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Experimental Analysis on a Set of Four CFT Subjected to Monotonic and Cyclic Loading

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Abstract: The main purpose of this work is the evaluation of the ultimate behaviour of Concrete Filled Tubes (CFT) subjected non uniform bending. The novelty point of this paper regards the use of big steel tubes whose material behaves like a high strength steel. Four experimental tests have been performed at the STRENGTH Laboratory of the of the University of Salerno under both monotonic and cyclic loading conditions. In particular, both constant and variable amplitude tests are considered. The three-point bending scheme is adopted for testing specimens, where a hydraulic actuator is used for the transmission of the transverse load at midspan under displacement control and an LVDT is used to measure the corresponding maximum transverse displacement.

Keywords: Concrete filled tubes, Ultimate behaviour, Cyclic tests, FEM

Introduction

Research on composite structures has attracted increasing interest, for their ability to provide excellent performance in terms of stiffness, strength and ductility, provided that adequate design and detail rules are applied (Romero et al., 2020; Lapuebla-Ferri et al., 2021). Therefore, researchers are increasingly focusing their attention on design issues concerning the behaviour of this structural typology not only with reference to building structures, but also in the case of bridges (Figure 1). CFT elements, in fact, can be effectively adopted as bridge stacks, exploiting their high ductility and energy dissipation capacity. They can also be adopted for the construction of columns, obtaining considerable advantages when large cross-sections are required.

In China, concrete-filled steel tubes have been used for over 50 years, mainly exploiting their compressive strength. Since the 80s, they have been used in buildings to avoid having very large columns, connected mainly to additional steel elements. An example is represented by the Canton Tower in Guangzhou (Figure 2), a tower about 454 meters high and reaching 600 meters at the pinnacle. Twenty-four inclined circular tubular steel elements, filled with concrete, were used for its construction, with a maximum diameter of each element equal to 2000 mm and a maximum thickness of 50 mm.

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Extensive research has been devoted to the study of concrete-filled tubes (CFTs), with particular emphasis on their structural behaviour under various loading conditions. Experimental tests play a crucial role in understanding the mechanical properties and performance characteristics of CFTs. In this study, a comprehensive series of experimental tests was conducted on four CFT specimens labeled S5-S8. These specimens were subjected to both monotonic and cyclic loading in bending, with consideration given to both constant and variable amplitude loading conditions. The primary objective of the experimental tests was to investigate the flexural behaviour of the CFTs.

Figure 1. CFTs in bridges - Juscelino Kubitschek Bridge.

Figure 2. Canton tower.

The tests involved measuring and recording the load-deformation responses, observing the failure modes, and determining the ultimate strength of the specimens. The experimental results provide valuable data for analyzing the structural response, understanding the deformation patterns, and assessing the overall performance of CFT members under different loading scenarios.

In addition to the experimental investigations, Finite Element (FE) modelling was utilized using ABAQUS software to further analyze the behaviour of the tested concrete-filled tubes. A sophisticated FE model was developed, taking into account the material properties of steel and concrete and capturing their non-linear behaviour. The FE simulations enabled a thorough examination of stress distribution, load transfer mechanisms, and deformation patterns within the CFT specimens. This comprehensive analysis provided valuable insights into the structural response and performance of the concrete-filled tubes under different loading conditions.

Mechanical Behaviour of Concrete-Filled Tubes

Concrete-filled tubes (CFTs) exhibit remarkable structural behavior and offer several mechanical advantages due to the interaction between steel and concrete, confinement effects, and their ability to mitigate buckling. Understanding these characteristics is crucial for comprehending the performance and benefits of CFT structures (Iannone et al., 2009)0.

Introduction and Main Advantages

It is known that the compressive strength of concrete is much higher than its tensile strength. For structural steel the tensile strength is high while the shape can locally bend under compression actions. In tubular steel elements filled with concrete, these two elements are used in such a way as to exploit their natural and most significant characteristics.

CFTs do not require other reinforcements as it is the pipe itself that acts as a longitudinal and lateral reinforcement for the concrete core. As regards the placement of steel in the longitudinal direction with respect to the perimeter of the section, this is the most efficient use of steel as it provides the best contribution to the moment of inertia and to the flexural strength of the section. In addition, the continuous confinement provided to the concrete core (Montuori et al., 2012; Montuori et al., 2013) by the steel pipe improves the strength and ductility of the core and prevents chipping of the concrete. The concrete core makes a great contribution to the load-bearing capacity under axial loads and delays the local instability of the steel pipe preventing inward instability (Han et al., 2005; Shams et al., 1999).

The local instability of a hollow steel tube, in fact, is characterized by the combination of inward and outward deformations of the plates while in the case of SHS (square hollow sections) and RHS (rectangular hollow sections) elements these deformations interact through rotations at the edges for compatibility needs. In contrast, only outward deformations of the plate elements that make up the steel tube are allowed in CHS elements. The local instability of a hollow steel tube, in fact, is characterized by the combination of inward and outward deformations of the plates while in the case of SHS (square hollow sections) and RHS (rectangular hollow sections) elements these deformations interact through rotations at the edges for compatibility needs. In contrast, only outward deformations of the plate elements that make up the steel tube are allowed in CHS elements (Susantha et al., 2002; Gourley et al., 2001; Nastri et al., 2022).

Fire Behaviour of CFTs

Among the non-negligible advantages should be considered the high fire resistance offered by this type of pillars thanks to the dissipating effect provided by concrete, which delays the increase in temperature in composite sections compared to bare steel sections. The literature suggests that the typical behavior of a CFT column subjected to standard fire testing can be divided into four phases (Lapuebla Ferri et al., 2021). At the beginning of the test, in fact, the steel pipe heats up more quickly and expands faster than the concrete core (phase 1), being directly exposed to the heat source. The increased thermal conductivity of steel accelerates the heating of the outer tube and thus its thermal expansion. Due to this faster axial elongation of the steel pipe and the occurrence of sliding at the steel-concrete interface, the concrete core loses contact with the plate and the axial load ratio of the steel increases progressively until the entire applied load is supported by the steel pipe alone. The outer tube remains at full load for a significant time until the critical temperature of the steel is reached. At this point the local failure of the steel pipe occurs and begins to shorten (phase 2), allowing the plate to meet the concrete core again. As the column gets shorter, the steel pipe progressively transfers the load to the concrete (phase 3) and a reversal of the axial force ratio occurs, so that it is the concrete core that becomes the main resistant element of the column, since the pipe has lost its bearing capacity. Thanks to its low thermal conductivity, the concrete core degrades slowly with advancing temperature, until the total loss of its strength and rigidity and, therefore, to failure. This, however, guarantees high fire resistance and longer times before complete collapse.

Experimental Tests

According to the pre-planned experimental procedure, four Concrete-Filled Steel Tube (CFT) columns were tested (Figure 3).

Figure 3. C5-C8 CFT specimens.

Description of the Experimental Tests

Four steel concrete filled columns were analysed, on which a series of cyclic tests have been carried out through a hydraulic actuator. The main difference between the tested specimens is the width-to-thickness ratio D/t. The steel used is S355 grade, but it behaves more like a high strength steel. As regards concrete, class C30/35 has been adopted (Roesler et al., 2007; Guo, 2014). Each model has been made from a rolled steel sheet, welded along a longitudinal side. The tubes tubes have an outer diameter (*D*) ranging from 249.2 to 260.4 mm, a height (*h*) of 2400 mm, and a wall thickness (*t*) varying between 6.1 and 10.6 mm. Both ends of these tubes were welded with 20 mm thick plates. The geometry is summarized in Table 1.

Table 1. Geometry of the CFT specimens.

Label	h [mm]	D [mm]	t [mm]	D/t [-]
C5	2400	249.2	6.1	40.85
C6	2400	260.4	10.4	25.04
C7	2400	249.4	6.2	40.23
C8	2400	255.2	10.6	24.08

To achieve composite action, the steel tubes were filled with the C30/35 concrete mix using a truck-mounted pump. Subsequently, internal consolidation of the concrete was accomplished using a vibrating poker. Finally, the specimens were carefully stored for an appropriate duration to ensure proper curing.

Experimental Setup

Four steel concrete filled columns were analysed, on which a series of cyclic tests have been carried out through a hydraulic actuator Regarding the CFT elements under examination, three-point bending tests were performed under both cyclic load conditions. In particular, the specimens called C5-CA and C7-CA were subjected to cyclic testing at constant amplitude (0-140 mm) and speed, while the C6-VA and C8-VA specimens were subjected to cyclic testing at increasing amplitude and speed (Table 2).

Table 2. Displacement history of the cyclic test (C6, C8).

n.cycles	Drift angle [rad]	Displacement [mm]
6	0.00375	5.64375
6	0.005	7.525
6	0.0075	11.2875
4	0.01	15.05
2	0.015	22.575
2	0.02	30.1
2	0.03	45.15
2	0.04	60.2
2	0.05	75.25
2	0.06	90.3
2	0.07	105.35
2	0.08	120.4
Until rupture	0.08	120.4

No axial load was applied to the specimens. Consequently the response of these structural elements has been strongly governed by flexural behaviour0 (Montuori et al., 2015).Figure 4 depicts a schematic view of the test setup used in the experimental investigation. The setup involved the arrangement of two articulated pins at the ends of the beam, with the two plates being fixed to the pins using 16 bolts of M20 type on each plate. The articulated supports were securely fixed to the testing machine's plane using 8 M22 pins. This setup allowed for free rotation of the specimen's ends within the plane, enabling a simply supported configuration.

The flexural load was applied to the specimen at its center using a hydraulic actuator To connect the specimen with the actuator, a hollow semi-cylindrical element was placed at the center of the specimen and secured with 3 bolts on each side to ensure a conforming connection.

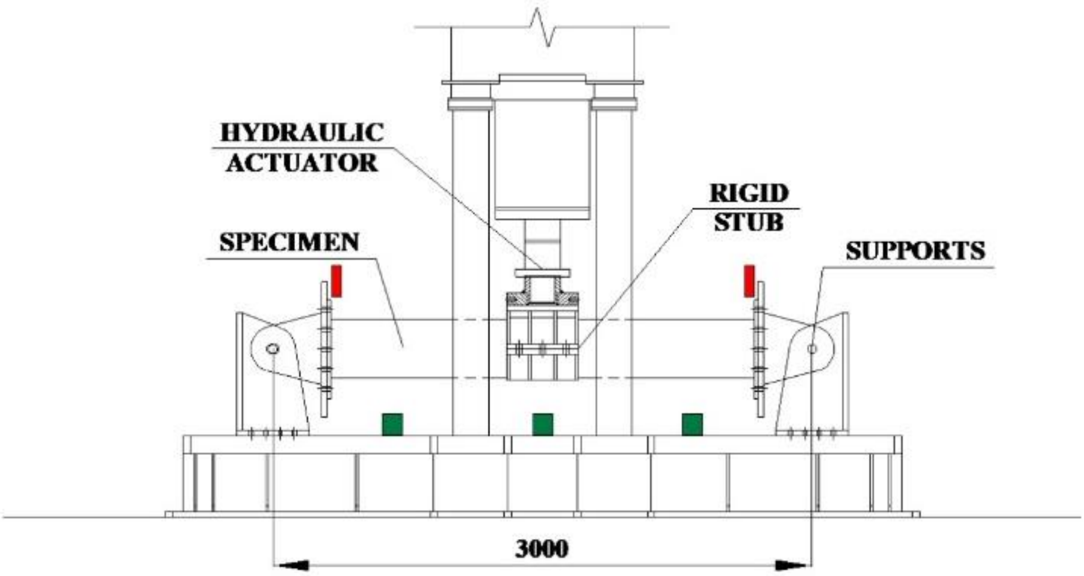


Figure 4. Experimental setup scheme.

The **C5-CA** specimen was subjected to a cyclic test at a constant amplitude of 0-140 mm, with a constant speed of 0.25 mm/s. The specimen developed two bulges and cracks near the attachment to the load cell and reached rupture after 21 cycles. (Figure 5).

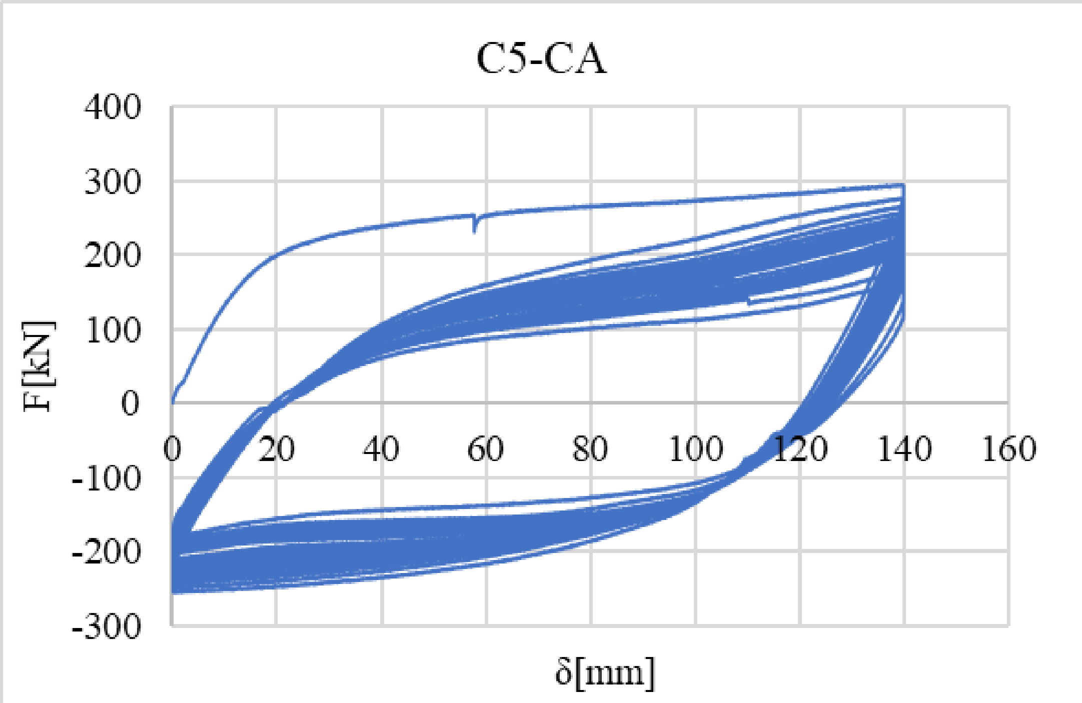


Figure 5. C5 Experimental curve.

The **C6-VA** specimen underwent a cyclic test with a variable and increasing amplitude following the AISC protocol. The initial amplitude was set at 0.1 mm, and the test started with an initial speed of 4.425 mm/s. It reached rupture after 28 cycles, occurring near the hinge side due to a welding defect

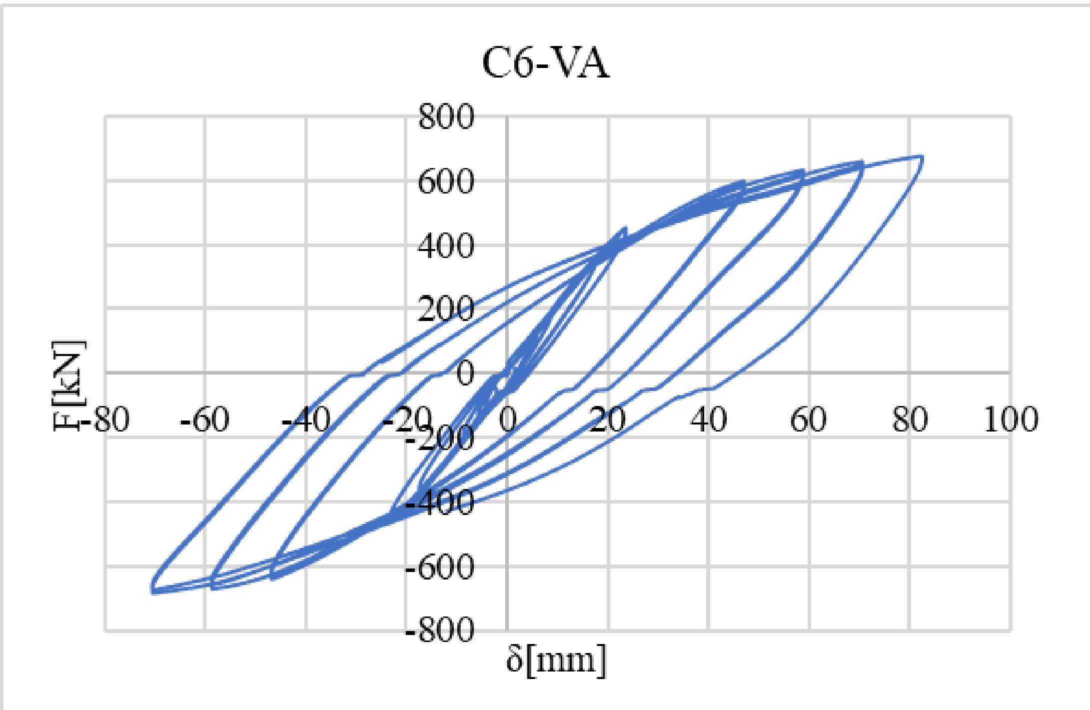


Figure 6. C6 Experimental curve.

The **C7-CA** specimen specimen also underwent a cyclic test at a constant amplitude of 0-140 mm, with a constant speed of 1 mm/s.. Similar to the C5-CA specimen, it developed two bulges and cracks near the attachment to the load cell and reached rupture after 24 cycles. (Figure 6).

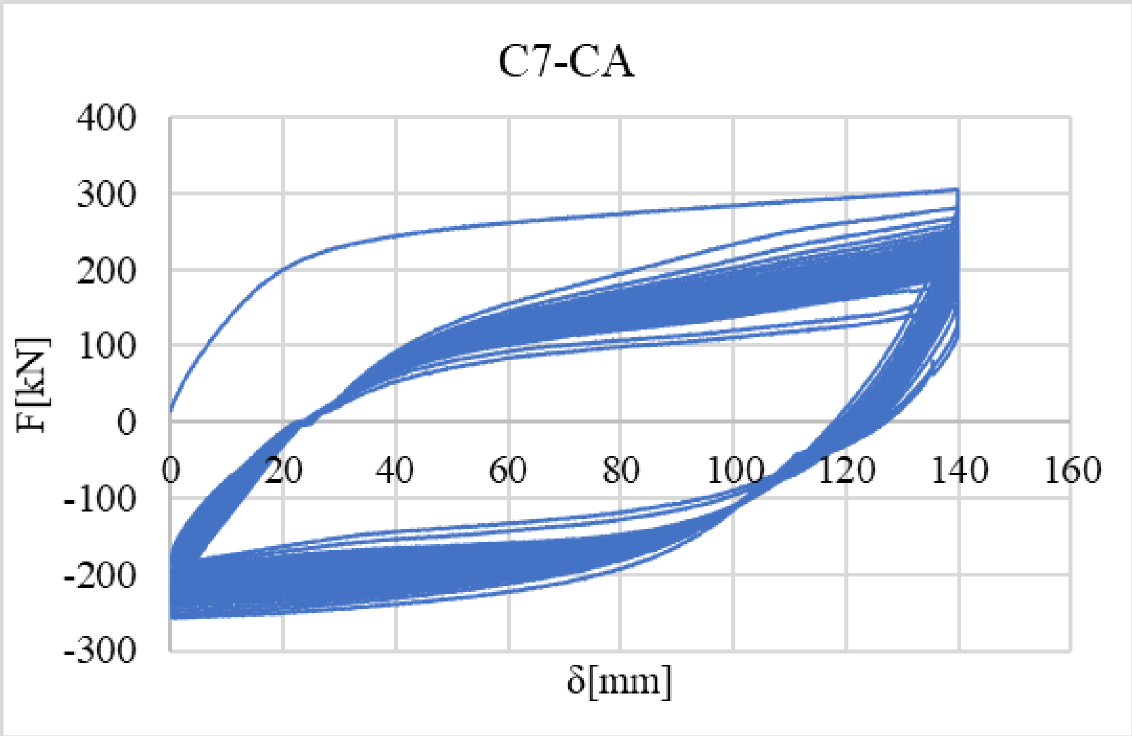


Figure 6. C7 Experimental curve.

The **C8-VA** specimen was subjected cyclic test with a variable and increasing amplitude following the AISC protocol. The initial amplitude was set at 0.1 mm, and the test started with an initial speed of 4.425 mm/s. It reached rupture after 48 cycles, occurring near the rigid stub (Figure 7).

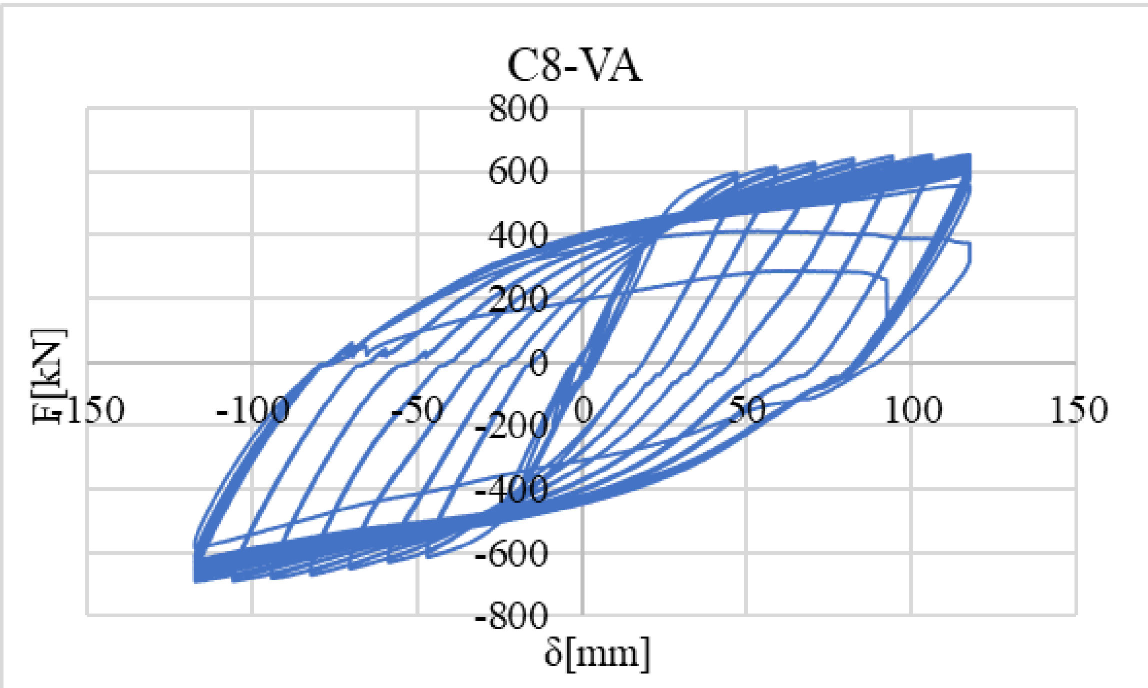


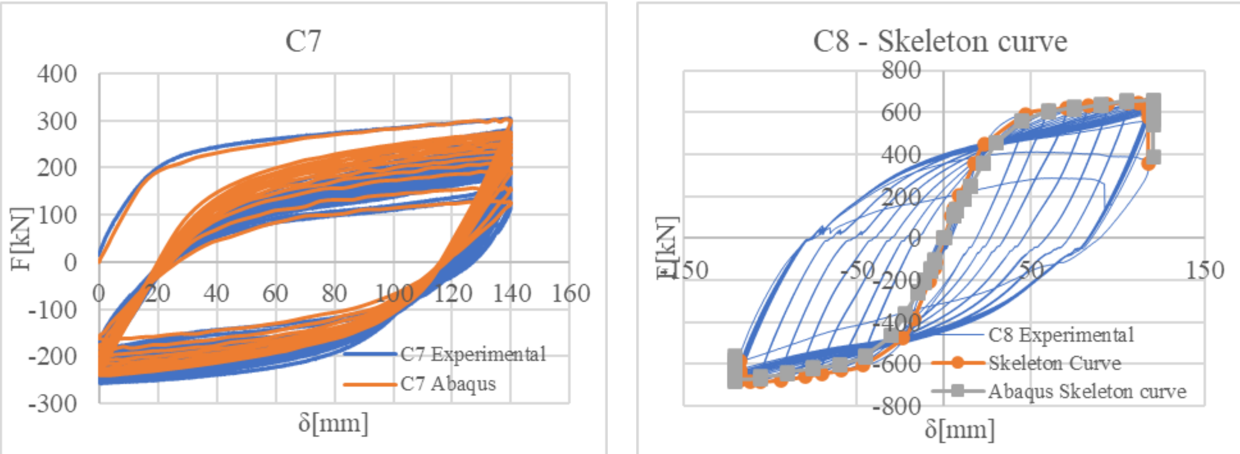
Figure 7. C8 Experimental curve.

Finite Elements Simulation

The finite element modeling in this study was performed using Abaqus software. The "Concrete Damaged Plasticity" failure criterion was utilized to model the plastic behavior and damage of the concrete core. This criterion requires input parameters such as uniaxial tension and compression curves, along with associated damage, calibrated based on average failure load values obtained from tests conducted on cubic specimens of concrete. The calibration parameters were determined based on (Nastri et al., 2022; Guo, 2014; Nastri et al., 2023).

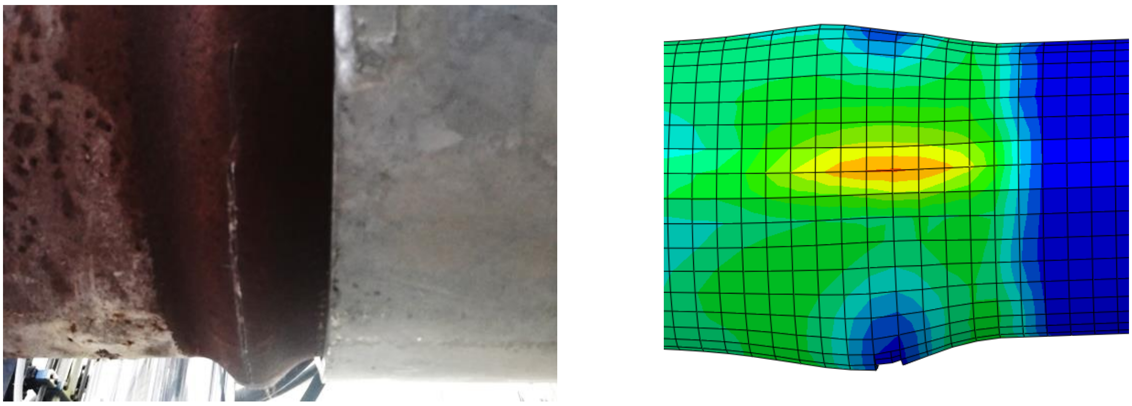
For modeling the plastic behavior of the steel, a combined hardening model was employed. This model was calibrated using experimental data obtained from dog bone specimens extracted from the concrete-filled tubes. The Johnson-Cook model was applied to capture the damage evolution, which requires the definition of damage initiation and displacement at failure. Interface contact was modeled with a tangential frictional coefficient of 0.6 and a hard normal contact (Montuori et al., 2015; Han et al., 2014).

To assess the accuracy of the simulations, a comparison was made between the experimental reaction force-displacement curve and the corresponding curve obtained from the finite element model for the constant amplitude specimens (C7) (Figure 8a). Furthermore, the skeleton curve, representing the locus of peaks resulting from the cycles, was used to compare the experimental and FE results for the variable amplitude tests. An example of this comparison is shown for specimen C8 (Figure 8b).



(a) (b)

Figure 8. C7-C8 Experimental vs Abaqus.



(a) (b)

Figure 9. Damage occurred near the rigid stub.

The agreement between the simulated and experimental results was evaluated by analyzing the area under the curves, which represents the energy dissipated during cyclic bending. The error in estimating this value ranged from 1% to 5% across all tests, indicating a satisfactory level of accuracy. The simulations accurately captured the plastic deformations that occurred under the tensional state.

A further aspect of comparison involves visualizing the damage formation in the steel material. Figure 9 illustrates the comparison between the observed damage during the experimental test (a) and the damage obtained by removing the mesh elements that reached the maximum damage level in the Abaqus simulation (b).

Conclusions

This study aims to contribute to the existing knowledge on concrete-filled tubes, providing valuable insights for engineers and researchers involved in the design and analysis of composite structures. The combined experimental and FE modeling approach offers a comprehensive evaluation of the structural behavior of CFTs under various loading conditions. The results obtained from the experimental tests and the corresponding FE simulations can provide guidance for future design improvements, optimization strategies, and practical applications of concrete-filled tubes.

The analysis of the results of the experimental tests carried out confirmed the high ductility and energy dissipation capacity of CFTs. The CFT profiles have shown failure in the expected area, except for a specimen evidently affected by a construction defect; Most profiles have collapsed by simple bending resulting in cracking and breaking of the steel profile; The combination of concrete and steel affects the strength of the profile increasing its performance.

Comprehensive information regarding the geometry of the specimens and the test procedures was provided for the experimental tests, serving as a valuable reference for future experiments. These details are also essential for developing a precise finite element (FE) model. In the FE simulation, failuree criteria and damage models were implemented for both the steel and concrete materials, considering their interaction. The comparison between the experimental and simulated results, specifically in terms of energy dissipation, revealed errors ranging from 1% to 5%. Furthermore, a graphical comparison of the formation of lesions was presented. In this aspect as well, the simulated model exhibited good agreement as the removal of mesh elements that reached the maximum damage level occurred near the bulging regions, similar to the observed behavior in the experimental tests.

Scientific Ethics Declaration

The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Notes

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