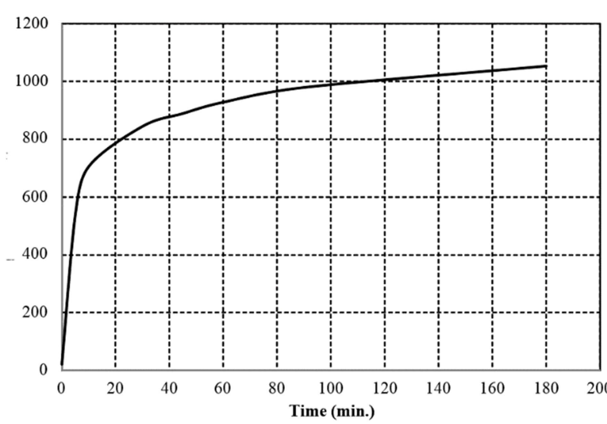


Figure 8.   ASTM E119 Standard fire curve [6]

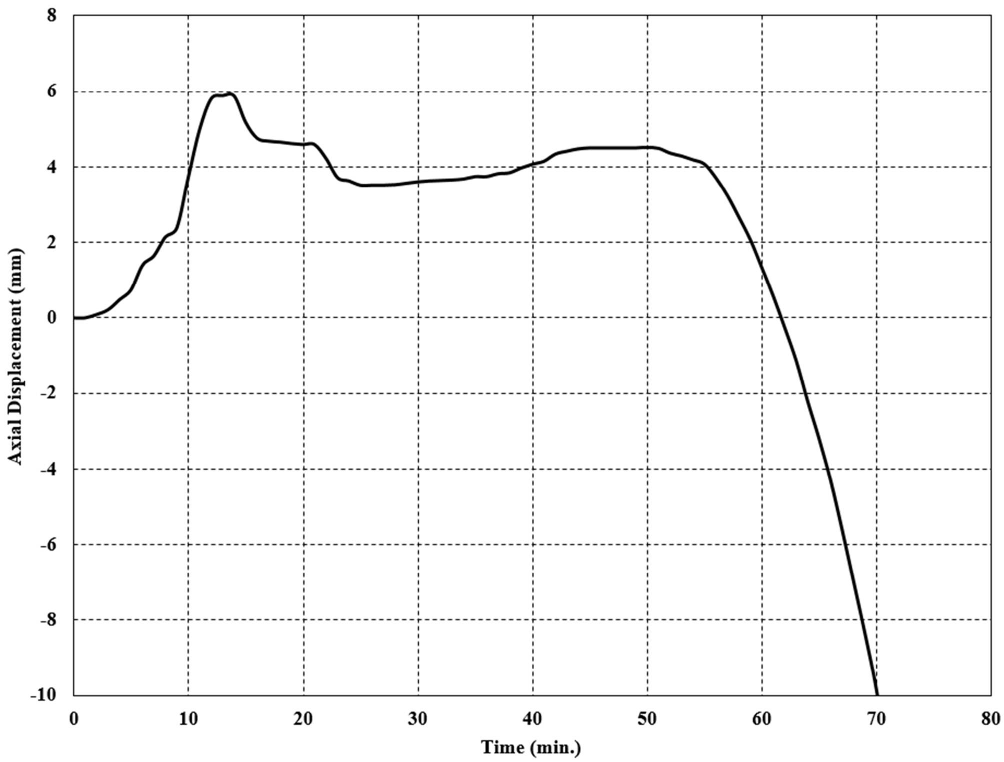


Figure 9. Time history of axial displacement of the moving (bottom) end plate of specimen S3, recorded in the fire test

Test 2: Specimen S1 (Damage Level 1)

Specimen S1 with a residual drift of 1.8% was selected for the second fire test. This column was considered to represent a structure with a moderate level of seismic damage. Note that the columns with residual drifts were rotated and placed in a way that the line of action of the applied axial load would go through the center of both top and bottom plates. The test was terminated due to the global buckling of the specimen with a recorded fire resistance time of 60-65 minutes. Time history of the axial displacement for specimen S1 went through the same four stages described above for specimen S3. The resistance time showed that the seismic damage hadn't significantly affected the general performance of the column under fire loading.

Test 3: Specimen S2 (Damage Level 2)

The third fire test was conducted on specimen S2 which had a residual drift ratio of 3.9%. Higher residual drift and impaired moment resistance of the specimen led to a slightly shorter fire resistance time (less than 10min. in difference) in comparison with the other two specimens. The difference in the resistance time was mainly due to the fact that the first two stages, consisted of the outer tube's expansion and local buckling close to the top beam of the furnace (the increase and subsequent decrease of the axial displacement in the first 30 minutes of the time history plot shown in Fig.9) did not occur for specimen S2.

Figure 10. Final state of specimen S3 at the end of the fire test

Conclusion

Three CFDST columns with different levels of simulated seismic damage (no damage, moderate, and high) were tested under the ASTM E119 standard fire. 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. The shortest fire resistance time was recorded for the specimen with the residual drift ratio of 3.9% (specimen S2), which was only marginally shorter than the time recorded for the undamaged specimen (less than 10 minutes in difference). Numerical models are being developed based on the experimental program to further investigate the relation between seismic and fire damage for CFDST columns.

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