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FIRE PERFORMANCE OF SELF-COMPACTED CONCRETE FILLED DOUBLE SKIN STEEL SQUARE TUBES UNDER CONCENTRIC AND ECCENTRIC LOADING

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ABSTRACT: While concrete filled double skin steel tubes offer superior structural performance, their behavior after fire exposure, particularly under eccentric loading conditions has not been adequately investigated, limiting the development of comprehensive fire safety design guidelines. They exhibited excellent load carrying capacity when compared to conventional columns. In this research, the performance of concrete filled double skin steel square tubular columns consisting of outer and inner square tubes with self-compacting concrete (SCC) infill between them after exposed to fire was studies experimentally. Twelve specimens were fabricated and tested under concentric and eccentric loading. For each loading conditions, two columns were exposed to 60 min fire, two were exposed to 90 min fire, and two columns were considered as control specimens which are not exposed to fire. These two columns, one with solid section and one with hollow section. The filling by SCC increased the capacity by 18-26% for concentric condition through enhanced confinement. Fire exposure reduced capacity by 8-25% due to steel softening and concrete thermal degradation with stiffness degrading more severely (44-59%), indicating interface deterioration. Eccentric loading caused 65-68 capacity reduction across all conditions. Failure modes included concrete crushing and local buckling with fire exposed specimens showing more sever buckling and concrete spalling from thermal damage. The dominant mode of failure was crushing of concrete at loaded end followed by tube local buckling. These findings contribute to understanding the fire resistance behavior of SCC-filled double skin steel tubes and provide essential data for developing fire safety design guidelines for such structural systems in building construction.

Keywords: Self-Compacting Concrete, Double Skin Steel Tubes, Fire Performance, Eccentric Loading

1. INTRODUCTION

Fire resistance of structural members is essential for the safety of high-rise buildings, industrial facilities, and tunnels, with column being particularly vital due to their role in maintaining overall structural stability during fire events [1]. Concrete filled steel tubes (CFST) columns have considered as one of the most effective composite systems, leveraging the composite strength of concrete and the ductility and confinement provided by steel to achieve superior load-bearing capacity and fire resistance [2,3]. While numerous studies have quantified the performance of traditional CFSR columns at ambient and elevated temperatures, the fire behavior of double skin tube columns filled with self-compacted concrete (SCC) remains inadequately characterized.

Despite extensive research on ambient temperature behavior and fire exposure tests, comprehensive understanding of SCC-filled CFST columns under both concentric and eccentric loading remains limited. Lu et al. [4] investigated fire behavior under primarily concentric loading, while Zheng et al. [5] examined circular sections with axial restraints. However, the combined effects of SCC, square cross-section and varying eccentricity ratios under fire exposure remain inadequately understood [4,5]. Existing studies often focus on stub columns or concentric loading scenarios, with fewer addressing eccentric compression and the complex interaction between steel tubes and SCC at elevated temperatures [6,7]. Controversies exist regarding the extent to which SCC improves fire resistance compared to normal concrete, with some findings indicating enhanced confinement and spalling resistance, while others highlight increased spalling risk due to SCC's dense microstructure [4]. Moreover, numerical models and finite element analysis approaches for predicting fire performance vary in their underlying assumptions. Zhu et al. [8] developed a finite element model with simplified transient creep assumption for square double skin CFDST columns, while Yao et al [9] implemented more details thermal-stress sequential coupling with explicit creep subroutine for circular section. These modeling differences highlight challenges in accurately capturing thermal gradients, material degradation, and time-dependent deformation mechanisms, particularly for square sections under eccentric loading. The lack of standardized design guidelines for fire resistance of SCC-filled CFDST columns under realistic loading conditions poses challenges for engineers and safety regulators.

Different studies have been employed to integrate the composite action of steel tubes and SCC, the thermal degradation of materials under fire, and the structural response under concentric and eccentric loads [4,5,10]. SCC's self-compacting properties facilitate uniform filling and confinement [11], which influence the fire-induced spalling and residual strength of the columns [4,12]. SCC behavior in fire filled composite columns involves complex thermo-mechanical interactions. Moisture migration and pore pressure from water evaporation can cause concrete spalling, especially in dense microstructures [13,14]. Thermal expansion mismatch between steel and concrete degrades interfacial bond and composite action [15,17]. Progressive material degradation occurs as steel softens and concrete deteriorates through dehydration, decomposition, and microcracking [17]. Double skin configuration provides temperature gradients due to inner tube thermal protection [4,18]. The interaction between the inner and outer steel tubes and the SCC core governs the load transfer and failure modes during fire exposure [8,19].

The effect of eccentric loading on fire resistance has emerged as a critical research focus, with experimental and numerical studies consistence demonstration that fire resistance decreases as load eccentricity increases across various cross-sectional configurations including T and L-shaped, circular and square CFST and CFDST column [20,21]. Parametric investigations have identified the axial load ration (the fraction of applied load to the ambient capacity) as the dominant parameter governing fire resistance under eccentric compression, with slenderness ratio, section geometry, and steel ratio exerting secondary effects primarily at moderate to low load ratio [20]. Eccentric loading primarily changes the mechanism of failure by promoting bending dominated responses, larger lateral deformation, and earlier local buckling of steel tubes during fire exposure, with distinct temperature-deformation coupling observed in both post-fire and real-time fire test [22]. Recent sequential thermal-mechanical finite element models validated against eccentric loading tests have enabled the development of simplified post-fire residual capacity estimation procedure, offering practical tools for engineers to assess structural safety after fire events [23].

Despite growing interest in double skin CFDST columns, the fire performance of square sections filled with SCC under eccentric loading remains inadequately characterized. This study addresses this critical gap by presenting a comprehensive experimental investigation of SCC filled double skin steel square tubes subjected to ISO 834 [24] standard fire exposure under both concentric and eccentric loading. The novelty lies in examining the interaction mechanisms between SCC and double skin configuration during fire exposure. The outer steel tubes provide confinement while experiencing thermal expansion and strength degradation. The dense SCC core exhibits delayed thermal penetration and maintains load-bearing capacity. While the inner tubes create non-uniform temperature distribution that interact with eccentric loading to produce asymmetric thermal strains and stress redistributions. The experimental program systematically evaluates loading eccentricity, fire duration, and filling configuration effects on structural behavior and failure mechanisms. The practical significance lies in enabling engineers to quantify SCC filling benefits for performance-based fire design and assess realistic scenarios combining fire damage with eccentric loading. It also enables engineering society to develop a reduction factor for CFST columns capacity exposed to fire and establish post-fire serviceability criteria which all inform post-fire structural assessment protocols.

This paper is organized in the following sections to describe the experimental program in terms of specimen's preparation, materials properties, protocol of fire exposure, and testing procedures. The experimental results in terms of load vs axial displacement, failure mode, can capacity degradation patterns are discussed. The paper ends with the key findings and provides recommendations for design practice and future research.

2. RESEARCH SIGNIFICANCE

The focus of most existing researches was on the concentrically loaded CFDST with traditional concrete. Studies that include the eccentric loading conditions were limited especially the studies that compare the performance of CFDST with both solid and hollow inner core section. This study addresses previous concern by investigating experimentally the fire behavior of SCC-filled double skin CFDST under concentric and eccentric loading, addressing the identified knowledge gaps in fire behavior characterization and provide a consolidated understanding of the effects of fire on SCC-filled composite columns under eccentric loading. Given the increasing use of SCC in construction and critical importance of fire safety, this study contributes to advancing safe and efficient composite structural design

3. EXPERIMENTAL PROGRAM

A total of 12 CFDST square columns were prepared in this work to evaluate the general behavior of hollow and solid CFDST exposed to fire. These columns were divided into two groups based on loading condition (concentric and eccentric). Each group has 6 specimens which was divided into two subgroups, three specimens have hollow core section and three have a solid core section. Two specimens from each subgroup were subjected to fire one for 60 min and the other for 90 min, while the third specimen were considered as a control specimen which has not been subject to fire (0 min).

Fig. 1 below shows the dimensions of the tested column. The double skin column has 100 mm square side length for the outer skin and 50 mm square side length for the inner skin. Both skins have 2.2 mm side thickness. All samples have the same height (900mm). The test matrix is shown in Table 1. The first letter (C) in name refers to column; the second letter refers to type of section (H for hollow and S for solid). The next two digits represent the time of fire burning in minutes (0,60, and 90). The last digit refers to loading condition (1 for concentric loading and 2 for the eccentric loading).

Table 1 Details of tested specimens

Specimens ID	Loading condition	Cross section types	Time of burning (min)
CH-00-1	Concentric loading	Hollow	0
CS-00-1		Solid	0
CH-60-1		Hollow	60
CS-60-1		Solid	60
CH-90-1		Hollow	90
CS-90-1		Solid	90
CH-00-2	Eccentric loading	Hollow	0
CS-00-2		Solid	0
CH-60-2		Hollow	60
CS-60-2		Solid	60
CH-90-2		Hollow	90
CS-90-2		Solid	90

3.1 Preparation of Specimens and Test Setup

Different materials were used in this research such as Portland cement, fine and coarse aggregate, powder, superplasticizer, and steel tubes. The proportions of the SCC mix are listed in Table 2. SCC mixes were performed and controlled according to EFNARC guidelines (2005). Fresh properties were evaluated through slump flow test and T500 time measurement for each patch prior to casting and the results were 685 mm and 2,2 second, respectively. Nine cubes (150x150x150 mm) were used to evaluate the compressive strength at age of 28 days for the SCC mixes before and after subjected to fire (3 for 0 min (control, 3 for 60 min, and 3 for 90 mins). The outcomes are listed in Table 3.

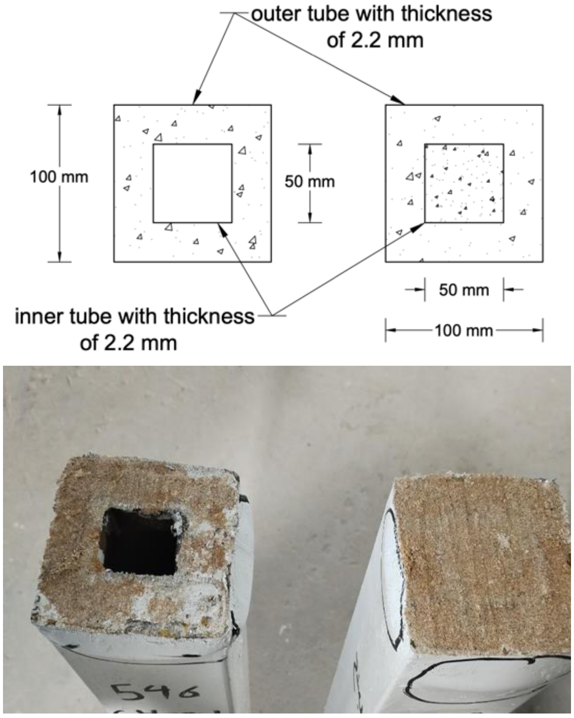


Fig. 1 Cross section of tested specimens

Table 2 SCC Mix Proportion

Materials	Weight (Kg/m^3)
Cement	446
Fine Aggragate	759
Coarse Aggragate	831
Superplasticizer	0.12
Limestone powder	132

Table 3 Compressive Strength Results

Cubes No.	1	2	3
Time of Burning (min)	0	60	90
Compressive strength Fcu (MPa)	27.5	17.67	14.85

Each column consists of two steel tubes with a thickness of 2.2 mm. The space between the double layers is filled with SCC for the solid section while only the outer space was filled with the SCC for the hollow section. In the preparation of the test specimens, inner tubes were placed in the center of the outer tube and confirmed using strips welded to the ends of each tube. Each steel tubes were filled with SCC vertically after sealed from bottom. The surface at top end was finished and sealed after casting to prevent moisture loss. Since the SCC is confined with both inner and outer tubes, traditional water curing was impractical. A well-water saturated burlap bags were used to wrap the tubes to maintain moisture supply to the concrete core for 28 days under ambient laboratory conditions. Three coupons were prepared before and after subjected to fire (one for 0 min, one for 60 min, and one for 90 min) from the square steel tube to be tested to evaluate the material properties of the tubes according to ASTM-A370 [25]. The yielding strength, ultimate strength, and elasticity modulus are shown in Table 4.

Table 4 Mechanical Properties of Steel Tubes

Time of Burning (min.)	Yielding stress (f_y) MPa	Ultimate stress(f_u) MPa	Modulus of elasticity (E_s) (MPa)
0	390	440	200695
60	320	355	170125
90	310	347	165125

A well prepared and insulated barrel was employed to applied the burning procedure. The temperature was controlled using Type K thermocouples and temperature measurement (Fig. 2) in accordance with ISO 834 fire curve [25]. Thermocouples were positioned at the out and inner tube surface to monitor thermal gradients during fire exposure. The temperature reached almost 1000°C for a certain period (90 min) to expose them to heat which coincidence with the standard curve. Four specimens were burned for 60 mins and other four specimens were burned for 90 mins as mentioned in Table 4. Additional, concrete cubes and steel coupon were subjected to the same periods of time to test both the concrete compressive strength and steel tubes tensile strength of tube as mentioned previously.

All specimens were tested according to the experimental program (previously mentioned). Dial gages were attached to bottom of columns to measure the axial displacement as shown in Fig.3. During the tests, 25 mm thick steel plates were placed at the ends of column for load distribution and to simulate simply supported case (Fig.4 (a)). Moreover, to ensure the eccentricity distance for the second group, additional steel with C-section were welded to the specimens ends (e/h=1) with a specially fabricated loading plate with offset beat position located at distance (e) from the geometric centerline as shown in Fig 4 (b).

Fig. 2 Burning Temperature at 90 min

All specimens were evaluated using a testing device having a 2500 kN capacity. During the testing, readings of the applied load and displacement were taken at regular intervals. Regular loading was done in increments of 10 kN in the elastic phase and 5 kN after steel yield, with a total loading time of around 2 minutes to guarantee that the load was properly transferred to each column. The load applied can be ended when the column load has fallen to 80% of its maximum applied load or when it is not acceptable to continue bearing the load that is too high to continue carrying the load owing to severe deformation.

4. RESULTS AND DISCUSSION

4.1 Control Specimen

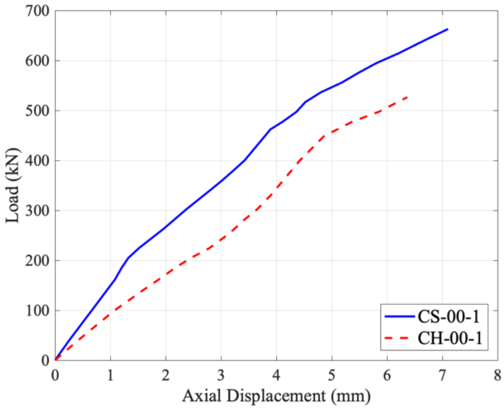
A comparison between solid and hollow CFDST control columns for under both concentric and eccentric loading are shown in Fig 5. Under concentric load, the ultimate load for the solid section specimen was 663 kN. For hollow section, the ultimate load was 526 kN which is less than the solid section by 20%. The displacements at the ultimate for the solid and hollow section specimens were 7.1 m and 6.4 mm, respectively. While for eccentric loading, the ultimate load and corresponding axial displacement for solid section specimens were 224 kN and 7.1 mm, respectively. For hollow section, the ultimate load and corresponding axial displacement were 185 kN and 7.6 mm, respectively. The reduction in the load capacity in the hollow section was 17% compared to the solid section under same loading condition. These differences related to the fact that the solid column has more stiffness than the hollow column by providing more confinement of the inner steel plate. This confinement prevents the steel pipe from buckling at early stages of loading.

Fig. 3 Test setup

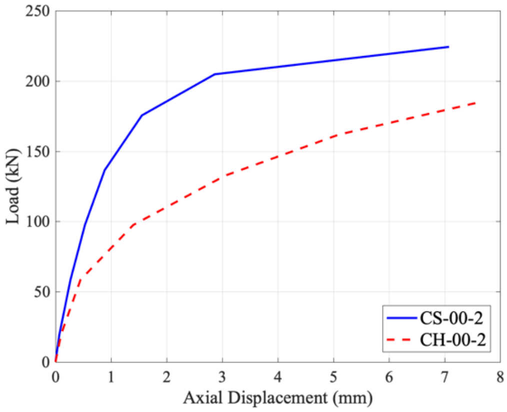
a) Loading Base Plate

b) C-section for Eccentric Columns

Fig. 4 Base plate and C-section for loading procedure



a) Under concentric load



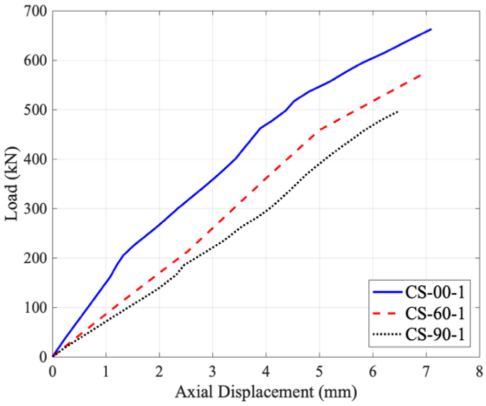
b) Under eccentric loading

Fig. 5 A comparison between solid and hollow control CFDST columns

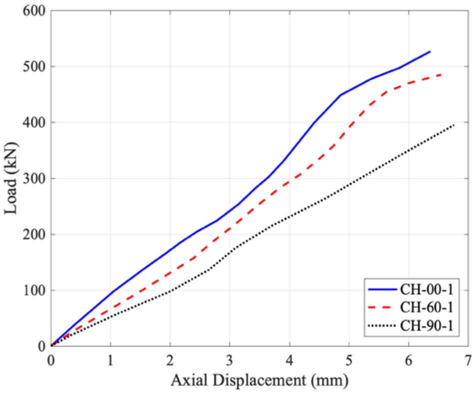
4.2 Effect of Fire and Time of Burning

Fig. 6 show the effect of fire and burning period on the behavior of CFDST square tubes under concentric load. It can be noticed that the fire affects both the ultimate load capacity and stiffness of the CFDST columns for solid and hollow sections. The ultimate load for the solid section after it has been subjected to fire for 60 and 90 min was 575 kN and 497 kN, respectively which is less than the corresponding control specimen by 13% and 25%, respectively. The axial displacement at the ultimate level after being burned for 60 and 90 min were 7 mm and 6.5 mm, respectively. For hollow section, the ultimate load for specimens that have been subject to fire for 60 min and 90 min were 486 kN and 395 kN, respectively. The decreases in ultimate load were 8% and 25% for 60 min and 90 min when compared to the corresponding control specimen. Moreover, the axial displacements at failure stage were 6.5 mm and 6.7 mm, respectively. The greater sensitivity of composite section to 60-minute fire exposure (13% vs. 8% for hollow) may be attributed to thermal-induced microcracking in the SCC, while the convergence at 90 minutes suggests that prolonged fire exposure cause similar degree of steel tubes degradation in both configurations.

The effect of fire and burning time on load-axial displacement curve for solid and hollow section under eccentric loading is shown in Fig 7. A reduction in both stiffness and ultimate carrying capacity can be noticed from this figure. For solid section, the ultimate load after 60 min of fire was 185 kN which is 20% less than the control solid specimen. However, after 90 min of fire, the maximum load was 173 kN that represent a 23% reduction relative to control specimen. The displacements at ultimate level were 7.5 mm and 6.5 mm after 60 min and 90 min of burning, respectively. For CFDST square tube with hollow section under eccentric, the ultimate load capacity was 163 kN and 142 kN after 60 min and 90 min of subjected to fire, respectively. The reduction in the maximum load capacity was 12% and 23% after 60 min and 90 min of subjected to fire, respectively. The displacements at the ultimate load for the hollow section after 60 min and 90 min of subjected to fire were 8.1 mm and 7 mm, respectively. Most specimen failed due to the crushing of concrete close to loading area as shown in Fig. 8 which led consequently to the local buckling of steel tube. The reason because the concrete's resistance to compressive stress was low because it lost its resistance properties. Under the effect of moment and eccentric load, it is clear the CFDST columns lost their strength as fire exposed increase, while the ductility is increased.



a) Solid section



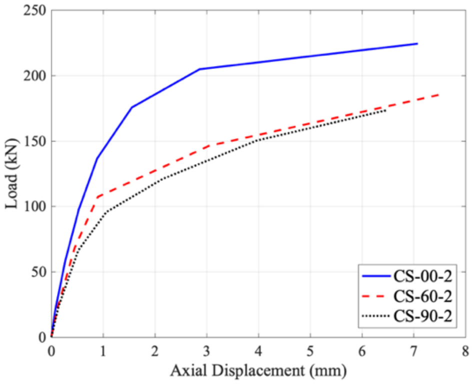
b) Hollow section

Fig. 6 Effect of fire and burning period of CFDST columns under concentric load

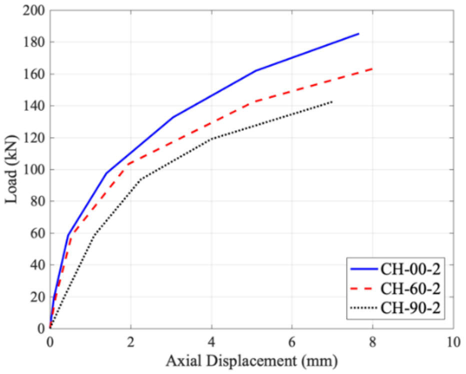
4.3 Effect of Filling of CFDST Specimen on the Fire Performance

The solid CFDST square columns retain substantially better fire resistance and residual axial capacity than the same section with a hollow inner tube. The concrete core delays the heating of steel tubes which lead to the changing in the failure mode to be concrete crushing rather than the steel buckling.

Figs. 9 and 10 show the effect of inner tube filling on the performance of CFDST square tube after being subject to 60 min and 90 min of fire under concentric and eccentric loading, respectively. The reduction in the ultimate load for hollow section after 60 min of fire duration was approximately 16% and 12% compared to the solid section under concentric and eccentric loading, respectively. Furthermore, the decrease in the ultimate capacity for hollow section after 90 min of fire duration was approximately 20% and 18% compared to the solid section under concentric and eccentric loading, respectively. It clear that after 90 min the specimens lost more of their capacity.



a) Solid section



b) Hollow section

Fig. 7 Effect of fire and burning period of CFDST columns under eccentric load

Table 5 summarizes the experimental results, revealing significant effects of fire exposure and loading eccentricity. Stiffness degradation proved more sever than capacity reduction, particularly for extended fire exposure. For hollow under concentric loading, stiffness decreased by 255 after 60 minutes and 44% after 90 minutes of fire exposure, compared to capacity. Reduction of only 8% and 25%, respectively. Solid section exhibited even greater stiffness sensitivity with 45% and 54% reduction after 60 and 90-minutes exposure. Under eccentric loading, the 90-minute fire exposure caused sever stiffness degradation:59% for hollow section and 31% for solid section. This greater stiffness sensitivity reflects fire-induced damage to the steel-concrete interface, local buckling initiation in steel tubes, and thermal-induced microcracking in concrete, all of which affect initial stiffness more severely than ultimate capacity. The disproportionate stiffness degradation has important implications for serviceability and post-fire assessment, as columns may experience excessive deformation under service loads even when ultimate strength remains adequate for safety.

The observed capacity reductions results from thermal degradation of both steel and concrete. The outer steel tubes, reaching 800-900°C, undergoes thermal softening and microstructural changes (grain coarsening, phase transformations) that persist after cooling. The SCC core experiences progressive deterioration: water evaporation and microcracking above 300°C, calcium hydroxide decomposition at 400-600 °C, and cement paste degradation above 600 °C. Differential thermal expansion between steel (10x10^{-6}/ °C) and concrete (10x10^{-6}/ °C) causes interface degradation, manifesting primarily as stiffness reduction (44-59%) rather than capacity loss (23-25%). These mechanisms combine to produce the observed 8-25% capacity reductions.

These findings have direct implication for fire safety design codes and engineering practice. The experimental data provide benchmark values for fire resistance of square SCC-filled double skin columns under eccentric loading- a scenario inadequately addressed in current design provisions. The results can inform the development of simplified design methods in Eurocode 4 and AISC 360, particularly regarding capacity reduction factors and fire protection requirements for eccentrically loaded composite columns.

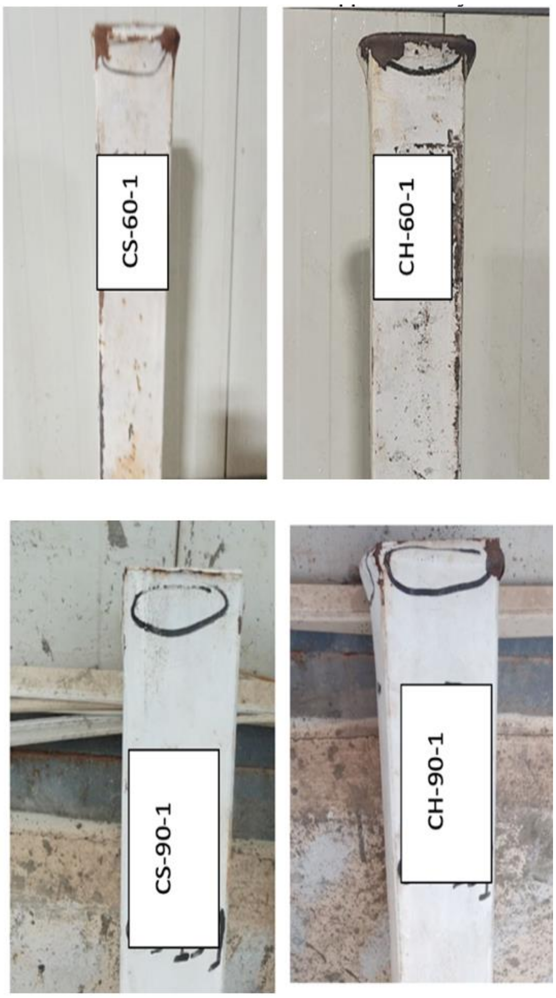
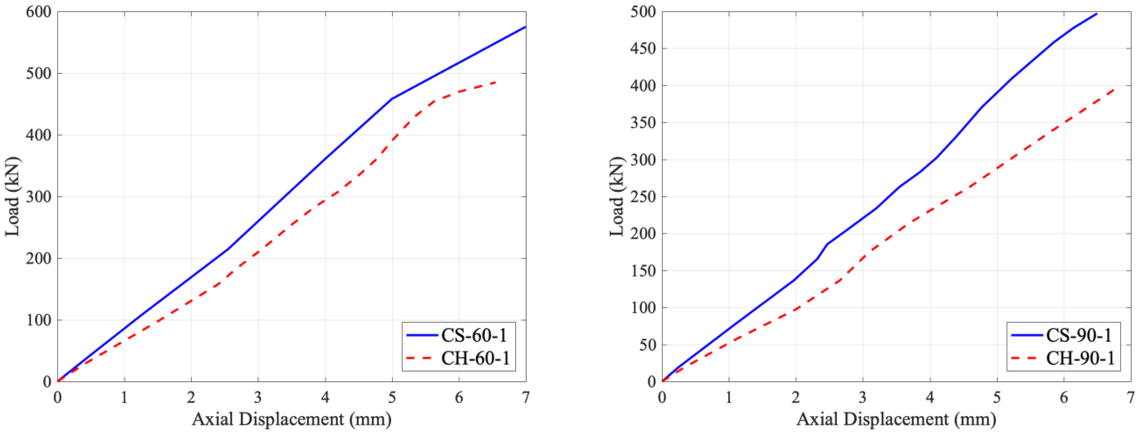


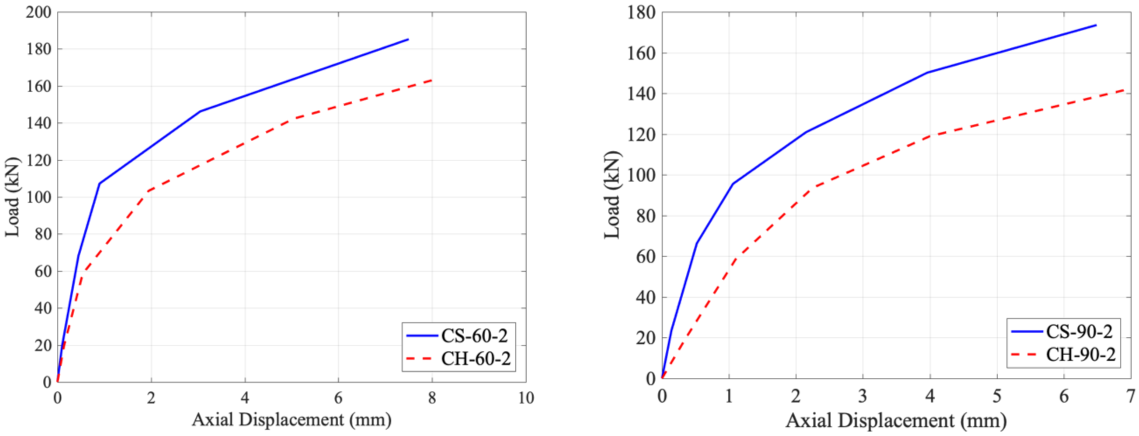
Fig. 8 Failure mode of some specimens



After 60 min

After 90 min

Fig. 9 Effect of core filling on CFDST after subjected to fire under concentric load



After 60 min

After 90 min

Fig. 10 Effect of core filling on CFDST after subjected to fire under eccentric load

Table 5 Summery of experimental results for all tested specimens

Specimen (ID)	Loading	Fire Duration (min)	Ultimate load Pu (kN)	Displacement At ultimate load (mm)	Stiffness (kN/mm)
CH-00-1	concentric	0	526	6.4	88
CS-00-1	concentric	0	663	7.1	154
CH-60-1	concentric	60	486	6.5	66
CS-60-1	concentric	60	575	7	84
CH-90-1	concentric	90	395	6.7	49
CS-90-1	concentric	90	497	6.5	71
CH-00-2	eccentric	0	185	7.6	130
CS-00-2	eccentric	0	224	7.1	184
CH-60-2	eccentric	60	163	8.1	108
CS-60-2	eccentric	60	185	7.5	152
CH-90-2	eccentric	90	142	7	53
CS-90-2	eccentric	90	173	6.5	127

5. CONCLUSIONS

In this study, concrete filled steel square tubes exposed to fire were examined under concentric and eccentric loading. The following conclusions can be drawn from this study:

1. Fire exposure reduced ultimate load capacity in range of (8-12%) for hollow section and (13-17%) for solid section after 60 minutes, increasing to 23-25% after 90 minutes for both configurations. The degradation in stiffness was more severe than capacity loss, with reduction of 44-59% after 90 minutes exposure showing disproportionate serviceability impairment from steel concrete interface deterioration and materials softening.
2. SCC filling improve load-capacity by 18-26% for concentric loading conditions and 13-22% for eccentric condition through improved confinement and composite action. This improvement persisted across all fire exposure durations, demonstrating the robustness of composite action even after thermal damage.
3. Eccentric loading reduced capacity by 65-68% across all fire conditions. The reduction percentage remained consistent regardless of fire exposure duration indicating that fire damage and eccentricity effects are approximately additive rather than synergistic.
4. Capacity reduction resulted from steel thermal softening (reaching 800-900ºC at outer tube), concrete thermal degradation (dehydration > 300ºC, decomposition 400-600ºC), and steel-concrete interface deterioration from differential thermal expansion. The inner tube provided thermal protection, creating temperature gradients that influence failure progression.

These findings inform fire resistance of CFDST columns by first providing capacity reduction factor of 0.85 (60 minutes fire) and 0.75 (90 minutes fire) for performance-based design. They are also confirming that SCC filling maintain 18-26% capacity enhancement post-fire, justifying its use in fire-prone applications. Moreover, they highlight that stiffness degradation exceeds strength loss, necessitating serviceability checking post-fire structural assessments.

This study addresses a critical gap by providing experimental database on post-fire SCC filled double-skin square columns under eccentric loading. The findings enable performance-based fire design and inform post-fire assessments. Future research should develop validated numerical models, investigate alternative shapes of columns and establish simplified design equation for code implementation.

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