AXIAL BEHAVIOUR OF REINFORCED CONCRETE FILLED STEEL TUBE STUB COLUMNS WITH PERFORATIONS EXPOSED TO FIRE

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Abstract:

Concrete Filled Steel Tube (CFST) has the potential to reduce cross-sectional dimensions, enhance structural aesthetics, and elevate resistance to high temperatures and blast events. One of the most important criteria in the design of CFST structures, apart from serviceability and load-bearing capacity, is fire resistance. CFST structures are more fire-resistant when compared to hollow steel sections and Reinforced Cement Concrete (RCC) sections, as core concrete absorbs heat and steel tubes prevent spalling of concrete at elevated temperatures, due to which fire resistance can be obtained without the necessity of external fire protection for the steel. Reinforcements in CFST members are commonly required to ensure fire safety, as stated in the European code EN 1994-1-2. Reinforcing the concrete core of CFST enhances its bearing capacity and also provides longer resistance in fire conditions. This study investigates the axial performance of steel-reinforced concrete-filled steel tube (SRCFST) stub columns featuring perforations when exposed to fire conditions. Seven SRCFST stub columns, differing in perforation configurations and concrete types, were created and subjected to high temperatures in an electric furnace, followed by axial compression testing. The results demonstrate that both perforations and fire exposure substantially reduce the structural capacity of SRCFST columns. Columns with perforations showed a marked decrease in load-bearing capacity under fire exposure compared to non-perforated samples. These results provide vital insights into the fire resistance and design optimization of SRCFST structures with geometric modifications.

Keywords: Reinforced Concrete Filled Steel Tube (RCFST), perforations, fire behaviour, axial load carrying capacity, failure mode, energy dissipation

Introduction

The utilization of concrete-filled steel tubes (CFST) as structural elements has gained significant prominence and extensive adoption in recent decades due to its numerous benefits, including enhanced load-bearing capacity, ductility, simplified construction processes, time and cost efficiencies, etc. CFST has the potential to reduce cross-sectional dimensions, enhance structural aesthetics, and elevate resistance to high temperatures and blast events. When compared to conventional RC columns, the enclosed environment that the steel tube provides outside the concrete reduces the shrinkage strain in the concrete and also provides continuous lateral confinement, which effectively prevents the core concrete from experiencing crushing and spalling. As a result, the strength and inelastic deformation capacity of the confined concrete are significantly improved. The concrete core prevents inward buckling of the steel tube, thus increasing the load-carrying capacity of the outer steel tube.

The Reinforced concrete-filled steel tube (RCFST), consisting of inner concrete, a reinforcement cage, and an outer steel tube. Steel Reinforced Concrete Filled Steel Tube (SRCFST) columns are an advanced composite structural system extensively used in high-rise buildings, bridges, tunnels, and other essential infrastructure due to their exceptional load-bearing capacity, fire resistance, improved seismic performance, and exceptional mechanical qualities [1]. The SRCFST system combines the benefits of both concrete and steel, utilizing the ductility and tensile strength of steel along with the compressive strength of concrete. Compared to traditional Concrete Filled Steel Tubes (CFST), SRCFST columns include a reinforcement cage within the concrete core, enhancing fire resistance and structural efficiency [2]. In a fire situation, it also enhances the performance of the composite columns because the inner steel surface is thermally protected by the surrounding concrete, which delays its degradation at high temperatures.

Research on the fire performance and axial behavior of CFST and SRCFST columns has been extensive, primarily focusing on their residual capacity, failure modes, and material degradation after exposure to elevated temperatures [3]. Medall et al. (2023) conducted experimental studies on steel-reinforced concrete-filled tubular columns, demonstrating that post-fire exposure, these columns exhibit increased ductility due to the composite interaction of steel and concrete. It is also noted that there is a considerable reduction in structural capacity, indicating that fire-induced degradation of material properties significantly compromises load-bearing performance. Bashar et al. (2022) conducted an experiment on CFST column to beam connections and revealed that fire exposure diminishes joint stiffness and affects failure modes, which proves the performance of the "strong column-weak beam" concept under fire scenarios. This result is crucial in understanding the performance of the different components of composite structures under simultaneous thermal and mechanical stresses. Huoa et al. (2009) experimented with the post-fire behavior of CFST stub columns under axial loads, which showed substantial strength losses when exposed to temperatures exceeding 400°C, with specimens failing in a ductile manner. It also concluded that the thermal exposure significantly affects the integrity of the composite structure, particularly in columns where the confinement effect of the steel tube plays a vital role in maintaining structural stability. Despite these valuable insights, the combined effects of fire exposure and geometric alterations, such as perforations, in SRCFST columns have not been adequately addressed [4]. Perforations are often introduced into columns for functional purposes, such as enabling connections, providing access for inspections, or facilitating the correction of initial concrete imperfections. While these modifications serve practical needs, they can potentially weaken the structural performance of SRCFST columns, particularly under adverse conditions like fire exposure. Perforations may disrupt the confining action of the steel tube, lead to local stress concentrations, and facilitate the ingress of heat, thereby accelerating the degradation of both steel and concrete materials. This poses significant concerns regarding the integrity and safety of such columns in fire-prone environments.

The limited exploration of SRCFST columns with perforations under fire exposure in existing research highlights the need for a detailed investigation into their structural behavior. The understanding of fire-induced thermal effect interaction with structural modifications like perforations is crucial for developing more effective design guidelines and enhancing fire safety standards of composite structures. This study aims to address this gap by systematically evaluating the impact of perforations on the axial load capacity, failure modes, and overall integrity of SRCFST stub columns under elevated temperatures. The research findings highlight the important insights to optimize the design of SRCFST columns for creating more safer and resilient composite structures, particularly in fire-prone environments.

2 Experimental Investigation

2.1 Materials

The materials used in this study were meticulously selected and prepared to ensure consistency and reliability in the experimental investigation of the SRCFST stub columns. A conventional concrete mix was cast in the laboratory with a mix proportion of 1:1.5:2.5 (cement: sand: coarse aggregate) and a water-cement (w/c) ratio of 0.42. No additional water-reducing admixtures were incorporated, allowing the behavior of the mix to be governed solely by the primary constituents. Ordinary Portland Cement (OPC) of grade 43 was employed as the binder, providing the necessary compressive strength and durability. Zone 2 sand served as the fine aggregate, while coarse aggregate passing through a 20 mm sieve was utilized to ensure optimal particle interlock and overall strength. Concrete cubes were cast and tested to determine the compressive strength, with average values of 30.1 MPa and 31.4 MPa recorded after 28 days of curing, indicating compliance with the target design strength.

For the steel components, hollow steel tubes were tested for their tensile properties. Three tensile coupons were extracted from each type of steel tube at different locations along the standard 6 m length, ensuring a representative sampling of the material properties. The coupons, cut from flat surfaces around the tube, adhered to standard dimensions for square steel tubes as shown in Figure 1. Despite variations in thickness, the yield and ultimate strengths between the different types of steel tubes were found to differ by less than 1%, leading to the adoption of average values for the material properties. The measured yield strength (fy) of the steel tube was 283.75 MPa, the ultimate strength (fu) was 358.58 MPa, and the modulus of elasticity (Es) was 211,250 N/mm², reflecting the steel's capacity to maintain structural integrity under load. In the case of the Steel Fiber Reinforced Concrete (SFRC) mix, steel fibers were added at a rate of 1% by volume to enhance tensile strength, crack resistance, and overall ductility. The selected fibers were low-carbon drawn round wire with a length of 35 mm and a diameter of 0.55 mm, providing an aspect ratio of 60. This configuration was chosen to optimize the interaction between the concrete matrix and the reinforcing fibers, thereby improving the composite action and structural performance of the SRCFST columns.

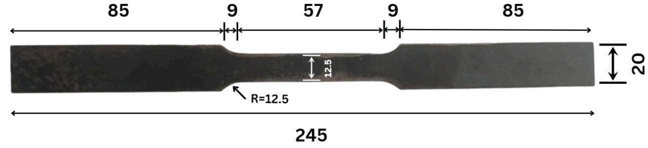

Figure 1 Dimension of flat coupon specimen (Huang et al., 2014)

The reinforcement cage was constructed using 12 mm diameter rebars as the main bars and 8 mm diameter rebars as stirrups. The main rebar length was 300 mm, and the stirrups were cut to a length of 504 mm, as calculated according to Table VIII of IS Code 2502, and bent to form the cage. A clear cover of 20 mm was maintained in compliance with IS 456:2000 to protect the reinforcement from environmental effects. These meticulously designed reinforcement cages were crucial for ensuring the structural integrity and load-bearing capacity of the SRCFST columns under both axial loading and fire exposure conditions.

2.2 Specimen preparation

A total of seven SRCFST stub columns with reinforcements were fabricated and categorized into three distinct groups based on the presence of perforations and the type of concrete used lised in Table 1 (M30 and SFRC). Figure 2 shows the CFST stub column specimens after casting. All columns had a square cross-section with dimensions of 150mm x 150mm x 300mm.

Table 1 Summary of SRCFST Column Specimens with Perforation and Concrete Type Details

Group	Number of column specimens	Perforation Details	Concrete Type
Group 1	2	No perforations	M30 grade concrete
Group 2	3	Perforations (50mm x 100mm) on all four faces	Steel Fiber Reinforced Concrete (SFRC)
Group 3	2	Perforations (50mm x 100mm) on all four faces	M30 grade concrete

In Group 3, one specimen of SFRC was designated as a control and was not exposed to fire. This control specimen served as a baseline to compare against the fire-exposed specimens, allowing for a direct evaluation of the impact of fire exposure on the structural integrity and performance of the columns.

Figure 2 Stub column specimens casted

2.3 Fire exposure protocol

To replicate realistic fire conditions, all specimens were subjected to a controlled high-temperature exposure in an electric furnace, designed specifically for fire testing [5]. The furnace temperature was increased progressively to avoid thermal shock and to ensure uniform heating of the specimens. The fire exposure curve was shown in Figure 3. Over a span of approximately six hours, the temperature within the furnace was raised incrementally until the target peak temperature of 1000 °C was reached. This gradual heating process is critical for simulating the thermal environment that structural elements would typically encounter during a fire event, allowing for an accurate assessment of the temperature distribution and its impact on the specimens.

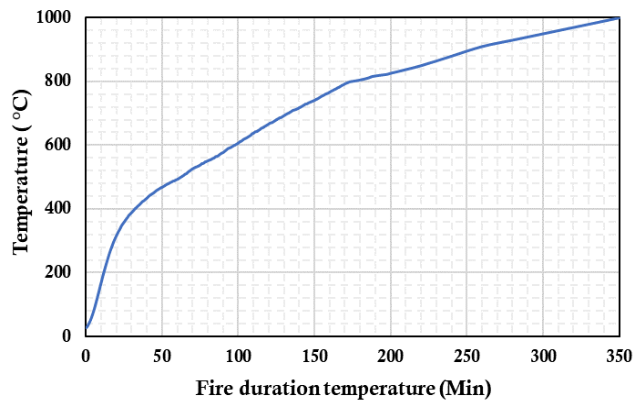

Figure 3 Fire Exposure Curve

Figure 4 shows the fire exposure of CFST specimens inside the furnace. Following this high-temperature exposure, a controlled cooling phase was initiated within the furnace. The controlled cooling process was carefully managed to prevent rapid thermal gradients, which could introduce additional stresses and alter the structural behavior of the specimens [6]. This experimental approach provides valuable insights into the fire resilience of these composite columns and is fundamental for developing effective design guidelines and fire safety standards for structures incorporating SRCFST columns.

Figure 4 Fire exposure of CFST specimens in furnace

2.4 Test setup and instrumentation

The experimental testing was carried out using a Compression Testing Machine (CTM) with a capacity of 5000 kN to evaluate the axial behavior of the SRCFST column specimens. The columns were placed vertically in the CTM, ensuring proper alignment to prevent eccentric loading, as depicted in the experimental setup shown in Figure 5. A Linear Variable Displacement Transducer (LVDT) was used to accurately measure the axial displacement of the columns throughout the loading process. The load was applied at a constant rate, and the testing continued until the axial load capacity of the specimen dropped below 65% of its peak value. This systematic approach enabled a detailed assessment of the structural response and failure characteristics of the SRCFST columns under compressive loads.

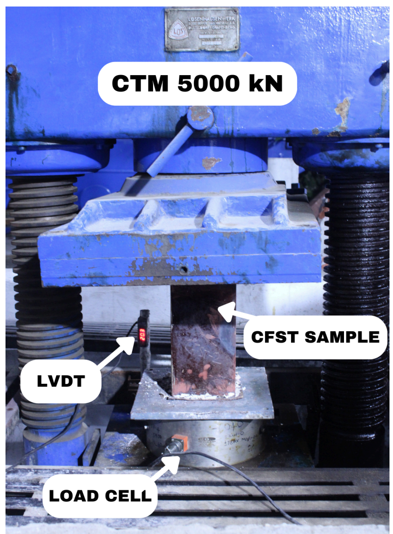

Figure 5 Experimental view of the test setup

3 Experimental Results and Discussion

3.1 Failure modes

The failure modes of the SRCFST column specimens varied depending on the presence of perforations and the type of concrete used. Figure 6 shows the failure modes of the CFST specimens.

3.1.1 Specimens Without Perforations

1. **SRCFST-S-M30-1 and SRCFST-S-M30-2:** These non-perforated columns cast with M30-grade concrete displayed typical failure characteristics of SRCFST columns under axial compression. The failure was primarily characterized by outward buckling of the steel tube, followed by crushing of the concrete core [7]. Outward buckling of concrete

was also observed during testing. The steel tube provided confinement to the concrete, delaying the onset of significant cracks until higher loads were applied. The columns maintained structural integrity until reaching their peak load capacities of 1136 kN and 1261 kN, respectively.

2. **SRCFST-SFRC-P3:** The control specimen with SFRC (Steel Fiber Reinforced Concrete) and without perforations exhibited a similar failure pattern. The steel fibers enhanced the concrete's tensile strength, leading to more ductile failure [8]. The column showed signs of concrete spalling and localized buckling of the steel tube. The peak load capacity was 1164 kN, slightly higher than the M30 concrete specimens, attributed to the improved properties of SFRC.

3.1.2 Specimens with perforations

1. **SRCFST-M30-P1 and SRCFST-M30-P2:** The M30 concrete specimens with perforations on all four faces exhibited premature failure due to stress concentrations around the perforation zones. The presence of perforations reduced the confining effect of the steel tube, leading to early local buckling and cracking of the concrete. The failure was characterized by significant deformation near the perforations and spalling of concrete, resulting in lower peak load capacities of 773 kN and 643 kN, respectively.

2. **SRCFST-SFRC-P1 and SRCFST-SFRC-P2:** These specimens, made with SFRC and perforations on all four faces, demonstrated a more gradual failure compared to the M30 specimens. The steel fibers helped to bridge the cracks and provided additional tensile strength, delaying the onset of failure. However, the presence of perforations still caused stress concentrations, leading to localized buckling and spalling of concrete around the perforation areas. The peak load capacities were 862 kN and 854 kN, which were higher than the perforated M30 columns but lower than the non-perforated SFRC control specimen.

Figure 6 Failure modes of column specimens

3.2 Axial Load versus Deformation

The effect of perforation and fire on the CFST specimens is shown in Figure 7. The ultimate load of the specimens was reduced significantly for the columns with perforation on their faces and also for the columns that were exposed to fire. The steel tube provides confinement to the concrete core, which is crucial for maintaining the composite action and preventing premature failure [9]. The perforations around the column faces in the center weaken the confining of the steel tube in the CFST middle region, which led to early local failure of the specimen in the perforation region. Compared to the M30 specimens without perforations, the peak load of the specimen with perforation reduced by 38% due to the weakening of the column. The columns subjected to elevated temperatures experienced a 26% reduction in peak load capacity compared to the control specimens, which were not exposed to fire. High temperatures cause a reduction in the yield strength and stiffness of steel, as well as a decrease in the compressive strength of concrete. The loss of these critical material properties under fire conditions results in a diminished load-bearing capacity and alters the deformation characteristics of the column.

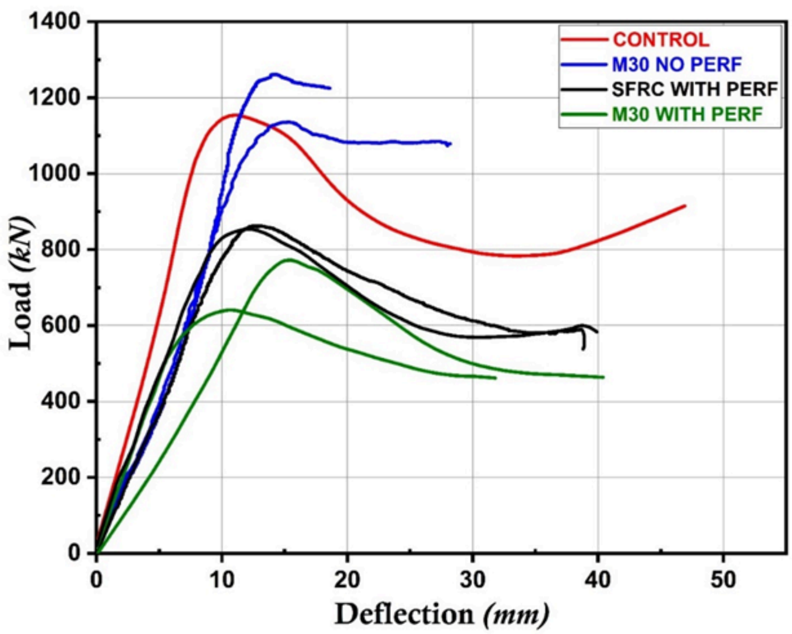

Figure 7 Load (kN) versus Deflection (mm) diagram

Table 2 shows the peak load capacity and details of the specimens. The initial stiffness of the control specimens was higher than the specimens exposed to fire and specimens with perforation. Initial stiffness is a key parameter of the column's ability to resist deformation under applied loads and is directly influenced by the material properties and the structural integrity of the composite section [10]. Similarly, the specimens with perforations also showed reduced initial stiffness compared to the control specimens. The presence of perforations disrupts the confining action of the steel tube, creating stress concentrations and reducing the effective area available to resist axial loads [11]. The post-behavior ofthe specimens exposed to fire was different from that of the control specimen. The fire-exposed specimens show reduced ductility than the control specimen due to the effect of fire in the concrete and steel [12].

Table 2 Summary of Peak Load Capacity and Characteristics of Column Specimens

S No	Specimen ID	Peak load (kN)	Perforations	Concrete grade	Details
1	SRCFST -M30-P1	773	All four face	M30	Square-shaped SRCFST stub column with perforation cast in M30 concrete
2	SRCFST-M30-P2	643	All four face	M30	
3	SRCFST-SFRC-P1	862	All four face	SFRC	Square-shaped SRCFST stub column with perforation cast in SFRC.
4	SRCFST-SFRC-P2	854	All four face	SFRC	
5	SRCFST-SFRC-P3 (control)	1164	All four face	SFRC	
6	SRCFST-S-M30-1	1136	-	M30	Square-shaped SRCFST stub column cast in M30 concrete
7	SRCFST-S-M30-2	1261	-	M30	

4 Conclusions

The behavior of the axially loaded SRCFST stub columns with perforations exposed to fire was experimentally investigated in the project. The following conclusions can be drawn based on the experimental results:

1. The SRCFST stub columns with perforations exposed to fire demonstrate different failure modes when compared to control specimens without fire exposure. The local failure of the specimens was early, and outward buckling at the top and bottom of the stub column was observed for specimens exposed to fire. The effect of perforations in the specimens was observed as the perforations reduced the confining effect, which led to cracks and buckling of steel tube near the perforation zone.

2. The load-carrying capacity of the columns exposed to fire was **26%** less than that of the columns that are not exposed to fire. The fire alters the material properties of concrete and steel, which in turn reduces the capacity of the column by a significant percentage. The perforations in the columns also facilitate the fire effect on the inner concrete, which was observed by a visible color change in the concrete.

3. The columns with perforations showed **38%** reduced load-carrying capacity than the specimens without perforations of the same configuration. The weakening of the column at the perforation region led to early local failure of the column, which prevented the specimen from attaining the peak capacity.

4. The influence of perforation on the load carrying capacity was more compared to fire on the CFST stub columns, and also the perforations in the column felicitate the fire damage to a significant extent.

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