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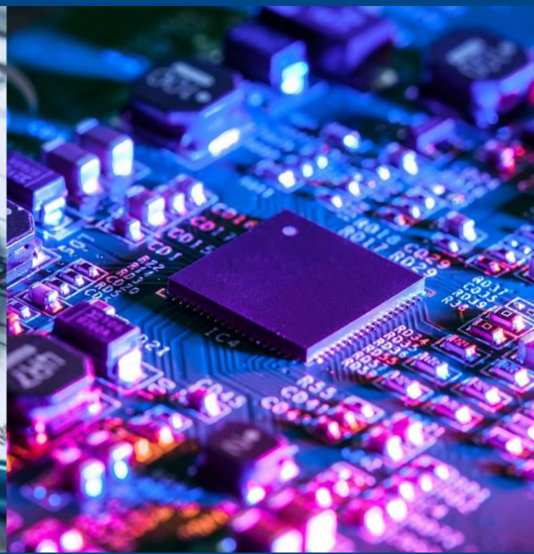

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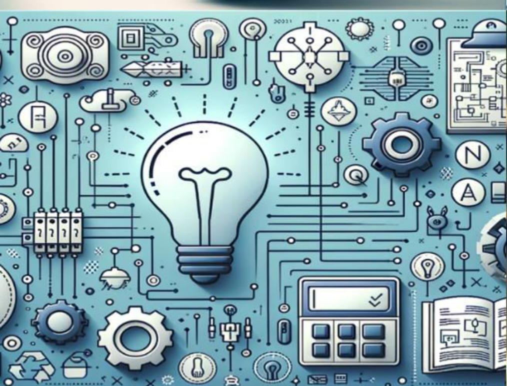

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Studying the Structural Behaviour of Steel Tubes and Concrete Filled Steel Tubes (CFST) Retrofitted with Glass Fiber Reinforced Polymer (GFRP)

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ABSTRACT: Concrete-Filled Steel Tubes (CFTs) are structural elements made by filling a hollow steel tube with concrete. These composite members are widely used in modern construction for their strength and durability. In international construction practices, CFT columns play a crucial role in providing lateral resistance in buildings, whether the structures are braced or unbraced. Additionally, these columns are used in Japan and Europe for constructing bridge piers, highlighting their versatility. Another important application of CFTs is in seismic retrofitting, where they are used to strengthen existing concrete columns in earthquake-prone areas. This study focuses on examining the behavior of CFT columns when they are wrapped with fiber-reinforced polymer (FRP) for additional strength and durability. A total of eleven columns were tested to analyze how different factors—such as the number of FRP layers, the thickness of the steel tube, and the strength of the concrete—affect the columns' ability to bear loads and resist deformation under axial forces. The results from these experiments showed that using an FRP wrap helps in confining the expansion of concrete and prevents the steel tube from experiencing local buckling too quickly. This confinement significantly improves both the load-bearing capacity and the deformation resistance of CFT columns. Based on these findings, a model has been developed to predict the load capacity of FRP-wrapped CFT columns. The predictions made by this model closely match the experimental results obtained in this research, as well as those reported in previous studies.

KEYWORDS: Concrete-Filled Steel Tubes (CFST), Steel Tubes, Glass Fiber Reinforced Polymer (GFRP), Structural Retrofitting, Axial Load Capacity, Buckling Behavior

I. INTRODUCTION

Steel-concrete composite columns have been used in construction for over a century. Initially, they were introduced mainly to provide fire protection for steel structures. However, engineers soon realized that encasing steel columns in concrete also improved their strength, leading to their incorporation into structural design. Despite this early development, serious research into Concrete-Filled Steel Tubes (CFSTs) did not begin until the 1960s. Today, CFST columns have become a widely preferred choice in construction due to their high strength-to-size ratio. This means that in tall buildings, instead of using large concrete columns on the lower floors, smaller CFST columns can be used to carry the same amount of load, making them more space-efficient. They are also commonly used as bridge piers, especially in congested areas where space is limited. Because these structural elements are often used in critical infrastructure, their behavior needs to be thoroughly studied before they are implemented in large-scale projects. Although CFSTs have been researched for about 50 years, their behavior under different types of loading is still not fully understood. This makes it necessary to conduct detailed studies on various factors that influence their performance. This study focuses on several key parameters, including the ratio of the steel tube's outer diameter to its thickness, the compressive strength of the concrete inside the tube, the rate at which load is applied, and the effects of using Glass Fiber Reinforced Polymer (GFRP) jacketing. One of the main advantages of CFST columns compared to traditional steel, reinforced concrete, or steel-reinforced concrete columns is the way the materials work together to optimize strength and stiffness. In a CFST column, the steel is positioned on the outer surface, where it provides the best resistance against tension and bending forces, while the concrete inside acts as a strong core to bear compressive

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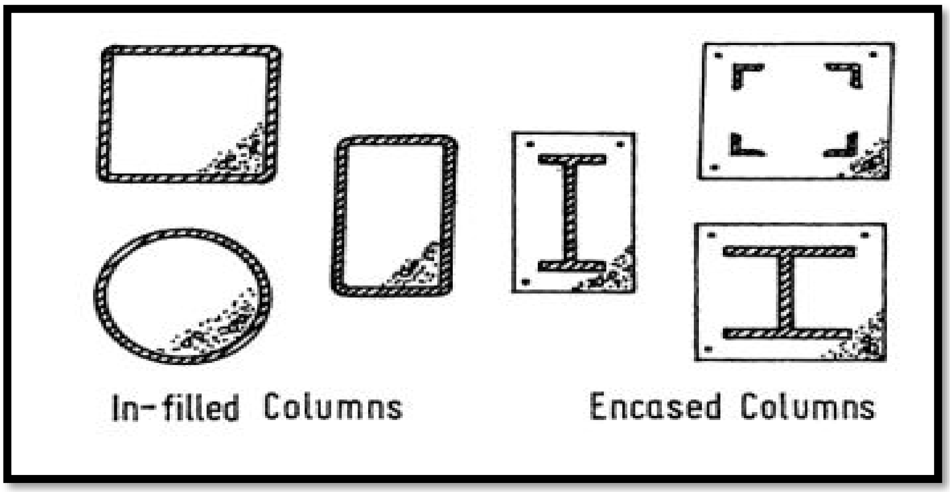
loads. The presence of the steel also significantly increases the overall stiffness of the structure, as steel has a much higher modulus of elasticity than concrete. This means the steel, placed at the farthest point from the column's center, plays a major role in increasing its resistance to bending. Additionally, the concrete core helps prevent local buckling of the steel tube, which is particularly beneficial for rectangular CFST columns. Research has also shown that in circular CFSTs, the steel tube provides confinement to the concrete, increasing its compressive strength, while in rectangular CFSTs, this confinement enhances ductility. Because of these advantages, CFST columns are highly effective in structures that need to support heavy compressive loads, making them a crucial component in modern engineering.

1.1 Concrete Filled Steel Tube (CFST)

In modern construction, composite structural elements are being used more frequently in tall buildings, bridges, and various other structures. The reason behind this is that composite materials allow engineers to combine the advantages of two different materials while reducing their individual weaknesses. In the case of steel-concrete composites, the interaction between the steel section and the concrete provides an efficient structural system that can bear heavy axial loads. The steel section helps the concrete resist bending moments, tensile forces, and shear forces, while the concrete, in turn, helps to prevent the steel section from buckling and efficiently resists compressive loads. There are two common types of steel-concrete composite columns used in construction: one where the steel section is filled with concrete (in-filled columns) and the other where the steel section is encased within a concrete layer (encased columns), as shown in Figure 1.1. Using composite columns, whether encased or in-filled, significantly reduces the overall column size compared to traditional reinforced concrete columns that carry the same amount of load. This reduction in column size results in substantial economic savings and is especially beneficial in buildings where floor space is limited, such as office buildings and parking structures. Another key advantage of composite columns is their effectiveness in resisting lateral loads when used with closely spaced spandrel beams in high-rise buildings. Concrete-encased steel sections are particularly preferred for structures designed to withstand seismic forces. When subjected to excessive flexural loads during an earthquake, the concrete encasement may crack, causing a reduction in stiffness, but the steel core continues to provide strength, shear capacity, and ductile resistance, ensuring the structure remains stable through repeated stress cycles. Additionally, since the steel section is enclosed within the concrete, it is naturally protected from corrosion and does not require additional fireproofing or painting. Concrete-filled steel tube (CFST) columns are widely used in earthquake-resistant structures, high-rise buildings, and bridge piers that experience high strain rates from vehicle and railway traffic. However, when fire protection is necessary, additional insulation is required for CFST structures. One of the main benefits of CFSTs is their ease of construction, as the steel tubes can serve as both formwork and a support system for pouring concrete, simplifying the construction process. Compared to concrete-encased steel sections, CFST columns also offer superior compressive strength and resistance to torsion in all directions, making them a highly efficient choice for modern structural applications.



[Fig.1.1: Types of composite column]

II. LITERATURE REVIEW

The study of various materials and techniques for strengthening concrete structures has been a focus of many researchers. Fardis and H. Khalili introduced Fiberglass Reinforced Polymer (FRP) as a new material for reinforcing concrete. Their experimental study on FRP-wrapped concrete cylinders and beams under compression and bending demonstrated that FRP significantly enhances strength and ductility. Analytical models developed in their research help understand how FRP affects load-bearing capacity and deformation behavior.

H. Saadatmanesh et al. focused on seismic strengthening of concrete columns, particularly in response to failures observed during earthquakes such as the 1989 Loma Prieta earthquake. Their research proposed using high-strength fiber composite straps wrapped around concrete columns to improve confinement, which increases both strength and ductility. Their study also developed analytical models to measure the improvement and conducted a parametric study to evaluate the effects of fiber type, thickness, and spacing on performance.

A. Nanni and N. M. Bradford conducted an experimental study on FRP-jacketed concrete members to validate existing analytical models. Their tests on 150x300mm concrete cylinders revealed that FRP jacketing significantly improves both strength and ductility. The research compared three different FRP confinement techniques, demonstrating their effectiveness in enhancing the load-bearing capacity of concrete structures.

M. D. O'Shea and R. Q. Bridge explored the performance of thin-walled steel tubes filled with concrete under different loading conditions. Their experiments focused on short specimens with a length-to-diameter ratio of 3.5 and concrete strengths ranging from 50 MPa to 120 MPa. The study highlighted the importance of bond strength between steel and concrete in preventing local buckling, which is critical in maintaining structural integrity.

Stephan Pessiki et al. conducted an experimental study on axial behavior of FRP-confined concrete columns. They tested both small-scale and large-scale specimens, including square and circular reinforced concrete columns wrapped with FRP jackets. Their findings showed that FRP confinement significantly improves both axial load-carrying capacity and deformation ability. They also identified key factors influencing the performance of FRP-wrapped concrete, such as material properties, thickness, and confinement effects.

Houssam Toutanji and Mohamed Saafi proposed a hybrid concrete column made of an exterior PVC-FRP shell with a concrete core. Unlike traditional FRP-wrapping methods, this system required fewer fibers while maintaining high strength and toughness. Their study examined the impact of different environmental conditions such as temperature variations, wet-dry cycles, and freeze-thaw effects. Test results showed that PVC-FRP tubes improve compressive strength, ductility, and energy absorption of concrete columns.

Walter O. Oyawa et al. examined steel-concrete composite structures and their suitability for earthquake-resistant construction. Their research found that while concrete-filled steel tubes (CFTs) offer high strength and stiffness, traditional concrete still suffers from issues such as shrinkage, brittleness, and low tensile strength. To address these limitations, the study suggested using polymer-based fill materials inside the steel tubes to enhance ductility and durability.

Yutian Shao and Amir Mirmiran studied the cyclic behavior of concrete-filled FRP tubes (CFFT), focusing on their potential for use in seismic regions. Their experiments tested six specimens under axial and lateral loads, using different fiber orientations and reinforcement ratios. The study found that fiber architecture plays a key role in failure behavior, with longitudinal fibers leading to brittle compression failure and off-axis fibers promoting ductile tension failure. Additionally, 1-2% internal steel reinforcement was found to improve seismic performance.

S. Matthys et al. investigated large-scale concrete columns confined with FRP reinforcement. Their research focused on circumferential failure strain and increasing confinement effects. A major objective of their study was to compare different compressive strength models with experimental results, providing valuable insights into the effectiveness of FRP confinement techniques.

G. Wu et al. conducted an extensive study on FRP-confined concrete cylinders, testing around 300 specimens. Their research analyzed confinement effects and failure mechanisms, with special attention given to predicting whether a specimen would exhibit strain-hardening or strain-softening behavior. The study found that in strain-hardening cases, the ultimate Poisson's ratio of FRP-confined concrete approaches an asymptotic value, providing insights into long-term performance.

2.1. Flexural Behaviour of High-Strength Rectangular Concrete-Filled Steel Hollow Sections (2004) By Wie-Min Gho, Dalin Liu The study "Flexural Behaviour of High-Strength Rectangular Concrete-Filled Steel Hollow Sections" by Wie-Min Gho and Dalin Liu, published in the Journal of Constructional Steel Research in 2004, investigates the performance of 12 high-strength rectangular concrete-filled steel hollow section (CFSHS) specimens under pure bending. The experimental results revealed local buckling as a primary failure mode, with high-strength materials exhibiting superior strength and ductility compared to normal-strength materials. Furthermore, the study identified that existing design codes, including EC4, ACI, and AISC, underestimated the flexural strength of CFSHS members by 11–18%. These findings highlight the need to update design methodologies to accurately account for the enhanced performance of high-strength materials in composite systems.

2.2. Analytical Modeling of Bending of Circular Concrete-Filled Steel Tubes (2012) By Jiho Moon, Charles W. Roeder, Dawn E. Lehman, Hak-Eun Lee The study "Analytical Modeling of Bending of Circular Concrete-Filled Steel Tubes" by Jiho Moon, Charles W. Roeder, Dawn E. Lehman, and Hak-Eun Lee, published in Engineering Structures in 2012, presents an analytical approach to predict the bending behavior of circular concrete-filled steel tubes (CFSTs). The model incorporates the nonlinear interaction between the steel tube and the concrete core, accounting for factors such as material properties, cross-sectional geometry, and confinement effects. Validation against experimental data showed accurate predictions of moment-curvature relationships, failure modes, and ductility. This research provides a robust framework for evaluating the flexural performance of CFST members, contributing to improved design practices for resilient structural systems.

2.3. Behavior of FRP-Confined Concrete-Filled Steel Tube Columns (2014) By Yiyan Lu, Na Li, Shan Li
The study "Behavior of FRP-Confined Concrete-Filled Steel Tube Columns" by Yiyan Lu, Na Li, and Shan Li, published in Polymers (MDPI) in 2014, examines the structural performance of concrete-filled steel tube (CFST) columns wrapped with fiber-reinforced polymer (FRP) composites. The research focuses on the combined benefits of steel and FRP confinement in enhancing axial load-bearing capacity, ductility, and energy absorption. Through experimental investigations and theoretical modeling, the study highlights the synergistic effect of the materials, which results in improved strength and deformation behavior under various loading conditions. The findings emphasize the potential of FRP-confined CFST columns as an innovative solution for high-performance structural applications, especially in seismic and extreme load environments.

2.4. A Study on Flexural Behaviour of Concrete Filled Steel Tubes (2017) By S. Aravind, D. Mohammed Rafi
The study "A Study on Flexural Behaviour of Concrete Filled Steel Tubes" by S. Aravind and D. Mohammed Rafi, published in IJSRST in 2017, focuses on the flexural performance of concrete-filled steel tubes (CFST). The research investigates the combined action of steel and concrete, emphasizing their role in enhancing the moment-carrying capacity, stiffness, and ductility of CFST members under flexural loads. Experimental and analytical approaches were employed to evaluate the influence of parameters such as cross-sectional shape, concrete strength, and steel tube thickness. The findings underscore the structural advantages of CFSTs, particularly in resisting bending forces, making them suitable for applications in modern construction where high performance is required.

2.5. Structural Behaviour of RC Beam and Concrete Filled Steel Tubes Retrofitted with Natural Rubber Sheet (2019) By P. Ramanan, M. Sharmila, P. Vennila, M. Suresh, Dr. M. Sivaraja The study "Structural Behaviour of RC Beam and Concrete Filled Steel Tubes Retrofitted with Natural Rubber Sheet," published in the International Journal of Engineering Research & Technology (IJERT) by P. Ramanan et al. in 2019, explores the retrofitting potential of natural rubber sheets in enhancing the structural performance of reinforced concrete (RC) beams and concrete-filled steel tubes (CFST). The researchers analyzed the effects of retrofitting on the flexural and axial load-carrying capacities, with a focus on energy dissipation and overall stability under applied loads. Their findings highlighted the significant improvement in ductility and strength due to the application of natural rubber sheets, emphasizing its cost-effectiveness and environmental benefits. The experimental study provides valuable insights into sustainable retrofitting techniques, paving the way for more eco-friendly and efficient methods in structural rehabilitation. This research underscores the growing interest in incorporating natural materials in modern construction for enhancing performance and sustainability.

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2.6. Behavior of FRP wrapped concrete filled steel tubular columns (2020) By Gajalakshmi Pandulu, Revathy Jayaseelan, Jemimah Thong The study "Behavior of FRP wrapped concrete filled steel tubular columns" by Gajalakshmi Pandulu, Revathy Jayaseelan, and Jemimah Thong, published in IJASE in 2020, investigates the performance of concrete-filled steel tubular (CFT) columns wrapped with fiber-reinforced polymer (FRP) under various loading conditions. The experimental results were compared with the computed load-carrying capacity from existing design codes. Among the codes compared, DL/T 1999 showed the least variation and was found to be the most reliable for predicting the ultimate load-carrying capacity of CFT columns. The study highlighted that CCFT columns wrapped with two layers of carbon fiber-reinforced polymer (CFRP) exhibited significantly enhanced strength and ductility compared to other CCFT columns, emphasizing the effectiveness of CFRP wrapping in improving column performance.

2.7. A Review on Structural Behavior of Steel Tubes and Concrete-Filled Steel Tubes (CFST) Retrofitted with Glass Fiber Reinforced Polymer (GFRP) (2022) By Sumit Bhusari, Harshavardhan Rangari The study "A Review on Structural Behavior of Steel Tubes and Concrete-Filled Steel Tubes (CFST) Retrofitted with Glass Fiber Reinforced Polymer (GFRP)" by Sumit Bhusari and Harshavardhan Rangari, published in the International Journal for Modern Trends in Science and Technology in 2022, examines the impact of retrofitting CFST columns with glass fiber reinforced polymer (GFRP). The review highlights that GFRP wrapping effectively improves the confinement of concrete, reducing its expansion and delaying the local buckling of the steel tube. The results from various studies reviewed demonstrated a significant enhancement in both the load-carrying capacity and axial deformation capacity of CFST columns when confined with GFRP. This retrofitting technique provides an efficient and cost-effective solution to enhance the performance and longevity of CFST structures.

2.8. Behavior of GFRP-concrete double tube composite columns (2022) By Shuai Li, Tak-Ming Chan, Ben Young The study "Behavior of GFRP-concrete double tube composite columns" by Shuai Li, Tak-Ming Chan, and Ben Young, published in Thin-Walled Structures in 2022, introduces a novel composite column system combining glass fiber reinforced polymer (GFRP) and concrete within a double tube configuration. The research demonstrates that this composite system offers enhanced deformability and load-bearing capacity compared to traditional column systems. The study found that increasing the thickness of the inner pultruded GFRP tube significantly improves the load capacity of the composite columns. Additionally, the authors developed predictive equations for the ultimate load-carrying capacity and axial strain, providing a useful tool for designing and analyzing GFRP-concrete double tube columns in structural applications.

2.9. CFST columns strengthened with CFRP textile grid-reinforced engineered cementitious composites under eccentric compression (2022) By Yuhong Yan, Shan Li, Yiyan Lu, Aohan Zheng The study "CFST columns strengthened with CFRP textile grid-reinforced engineered cementitious composites under eccentric compression" by Yuhong Yan, Shan Li, Yiyan Lu, and Aohan Zheng, published in Composite Structures in 2022, proposes a novel technique for enhancing the performance of concrete-filled steel tube (CFST) columns using carbon fiber-reinforced polymer (CFRP) textile grid-reinforced engineered cementitious composites. The research demonstrated that this strengthening method increased the load-bearing capacity of CFST columns by 11.6%–38.2%. Key factors such as the number of CFRP layers, the diameter-to-thickness (D/t) ratio, and the strength of the concrete were found to significantly influence the results, with higher concrete strength contributing to increased brittleness. A predictive model for the load-bearing capacity and N–M curves was also developed, providing valuable insights for the design and optimization of CFRP-strengthened CFST columns.

2.10. Study on Strength and Behaviour of Concrete Filled Steel Tubular Rectangular Composite Long Columns (2023) By Rajshree Charan, Ankit Goad The study "Study on Strength and Behaviour of Concrete Filled Steel Tubular Rectangular Composite Long Columns" by Rajshree Charan and Ankit Goad (2023) investigates the structural performance of concrete-filled steel tubular (CFST) rectangular composite long columns. This research evaluates the strength, stiffness, and load-bearing behavior under axial and eccentric loading conditions. The authors conducted experimental tests and analytical assessments to understand the interaction between the steel tube and concrete core, highlighting the benefits of composite action in enhancing overall performance. Their findings demonstrate improved load capacity and ductility, making CFST rectangular columns a viable option for modern high-rise and industrial structures. This work contributes to the development of design guidelines for CFST columns in challenging loading scenarios.

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III. PROPOSED METHODOLOGY

3.1 Test Specimens

A total of eleven specimens were tested under axial load, including seven CFRP-confined concrete-filled steel tube (CFCCFST) specimens, three GFRP-confined concrete-filled steel tube (GFCCFST) specimens, and one unconfined CFST specimen. The key test parameters included the number of FRP layers (nf) (1, 2, and 3), the steel tube thickness (ts) (3.0 mm, 4.0 mm, and 5.0 mm), and the concrete strength (fcu) (40 MPa, 50 MPa, and 60 MPa). Each specimen had a length (L) of 400 mm, with a length-to-diameter ratio (L/D) between 3 and 3.5. The detailed column specifications are listed in Table 4.1. The specimen nomenclature consists of three components: the first part indicates the type of FRP confinement, with CF representing CFRP-confined specimens and GF representing GFRP-confined specimens, followed by the number of FRP layers. The second part, denoted by t, indicates the steel tube thickness. The third part, represented by C, is followed by the nominal concrete strength.

Table 4.1: Details of the specimens

Specimens	L (mm)	D (mm)	FRP type	nf	ts (mm)	fcu (MPa)	fy (MPa)	ξs	ξf
t4C40	400	128	-	-	4	44.9	248	0.95	0.00
CF1t4C40	400	128	CFRP	1	4	44.9	248	0.95	0.39
CF2t4C40	400	128	CFRP	2	4	44.9	248	0.95	0.78
CF3t4C40	400	128	CFRP	3	4	44.9	248	0.95	1.17
GF1t4C40	400	128	GFRP	1	4	44.9	248	0.95	0.48
GF2t4C40	400	128	GFRP	2	4	44.9	248	0.95	0.97
GF3t4C40	400	128	GFRP	3	4	44.9	248	0.95	1.45
CF2t3C40	400	126	CFRP	2	4	44.9	243	0.69	0.77
CF2t5C40	400	130	CFRP	2	4	44.9	242	1.17	0.79
CF2t4C50	400	128	CFRP	2	4	54.2	248	0.79	0.65
CF2t4C60	400	128	CFRP	2	4	60.0	248	0.71	0.58

3.2 Materials Properties

The columns were cast using three different concrete mixtures. For each mix design, three concrete cubes were tested to determine the concrete compressive strength, and the average strengths (fcu) are listed in Table 4.1. Seamless steel tubes were used as formwork for all columns, with thicknesses of 3 mm, 4 mm, and 5 mm to achieve different diameter-to-thickness ratios. The 3 mm and 4 mm tubes were obtained by machining a seamless 5 mm steel tube. The steel properties were determined through coupon tests, yielding a measured yield strength (fy) of 248 MPa and an elastic modulus (Es) of 191 GPa. To provide confinement, carbon fiber-reinforced polymer (CFRP) and glass fiber-reinforced polymer (GFRP) were used. Their tensile properties were determined following ASTM D3039. The CFRP had a nominal thickness (tf) of 0.111 mm, an ultimate strength (ffu) of 3550 MPa, an ultimate strain (εfu) of 1.34%, and an elastic modulus (Ef) of 250 GPa. The GFRP had a thickness of 0.169 mm, an ultimate strength of 2930 MPa, an ultimate strain of 2.58%, and an elastic modulus of 109 GPa. A two-component, solvent-free epoxy resin was used for bonding, mixed in a 4:1 ratio of component A (resin) to component B (hardener) by weight. The manufacturer-reported properties of the epoxy included an elastic modulus of 15 GPa, a tensile strength of 35 MPa, and a shear strength of 13 MPa.

3.3 Preparations of Specimens

The circular steel tubes were precisely cut and machined to the required length. The inner surfaces of the tubes were wire-brushed to remove any rust, grease, or oil deposits. A 10 mm thick stiffened end-cap was attached at the base of each steel tube to ensure uniform load distribution. Concrete was filled in layers, and each layer was compacted using a poker vibrator to eliminate air voids. The specimens were then left to cure in the laboratory for 28 days. After curing, the CFRP or GFRP wrap was applied using the wet lay-up method, with fibers oriented in the hoop direction for optimal confinement. Before wrapping, the steel tube surface was cleaned with alcohol. A single continuous fiber sheet was wrapped around the steel tube with an overlap of 150 mm at the joint to ensure structural integrity. A paddler roller was used to remove air bubbles and maintain a uniform bond thickness. Before testing, the top surface of the concrete

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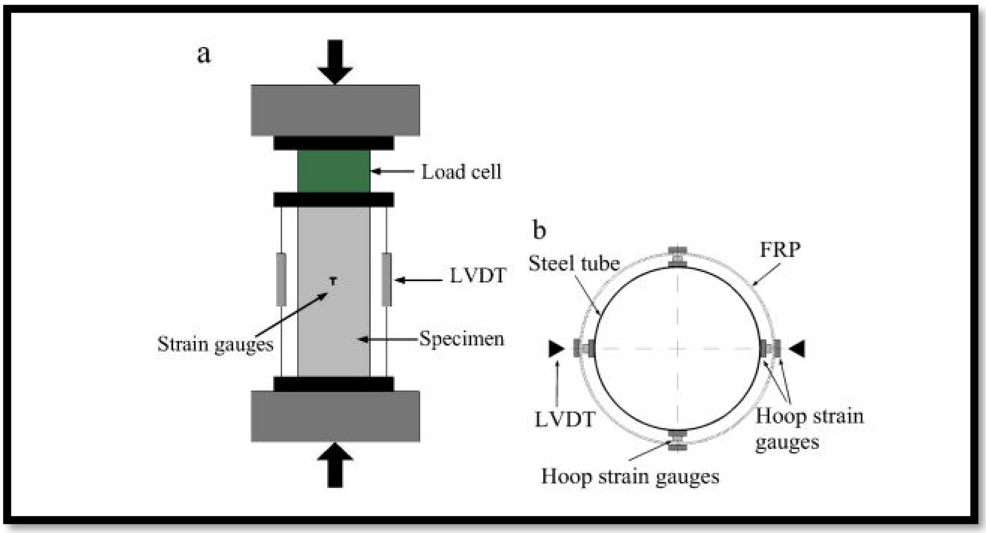
core was roughened with a wire brush, and a thin layer of high-strength cement was applied. This step minimized the effects of concrete shrinkage, ensuring that the steel tube and concrete core were simultaneously loaded during testing.

3.4 Test and Experimental Setup

The tests were conducted using a universal testing machine with a capacity of 5000 kN. The test arrangement for the specimens is shown in Figure 4.1a. The load was applied in increments of 50 kN before peak load. Each load interval was maintained for 2–3 min. The load was slowly applied near and after the maximum load to investigate the post-peak behavior of the columns. Two linear variable differential transducers (LVDTs) were positioned vertically to measure the axial shortening of the specimens. For each FCCFST specimen, a total of eight strain gauges were placed on the steel tube to capture vertical deformations and perimeter expansion at mid-height. Additionally, four strain gauges were mounted at the mid-height of the FRP wrap to monitor lateral confinement, as shown in Figure 4.1b. The strain gauge layout for the CFST specimens was identical to that of the FCCFST specimens to ensure consistency in data collection. To guarantee uniform compression, preliminary tests were performed within the elastic range. The specimen position was carefully adjusted based on strain gauge readings at mid-height. Adjustments continued until the difference between the measured strain and the average strain value was within 5%, ensuring precise alignment before formal testing.



[Fig.4.1: Test arrangement and instruments: (a) test arrangement; (b) layout of strain gauges for fiber-reinforced polymer (FRP)-confined concrete-filled steel tube (FCCFST) specimens. LVDT, linear variable differential transducer]

IV. RESULTS AND DISCUSSIONS

5.1 Observation's

In the CFST specimen, the middle section expanded continuously, and the steel tube showed outward buckling near its ends when subjected to large axial shortening, as seen in Figure 5.1a. For FCCFST specimens, failure occurred when the FRP wrap ruptured in the middle due to concrete expansion, as shown in Figures 5.1b and 5.1c. However, compared to CFST specimens, the concrete expansion and steel tube buckling were less noticeable in FCCFST specimens.

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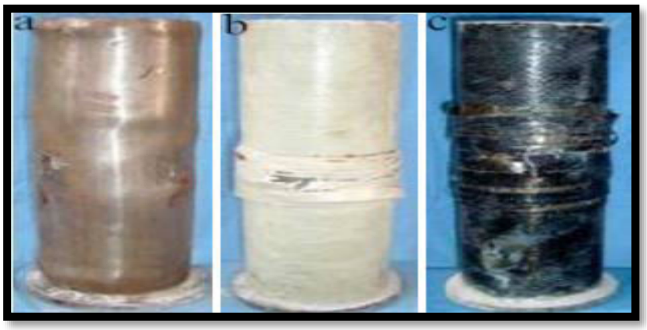

[Fig.5.1: Typical failure modes: (a) concrete-filled steel tube (CFST) specimen; (b) GFCFST specimens; (c) CFCFST specimens]

4.2 Axial Load- Axial Shortening Behaviour

The axial load versus axial shortening curves for the specimens are shown in Figures 5.2, 5.3, and 5.4. The axial shortening values are based on the average readings from two LVDTs. These figures illustrate the relationship between axial load and axial shortening until the specimens reach their ultimate state.

For FCCFST specimens, the ultimate state occurs when the FRP wrap ruptures explosively at the mid-height. In these specimens, the ultimate state load is the same as their maximum load. Similarly, for CFST specimens, the ultimate state is defined as the point when they reach their maximum load.

At the beginning, the FCCFST specimens followed a similar load-shortening curve as the corresponding CFST specimens. However, after reaching a specific shortening value (where specimen t4C40 carried about 75% of its ultimate load), the FCCFST specimens showed a higher stiffness compared to CFST specimens. Eventually, they behaved almost linearly until the FRP wrap ruptured at mid-height.

The test results for all specimens are presented in Table 5.1. The key parameters include:

- Ny: Axial load when the steel tube starts yielding.
- Nf: Axial load when the FRP wrap starts to fail (audible or visible fracture).
- Nu & δu: Ultimate load and the corresponding axial shortening.
- εf: Maximum hoop strain in the FRP at the ultimate state.

As expected, the FRP confinement significantly improved both the load-bearing capacity and axial deformation capacity. The improvements were more pronounced with an increase in the number of FRP layers, for both CFCCFST and GFCCFST specimens.

Table 5.1: Test results for the columns

Specimens	Ny (kN)	Nf (kN)	εf (με)	Nu (kN)	δu (mm)	kε2	Nup (kN)	Nu/Nup
t4C40	800	-	-	1130	3.5	-	1101	1.03
CF1t4C40	850	1200	10227	1300	5.2	0.76	1283	1.01
CF2t4C40	900	1400	11025	1440	6.5	0.82	1466	0.98
CF3t4C40	900	1670	10821	1685	9.4	0.81	1648	1.02
GF1t4C40	900	900	19890	1355	9.5	0.77	1327	1.02
GF2t4C40	850	1350	22288	1693	11.8	0.86	1554	1.09
GF3t4C40	950	1450	24282	1845	13.6	0.94	1780	1.04
CF2t3C40	800	1330	10816	1330	7.1	0.81	1271	1.05
CF2t5C40	1150	1550	11104	1650	7.3	0.83	1631	1.01
CF2t4C50	900	1430	10189	1548	8.3	0.76	1550	1.00
CF2t4C60	950	1658	8853	1658	8.5	0.66	1602	1.03

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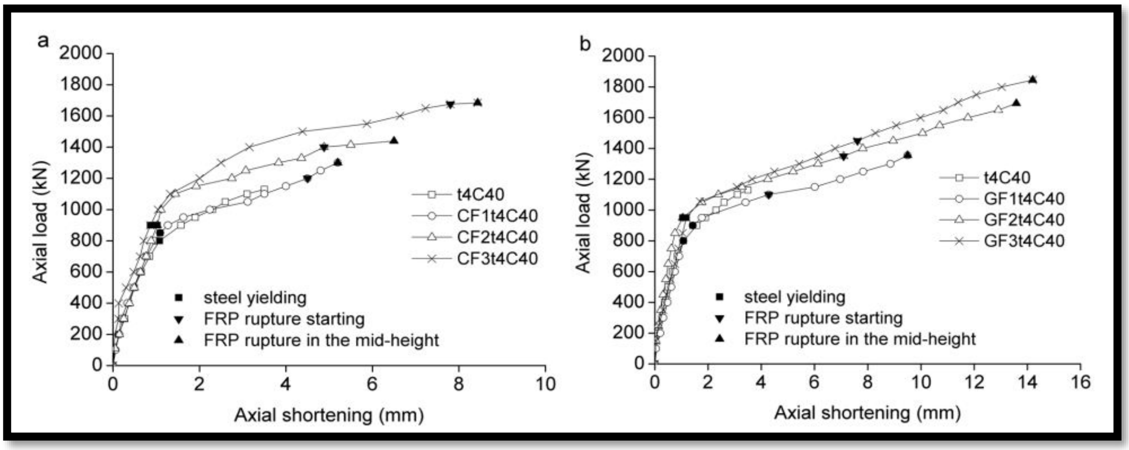
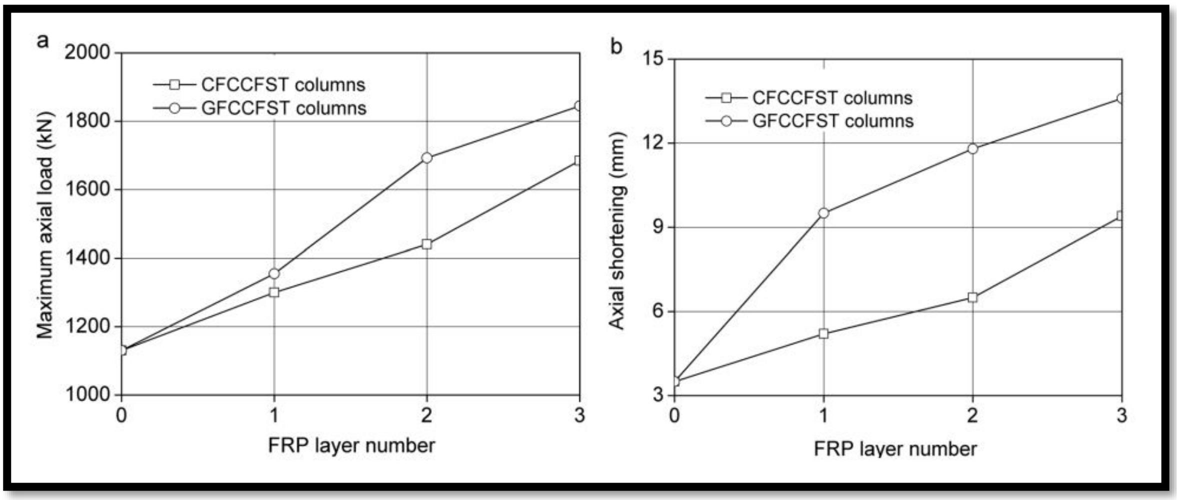
4.3 Effect of Fiber Reinforced Polymer (FRP) Confinement

Figure 5.2 compares the axial behavior of FCCFST specimens with CFST specimens. Both behaved similarly until the steel tube started yielding. After yielding, the FCCFST specimens continued to carry more load in a nearly linear manner because the FRP wrap provided additional support, delaying the stiffness loss in the CFST columns. The FCCFST specimens had a higher yield load than CFST specimens, but both had similar axial shortening at the yield point. As the number of FRP layers increased, the axial shortening at Nf (FRP failure load) also increased. It was observed that CFCCFST specimens (CFRP wrap) failed suddenly, with Nf and Nu (ultimate load) being close, whereas GFCCFST specimens (GFRP wrap) failed more gradually, with a larger difference between Nf and Nu. Figure 5.3 shows that adding more FRP layers increased both the ultimate load and axial shortening at ultimate load. With CFRP wrap, the ultimate load increased by 50%, and axial shortening increased by 169%. With GFRP wrap, the ultimate load increased by 60%, and axial shortening increased by 289%. Overall, GFCCFST specimens showed greater improvements in both ultimate load and axial deformation capacity, especially in deformation capacity, compared to CFCCFST specimens.



[Fig.5.2: Axial load vs. axial shortening curves in terms of the FRP layer number: (a) CFCCFST specimens; (b) GFCCFST specimens]



[Fig.5.3: The effect of FRP confinement: (a) ultimate load; (b) axial shortening at the ultimate load]

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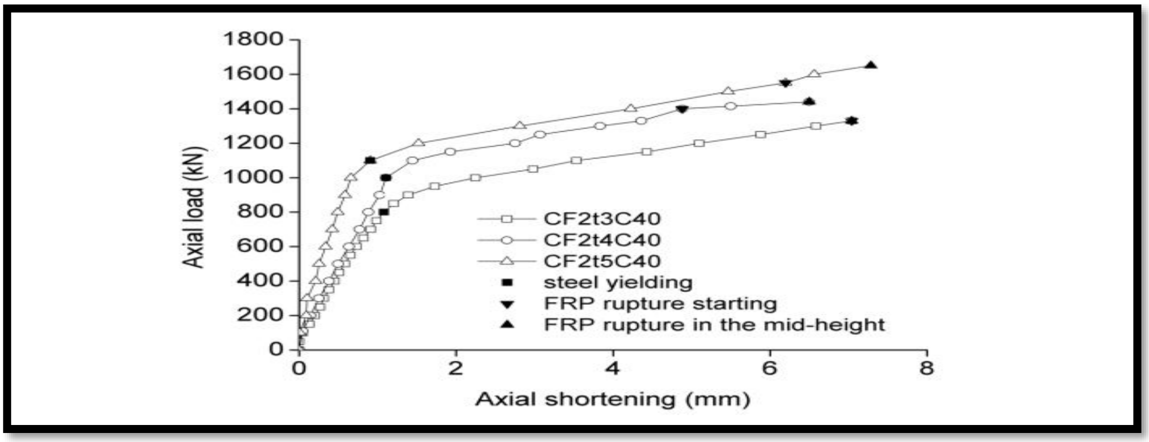
4.4 Effect of The Thickness of The Steel Tube

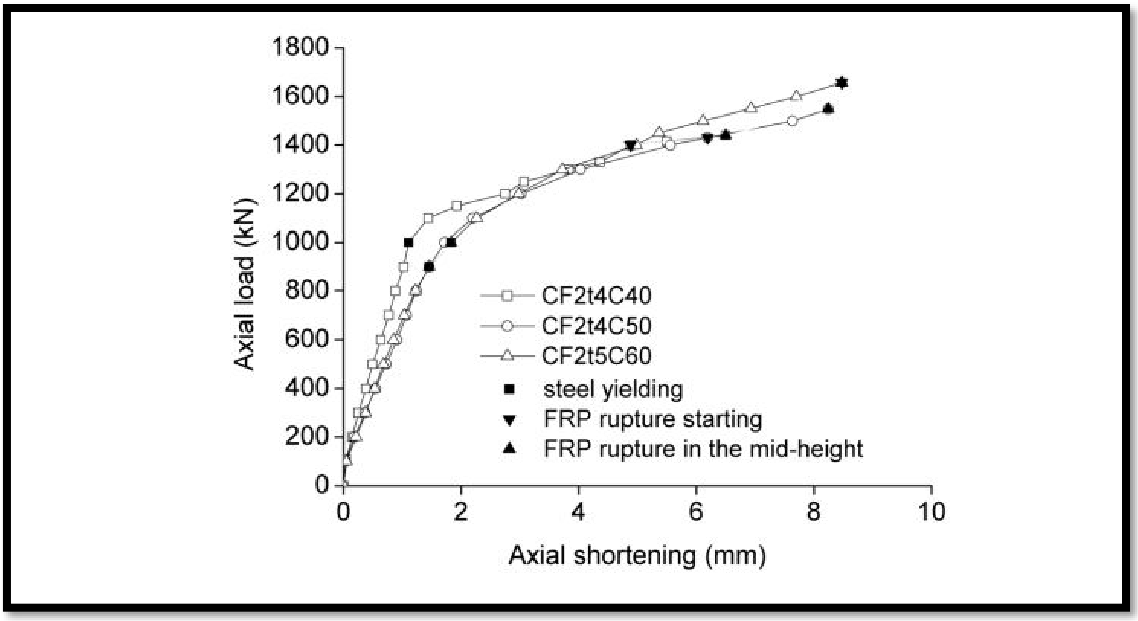
Figure 5.4 illustrates the impact of steel tube thickness on the axial behavior of FCCFST specimens. As the steel tube thickness increased, the ultimate load also increased. However, this increase in thickness had no significant effect on the axial shortening at the ultimate load. In the initial phase of loading, the specimen with a thicker steel tube exhibited a steeper curve, indicating higher rigidity. In the later phase, after the steel tube yielded, the load-shortening curves of all three columns became parallel. This suggests that after yielding, the additional axial load was mainly supported by the FRP wrap, which provided confinement in a linear elastic manner, dominating the behavior in this stage.



[Fig.5.4: Axial load vs. axial shortening curves in terms of the thickness of the steel tube]

4.5 Effect of Concrete Strength

Figure 5.5 illustrates the effect of concrete strength on the compressive behavior of FCCFST specimens. All three specimens exhibited similar behavior. As the concrete strength increased, there was a slight increase in both the ultimate load and the axial shortening at the ultimate load.



[Fig.5.5: Axial load vs. axial shortening curves in terms of concrete strength]

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4.6 Behaviour of Confined Concrete

By ignoring the small axial stiffness of the FRP wrap, the axial load carried by the concrete core can be determined by subtracting the axial load carried by the steel tube from the measured ultimate load. The axial load carried by the steel tube is calculated as the product of its cross-sectional area (As) and its yield strength (fy). The axial stress of the confined concrete is then obtained by dividing the deduced axial load by the cross-sectional area of the concrete core. Based on the previously defined ultimate state, the axial strain of the columns corresponds to the axial strain of the confined concrete at the ultimate load. Table 5.2 summarizes the stress and strain values of confined concrete at the ultimate load, where fccf represents the concrete stress in an FCCFST specimen, fcc represents the concrete stress in a CFST specimen, εccf is the axial strain of an FCCFST specimen, and εcc is the axial strain of a CFST specimen at the ultimate load. The nominal axial strain, obtained by dividing axial shortening by the column height, is used to interpret εccf and εcc. As evident from Table 5.2, FRP confinement significantly enhances both the concrete stress and axial strain at the ultimate state.

Table 5.2 Stress and strain of the confined concrete at the ultimate load

Specimens	fcc, fccf	fcc/fccf	εcc, εccf	εcc/εccf
t4C40	65.80	-	0.0088	-
CF1t4C40	80.83	1.23	0.0130	1.49
CF2t4C40	93.22	1.42	0.0163	1.86
CF3t4C40	114.89	1.75	0.0235	2.69
GF1t4C40	85.70	1.30	0.0238	2.71
GF2t4C40	115.60	1.76	0.0295	3.37
GF3t4C40	129.05	1.96	0.0340	3.89

V. CONCLUSION

This project explores how FRP (Fiber-Reinforced Polymer) wrapping affects the strength and behavior of concrete-filled steel tube (CFST) columns. The FRP wrap helps control outward buckling of the steel tube and provides better support to the concrete inside. The study focused on three key factors: the number of FRP layers, the thickness of the steel tube, and the strength of the concrete.

Key Findings:

- Improved Strength & Deformation Capacity: The FRP wrap significantly increases the load-bearing capacity and ability to withstand deformation. However, all test specimens eventually failed when the FRP ruptured in the middle due to concrete expansion.
- Delayed Buckling & Better Confinement: The FRP wrap helps prevent early buckling of the steel tube and controls the lateral expansion of concrete, making the structure stronger.
- GFRP vs. CFRP Efficiency: GFRP (Glass Fiber-Reinforced Polymer) performs better in terms of strain capacity compared to CFRP (Carbon Fiber-Reinforced Polymer). The effectiveness of CFRP improves with more layers but decreases when the concrete strength increases.
- Load Capacity Prediction Model: A model was developed to estimate the load capacity of FRP-wrapped CFST columns. It works well for columns with moderate FRP confinement but tends to overestimate strength when FRP confinement is very strong. Further research is needed to improve accuracy in such cases.

This study highlights the benefits of FRP wrapping in improving CFST columns but also points to the need for better design models when using strong FRP confinement.

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