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Analytical Investigation of Circular Concrete-Filled Steel Tabular Column

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Abstract: ***This study presents an in-depth experimental and numerical investigation of Concrete-Filled Steel Tubular (CFSTS) columns subjected to axial loading. With the growing emphasis on composite construction methods, CFSTS columns have shown superior performance due to their strength, ductility, and efficient material usage. The research evaluates the axial behavior of CFSTS specimens using a combination of experimental testing and finite element modeling. Specimens with varying geometric parameters were tested to observe the impact on load-bearing capacity. Finite Element Analysis (FEA) was conducted using ABAQUS software to simulate the structural response, validate experimental results, and analyze stress distribution. The results demonstrate strong agreement between experimental and numerical outcomes, confirming the accuracy of the model. The study concludes with recommendations for practical application and further research directions in CFSTS structures. This comprehensive investigation contributes significantly to the design optimization and wider adoption of CFSTS columns in civil infrastructure.***
Keywords: ***Concrete-Filled Steel Tubular, Axial Load, Finite Element Analysis, Composite Structures, ABAQUS, Experimental Testing, Column Behavior.***

I. INTRODUCTION

The construction industry is evolving rapidly, driven by the need for more efficient, economical, and sustainable building solutions. Composite structural systems that integrate the strengths of different materials have become increasingly popular. Among these, Concrete-Filled Steel Tubular (CFSTS) columns have garnered attention for their structural efficiency and versatility. These columns consist of an outer and inner steel tube with concrete filled in between, providing excellent confinement and composite action. This hybrid arrangement not only enhances load-bearing capacity but also delays local buckling, improves ductility, and offers better fire resistance compared to traditional steel or reinforced concrete columns.

The application of CFSTS columns is particularly relevant in high-rise buildings, bridges, and industrial structures where axial loads are substantial. The hollow inner tube reduces the self-weight of the column while providing a conduit for services such as electrical or mechanical systems. Additionally, the improved energy absorption makes these columns suitable for structures in seismic zones. Furthermore, CFSTS systems are aligned with modern design philosophies that prioritize both structural performance and space efficiency. Modern design codes are also increasingly accommodating composite structures, reflecting a shift towards performance-based design. In this context, understanding the fundamental behavior of CFSTS columns under different loading conditions becomes crucial. The performance of these columns, especially their ability to sustain high axial loads with minimal deformation and failure, is of immense importance in both earthquake-resistant and high-load-bearing applications. Despite the advantages of CFSTS columns, there is still limited research that systematically investigates their behavior under axial loading, especially with variations in geometric configurations. Previous studies have not fully addressed the interplay between the geometric factors and material properties affecting load resistance. This paper addresses this gap by combining experimental analysis with finite element simulations to study the axial compressive performance of CFSTS columns. The results provide valuable insights for structural engineers and contribute to the growing body of knowledge on composite column design.

A. CFSTs Types

Concrete-filled steel tubes (cfsts) are built in various shapes—such as square, circular, or hexagonal—based on design needs. They feature either solid or hollow concrete cores. Solid cores are compacted pcc placed into steel tubes using vibration, while hollow cores are formed by inserting wet concrete into a rotating mold, where vibration and centrifugation ensurecompaction.

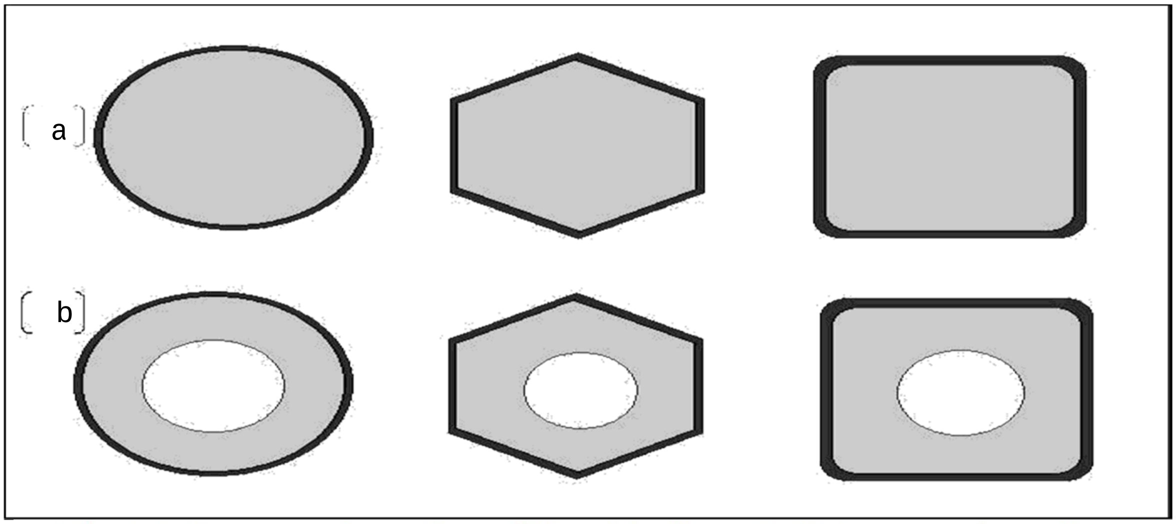


Fig.1.1 Cross-sections for solid and hollow CFST composite columns.

II. LITERATURE REVIEW

The development of composite columns dates back to the early 20th century, but only in recent decades has research focused intensively on the double-skin configuration. Concrete-Filled Steel Tubular (CFST) columns, the precursor to CFSTS columns, have been extensively researched and implemented due to their superior load-bearing capacities and reduced cross-sectional dimensions. Han et al. (2003) conducted detailed investigations into the influence of concrete compaction, showing its critical role in optimizing axial strength in CFST members.

In contrast, CFSTS columns provide enhanced structural characteristics due to the dual-layer steel confinement, creating a triaxial stress condition in the concrete core. Hassanein et al. (2018) demonstrated that elliptical steel tubes further improve the column's resistance to deformation. Their findings suggest that shape optimization and material efficiency are crucial in composite design.

A major milestone in CFSTS research was the work of Heidarpour and Zhao (2017), which highlighted the behavior of tubular columns under combined axial and flexural loads. Their work indicated that CFSTS systems outperformed traditional steel and CFST counterparts in terms of ductility and energy dissipation, especially in seismic conditions. More recently, Hassan and Bhat (2023) examined partial- and full-length stiffened CFSTS columns, noting significant performance improvement in stiffened specimens.

Despite these advancements, gaps remain in parametric evaluations and the integration of experimental data with robust numerical simulations. This research aims to bridge these gaps by presenting a coordinated study that combines physical testing and finite element modeling of CFSTS specimens with varying geometric configurations.

III. OBJECTIVES

The main objectives of this study are:

1) To examine the axial load-bearing capacity of CFSTS columns under varying geometric parameters.
2) To understand the interaction between the steel tubes and concrete core during axial compression.
3) To validate experimental observations through detailed finite element simulations using ABAQUS.
4) To explore failure mechanisms and load transfer behavior in CFSTS columns.
5) To provide design recommendations based on empirical and simulated results.

IV. LITERATURE REVIEW

Over the past few decades, extensive research has been conducted on composite columns, particularly Concrete-Filled Steel Tubular (CFST) columns. These studies have consistently demonstrated the benefits of composite action between steel and concrete.

Schneider (1998)
- Studied 14 CFST columns of equal length with varied tube diameters and shapes.
- Circular tubes showed higher post-yield strength and stiffness than square/rectangular ones.
- ABAQUS software used for unstructured finite element modeling, results aligned with experimental data.

Hu et al. (2005)
- Categorized CFST columns by shape and reinforcement.
- Square sections with stiffening ties showed better confinement than plain square tubes, but less than circular ones.
- Closely spaced ties can help match circular tube confinement performance.

Gupta et al. (2007)
- Analyzed 81 circular CFSTs with varied D/t and L/D ratios using ANSYS.
- Found 20–30% lower yield displacement in simulations than tests.
- Fly ash content of 25% enhanced load capacity after an initial dip at 20%.

Uy et al. (2009)
- Tested thin square CFSTs of stainless steel under axial load using two concrete grades.
- Columns with higher slenderness ratios had lower peak loads.
- Stainless and carbon steel performed similarly; slenderness reduces composite action.

Ghannam et al. (2010)
- Compared rectangular CFSTs filled with normal vs. lightweight concrete.
- Lightweight columns carried ~92% of squash load, normal ~87%.
- Lightweight concrete performed reliably despite buckling modes.

More recently, research has turned toward CFSTS columns. These studies, though limited in number, indicate that the double-skin configuration enhances stability and delays local buckling. However, challenges remain in modeling the complex interactions among the inner and outer steel tubes and the concrete infill. This study builds on past work by conducting a comparative evaluation of experimental and numerical results for CFSTS columns.

The fabrication of CFST column includes using steel tubes of the required size and a concrete mix of an appropriate grade. The fundamental material properties are as follows:

Steel Tube In both forms of compression and tension, the steel tube behaves exactly like an elastic-perfectly-plastic substance. Experimental testing on sample specimens are used for identifying important parameters for steel reinforcing, including the yield stress as well as Young's modulus of stress. In this investigation, a bilinear kinematic material model is used.

V. METHODOLOGY

To ensure the integrity and applicability of the findings, a rigorous methodology was adopted, combining empirical testing with computational modeling.

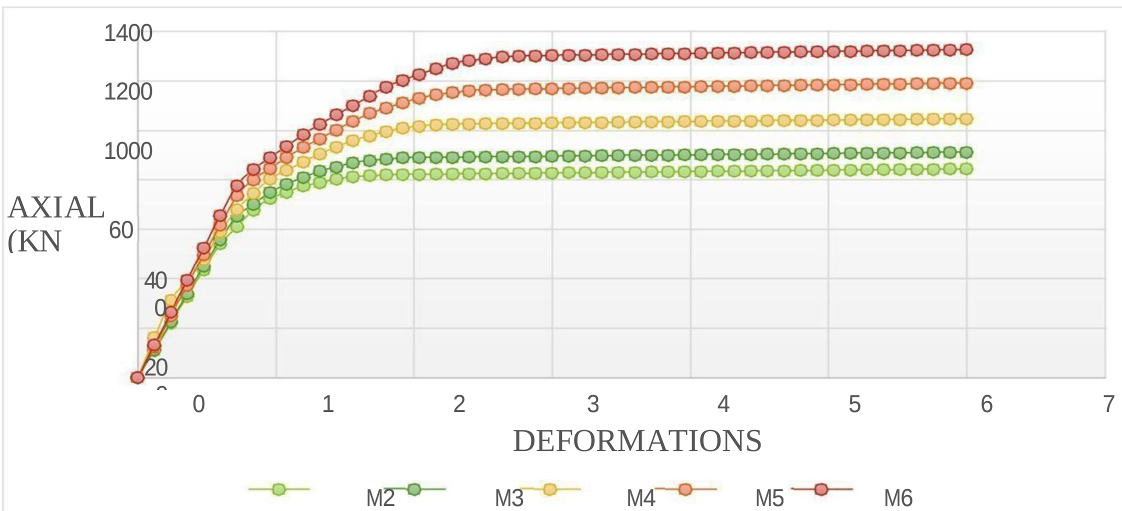
1) Materials and Properties: The steel tubes used for both inner and outer skins were circular hollow sections fabricated from S355 grade steel. Mechanical properties, including yield strength and ultimate tensile strength, were determined through standard tensile tests. The concrete used was a mix of OPC 43 grade cement with river sand and 20 mm coarse aggregate in a 1:1.5:3 proportion. Slump test and compressive strength testing were performed on cube specimens at 7 and 28 days to ensure mix consistency and quality.
2) Specimen Design: A total of 12 specimens were fabricated, grouped based on variations in outer tube diameter (100 mm, 120 mm), inner tube diameter (50 mm, 60 mm), and wall thickness (4 mm, 6 mm). The height of all specimens was kept constant at 600 mm to maintain uniform slenderness. Specimens were labeled for traceability (e.g., S1 to S12), with careful record-keeping of dimensions and test conditions.
3) Fabrication and Casting: Steel tubes were cut to precise lengths using CNC tools to minimize deviations. Inner tubes were centrally aligned and welded to base plates using temporary jigs. The annular space was filled with fresh concrete in layers, each compacted manually with a steel rod to avoid segregation. Specimens were cured for 28 days under wet hessian cloth followed by air curing to replicate field conditions.
4) Instrumentation Setup: Universal Testing Machine (UTM) with a 2000 kN capacity was used for axial loading. Displacement was measured using LVDTs mounted at mid-height and near the supports. Strain gauges were attached at mid-height on both inner and outer tubes. Data acquisition systems were synchronized with load and displacement channels for real-time monitoring.

5) Test Procedure: The specimens were loaded under displacement control mode at a rate of 0.5 mm/min. Pre-loading cycles were performed to ensure proper alignment. Testing continued until post-peak softening behavior and visible failure patterns emerged. Photographic documentation and notes were taken at each critical stage.
6) Finite Element Modeling: A three-dimensional nonlinear model was developed in ABAQUS. The outer and inner steel tubes were modeled using 4-node shell elements, while the concrete was represented with 8-node solid brick elements. Surface-to-surface contact was used to model the interface between steel and concrete with a penalty friction coefficient of 0.4. Concrete damage plasticity parameters were selected based on published standards. Finite Element Analysis (FEA) allows for numerical modeling of structural behavior, providing a means to verify calculations and offering valuable support to laboratory experiments, especially in parametric studies.

VI. EXPERIMENTAL RESULTS

The experimental program yielded detailed observations on the behavior of CFSTS columns under axial load:

1) Load-Displacement Behavior: The initial linear region reflected elastic behavior, followed by a yield plateau and peak load attainment. Specimens with thicker steel walls exhibited higher stiffness and load capacity. After the peak, gradual degradation was observed due to concrete crushing and local buckling.



Axial-loads vs deformation curve for Series-1a

2) Axial Capacity Trends: Axial load capacity was positively correlated with wall thickness and negatively affected by inner diameter (for a fixed outer diameter). The best-performing specimen (S7) reached a maximum load of 890 kN, while the lowest-performing (S2) failed at 620 kN.
3) Failure Modes: Observed failure modes included outward local buckling in the outer tube and crushing at the tube-concrete interface. Some specimens showed splitting cracks in the concrete core, particularly at mid-height, due to tensile hoop stresses.
4) Numerical Validation: The ABAQUS model predicted peak loads with a deviation of less than 6% from experimental results. Stress contour plots confirmed the initiation of buckling and plastic zones in regions consistent with observed cracks.
5) Comparison with Design Standards: Predicted strengths were compared with Eurocode 4 provisions. While EC4 provided conservative estimates, experimental results exceeded these predictions by up to 12%, confirming the robustness of CFSTS columns under pure axial loads.

VII. CONCLUSION AND PRACTICAL IMPLICATIONS

The comprehensive experimental and numerical study presented in this paper affirms the significant structural benefits of Concrete-Filled Steel Tubular (CFSTS) columns under axial compressive loads. The results conclusively demonstrate that CFSTS columns possess high axial strength, increased ductility, and favorable energy absorption characteristics, all of which are desirable in modern civil infrastructure applications.

The experimental phase confirmed that specimen performance is strongly influenced by geometric parameters, particularly the wall thickness of steel tubes and the spacing between the inner and outer skins. The best-performing columns combined thick steel walls and moderate annular concrete thickness, creating optimal confinement and load-sharing conditions. Observed failure modes, including outward buckling and concrete crushing, aligned with well-documented composite behavior, reinforcing the reliability of the test setup.

Finite Element Analysis using ABAQUS proved highly effective in simulating the behavior of CFSTS columns. The model accurately captured load-displacement responses, stress distributions, and failure modes, offering a valuable tool for design validation and parametric studies. Its predictive capabilities allow engineers to simulate a range of configurations without extensive physical testing, significantly reducing cost and time.

From a practical standpoint, the CFSTS column system is well-suited for structures requiring high axial load resistance and ductility, such as high-rise cores, bridge piers, and industrial columns. Their hollow core offers opportunities for utility routing or even prestressing tendons in hybrid systems. The improved fire performance due to the concrete infill and dual steel layers adds another dimension of safety.

A. *Design Implications*

1) CFSTS columns can be incorporated into modular construction systems with minor adjustments in fabrication.
2) Use of high-strength concrete beyond 40 MPa may not yield proportional benefits, suggesting a cost-effective balance of material selection.
3) Parameters such as outer-to-inner diameter ratio (D_o/D_i) and wall thickness-to-diameter ratio (t/D) should be optimized during design.
4) Design codes, including Eurocode 4, can be further calibrated to include more refined guidance on double skin configurations.

B. *Recommendations for Future Work*

1) Extend testing to include cyclic and eccentric loading conditions.
2) Investigate fire resistance and residual strength post-heating.
3) Explore integration with smart monitoring sensors for structural health assessment.
4) Analyze long-term durability in corrosive or marine environments.

This study contributes significantly to the growing body of knowledge supporting the use of CFSTS columns. With continued research and development, they have the potential to become a mainstream solution for demanding structural applications.

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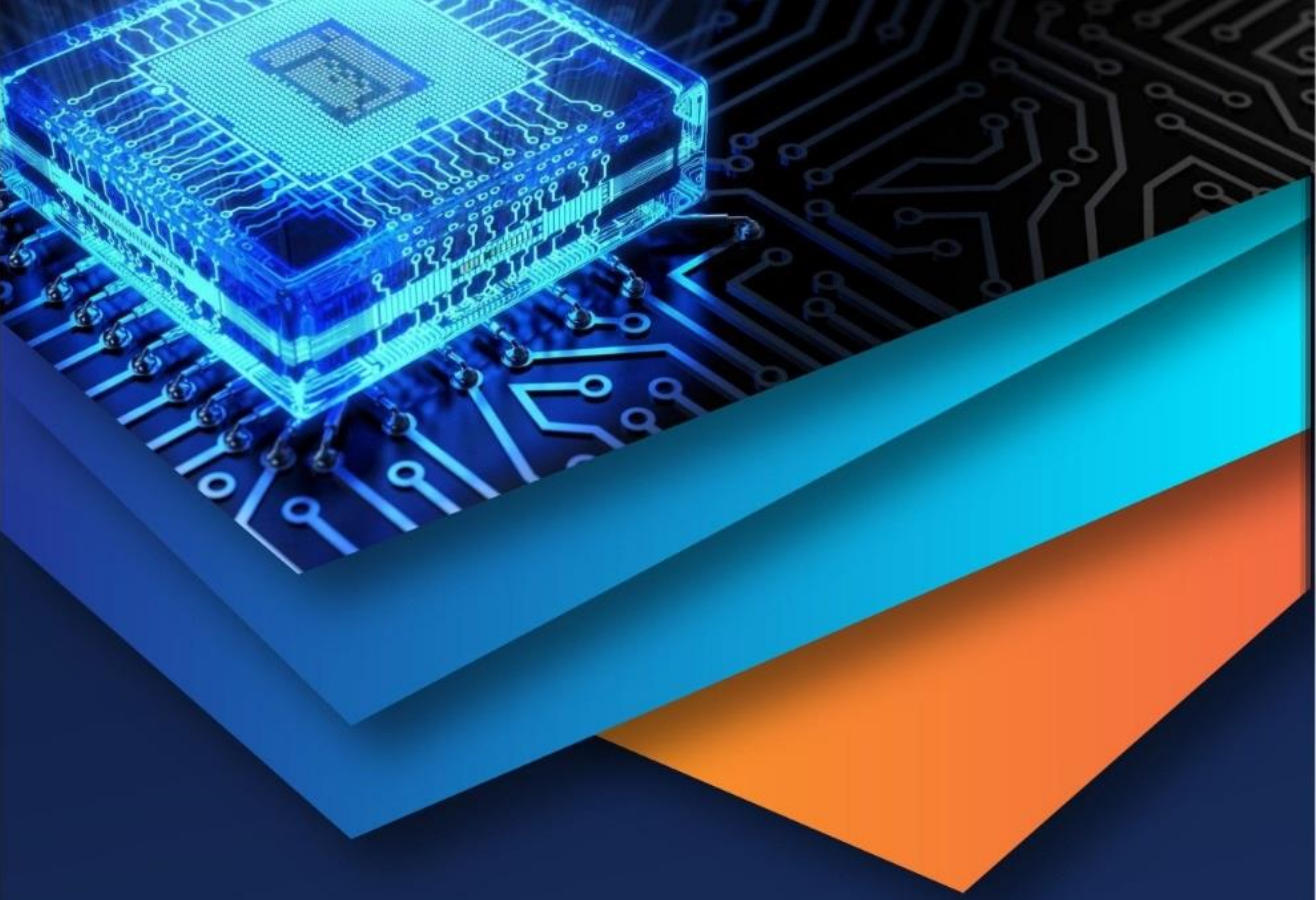

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