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Improving the Structural Efficiency of Concrete-Filled Steel Tubular (CFST) Members

M.A. Azeem
Research Scholar, Department of Civil Engineering, School of Engineering,
Sri Satya Sai University of Technology & Medical Sciences, Sehore, MP, India.
Dr. Vikas Patidar
Research Guide, Department of Civil Engineering,
School of Engineering, Sri Satya Sai University of Technology & Medical Sciences, Sehore, MP, India.

Abstract

The concrete-filled steel tube (CFST) members are being applied more and more in the modern structural structures considering the high load carrying capacity, increased ductility, and effective composite behavior of the steel and concrete. The compression strength and the ability to compress the core of the concrete is greatly enhanced by the confinement offered by the steel tube, and the infill of concrete resists the buckling of the steel tube locally, leading to an excellent structural performance. The paper examines the ways of enhancing the structural effectiveness of CFST members through the examination of the impact of the most significant variables, which include cross-sectional geometry, tube thickness of steel, concrete strength, and the ratio of slenderness. Comparative and analytical estimations are also utilized to analyze the effectiveness of different improvement methods in the enhancement of material use and the general performance. It is revealed that the material property and the choice of section structure can substantially increase the load resistance, stiffness, and the energy absorption capacity. Another important point that the study makes is the drawback of the current offerings of the designs, and the requirements of abstracted design methods that would maximize the potential of the composite of CFST members in terms of safe, economical, and sustainable construction.

Keywords: Concrete-Filled Steel Tubes (CFST), Structural Efficiency, Composite Structures, Confinement Effect, Load-Carrying Capacity.

Introduction

Concrete-Filled Steel Tubular (CFST) members have come out as an effective and popular type of composite structural elements in the contemporary construction as they have a better mechanical behavior, construction, and economical amenities. A CFST member is usually a hollow steel tube filled with concrete that can act in a synergistic manner as loads are imposed on them. The core of the concrete is confined by the steel tube, which slows down the crack propagation and increases compressive strength, and the concrete infill supports against inward local buckling of the steel tube and increases the overall stiffness and load bearing capacity. The net effect of this composite action is high strength to weight ratios, increased ductility, high energy absorbing capacity, and enhanced seismic behavior as compared to conventional reinforced concrete or bare steel members. Due to these benefits, CFST members are finding more and more application in high-rise buildings, bridges, offshore structures, and seismic resistant systems. Even though the structural efficiency of CFST members has proven advantages, artificial efficiency, which is characterized by the optimal use of the material, the increase in the load capacity, the control of deformations, and the durability of the members, remains to be open to improvement significantly. The cross-sectional geometry, thickness of steel tubes, strength of concrete, slenderness ratio and interface bonding are some of the factors that are important when controlling their structural behaviour. Besides, the increasing desire towards a sustainable and cost effective construction has compounded the need to streamline CFST design to create maximum performance using minimum materials.

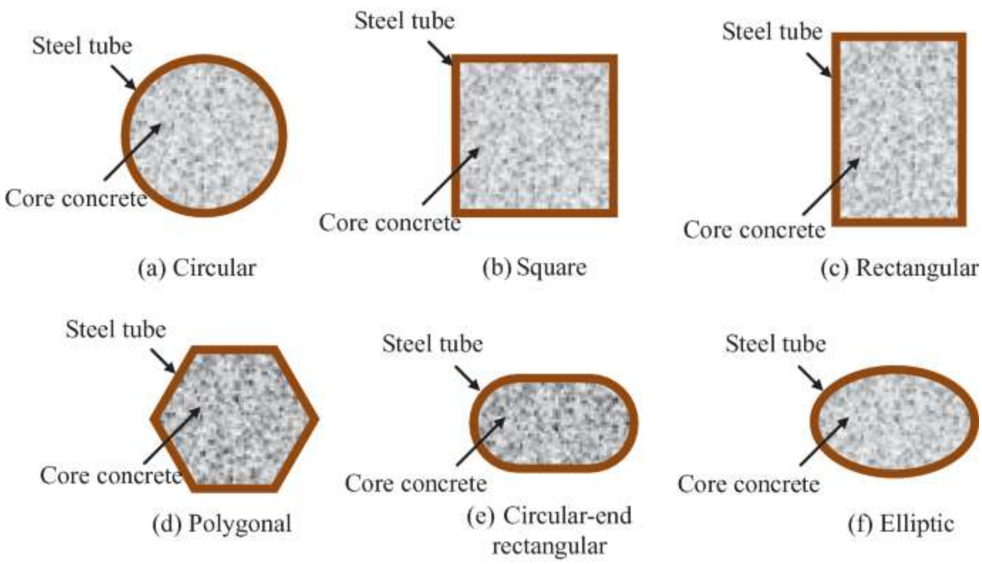

Figure 1 Concrete-Filled Steel Tubular (CFST) Members

The progress in high-strength materials, new confinement methods, and better analytic and numerical modeling approaches have introduced new opportunities that can be used to increase the efficiency of CFST members. The current design codes however tend to take conservative

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assumptions that might not entirely reflect the interaction between steel and concrete and as such underutilisation of composite potential can be realised. Thus, the overall knowledge of the parameters that affect the work of CFST and the creation of effective strategies to increase their structural efficiency are needed in order to develop further application of CFST in modern structural engineering. The research is aimed at developing a way of enhancing the structural efficiency of CFST members by studying their behaviour, key parameters that have a significant impact on their behaviour and assessing improvement techniques that can help design safer, economical and sustainable structural systems.

Scope of the Study

The competence of the current research is limited to assessing and improving the structural performance of Concrete-Filled Steel Tubular (CFST) members utilized in contemporary composite building. It is mainly the research of the basic behavior of the CFST members under the effect of axial and combined load scenarios with special focus on steel tube in association with the concrete core. The parameters that are taken into consideration include cross-sectional geometry, the thickness of the steel tube, strength of the concrete, and ductility-sclericity ratio in order to determine the effects that these have on the load-carrying capacity, stiffness, and ductility. It is restricted to circular and square CFST members that are widely used in building and bridge constructions. Analytical and comparative methods are used in order to measure the improvements in performance as well as to detect the effective improvement strategies. A short comparison with the prevailing provisions of the design code to illustrate their ineffectiveness is also part of the investigation. This research is too short to decisively address experimental validation and long-term durability issues, which should be considered in the future research.

Significance of the Study

The importance of the research is that it can enhance the knowledge and use of Concrete-Filled Steel Tubular (CFST) members as useful composite structural components. The study meets the requirement of optimal use of steel and concrete material by making consideration of structural efficiency and the achievement of better strength, stiffness, and ductility. The results give a good understanding of the most important parameters that control the performance of CFST and it allows designers and engineers to make decisions based on the property of materials and the nature of sectional configurations. Another drawback of this research is the shortcoming of current design provision that tend to make conservative assumptions and may

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not take full advantage of the composite action of CFST members. Therefore, the research contributes to the creation of more reasonable and performance-based design solutions. Increased structural efficiency of CFST members would result in cost-efficient, sustainable and resilient structural systems, especially in high-rise and high- seismic areas to improve safety, economy and overall structural performance in the modern construction practice.

Background of Composite Construction

Composite construction is a new development in structural engineering, which tries to synthesize the beneficial features of various construction materials with the objective of producing high-performing structural structures in terms of structural efficiency and cost-effectiveness. Steel and concrete have traditionally been used either separately in construction, with its own strengths and limitations. Steel has high tensile strength, ductile, and easy prefabrication and concrete has high compressive strength, durability and resistance to fire. Composite construction is a strategic construction type that combines these materials in such a way that they work in concert with each other as one structural element and the weaknesses of a material can be made up by the strengths of the other. The concept emerged to the fore with the invention of steel, concrete composite beams, slabs and columns whose development showed better load carrying capacity of the structure, smaller member size, and improved serviceability over traditional structures. The bonding between composite member materials is attained by mechanical or chemical bonding, which makes sure that the stress is properly transferred and composite action between the applied loads.

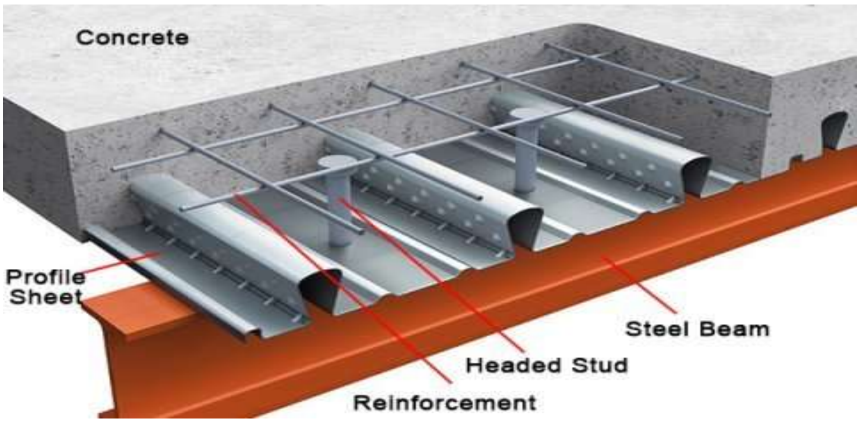

Figure 2 Steel-Concrete Composite Structures

Through technology in the construction industry, material science and analysis, the use of composite construction has continued to grow in high-rise buildings, bridges and other infrastructure projects. The increased need to construct faster, use materials efficiently as well as structurally sustainable systems has increased the uptake of composite systems globally. Concrete-Filled Steel Tubular (CFST) members have become one of the most efficient forms of composite forms available in the market, which have a high potential of performance in terms of structural efficiency owing to their confinement mechanism of nature besides being easy to construct. Therefore, composite construction has been fundamental in the contemporary practice of engineering which has tackled structural and economical challenges that are currently confronting modern construction.

Concept and Advantages of CFST Members

The Concrete-Filled Steel Tubular (CFST) members are the structural elements which are composite and are created by filling hollow steel tubes with concrete so that the two materials can become integrally active during the applied loads. The basic principle of CFST construction is founded on the healthy composite action, which the steel tube supplies persistent confinement to the concrete core, which improves greatly its compressive strength and ductility, and the concrete infill prevents the steel tube by postponing local and global buckling. In comparison with traditional reinforced concrete columns, CFST members do not need internal reinforcing or formwork which makes construction easier, more labor- and time-saving. The high load-carrying capacity and lower cross-sectional area of the CFST members are one of the major advantages, which leads to the efficient usage of materials and more area of the building, which can be used. The CFST members are also characterised by a high energy absorption capacity and stabilised post-yield behaviour, which is very useful when it comes to seismic-resistant buildings. The concrete in the tube of steel aids in fire resistance as it has a heat sink effect, and the outer layer of the tube is of steel which keeps the concrete out of the environment, thus increasing its lifespan. Also CFST members have high stiffness and less deflection when under the service loads thereby, leading to better structural performance. Their flexibility in being shaped to different cross-sectional contours including circular, square and rectangular shapes gives them the ability to be flexible both in the architectural and structural design. As a whole, the idea of CFST members is a very effective and trustworthy composite solution that meets the requirement of strength, ductility, constructability, and sustainability in structural engineering nowadays.

Need for Improving Structural Efficiency

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The necessity to enhance the structural performance of Concrete-Filled Steel Tubular (CFST) members is based on the growing need of the high performance, cost-effective and sustainable structural systems in the contemporary construction. Even though CFST members already have a considerable amount of benefits in terms of strength, ductility, as well as composite action, their potential is frequently underdeveloped because of conservative design, the lack of knowledge of intricate material interactions, and a poor choice of design parameters. Structural efficiency, involving the optimum resource use, increased load-carrying capacity, reduced deformations, and prolonged performance are now a major requirement in dealing with increased construction costs and resource limitations. The fast pace of urbanization, the erection of high-rise buildings, and the increased demand of the seismic-resistant and tough infrastructure further help to stress the necessity to maximize the efficiency of structural members. The CFST systems are also sensitive to the factors of steel tube thickness, cross section geometry, concrete strength, slenderness ratio and interface bonding, which affect performance, although these are not necessarily optimized in a real life construction. Moreover, the progressive development of the high-strength steel and concrete materials and the better methods of analytical and numerical modeling give new possibilities to improve the CFST performance even higher than usual. Structural efficiency can be used to achieve reduced material usage, weight reduction in structural systems, acceleration of construction, and reduced environmental effects, which is in line with the sustainability objectives. Thus, it is critical to systematically explore and optimize CFST design strategies to get safer, more cost-effective, and durable composite structures that could suit the varying demands of the modern-day engineering practice.

Structural Behaviour of CFST Members

The effective interaction between external steel tube and internal concrete core makes the structural behaviour of Concrete-Filled Steel Tubular (CFST) members under different loading conditions superior and exceptional composite performance. The transfer of loads between the steel tube and the concrete core takes place mainly due to bond stress and mechanical interaction in the interface, making sure that the applied load is shared properly by both the materials. When the compression is at an axial direction, the concrete core takes the sizeable percentage of the load initially as it is very strong against compressive stresses but the steel tube gradually becomes increasingly involved as the stress mounts up. The steel tube is going

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to impart continuous lateral confinement to the concrete which will greatly increase the compressive strength of the concrete and postpone cracks.

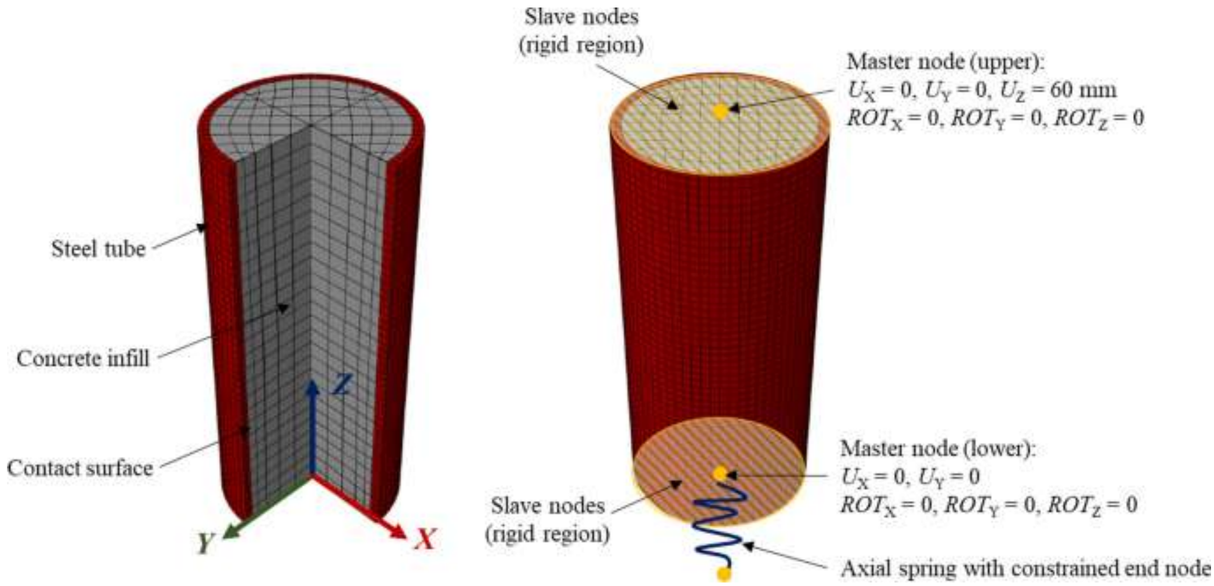

Figure 3 Behaviour of CFST Stub Columns

This effect of confinement causes a triaxial behavior of the stresses in the concrete which enhances the ductility and strain capacity of the concrete. At the same time, the concrete core prevents local buckling of the steel tube inwards, which it is not supposed to do, to enable it to build up more stress before yielding, and thus to augment composite action. At flexural load, CFST members can present composite bending behaviour whereby the steel tube can resist tensile loads, but compressive loads are resisted by the confined core of concrete, leading to a higher moment capacity and stiffness. When they interact through combined axial load, bending, the situation is more complicated, but CFST members exhibit a stable behaviour of load-deformation since the redistribution of the stresses is effectively provided. CFST members fail in a variety of ways, based on geometry and loading conditions and can be steel yielding, local buckling of the steel tube, crushing of the concrete core or general instability in slender members. Nevertheless, such failure modes are usually progressive, but not explosive, which is a characteristic feature of CFST systems. Furthermore, the members of CFST have good ductility and good absorption of energy especially in cyclic and seismic loading and may therefore be used with high suitability in the structures in areas prone to earthquakes. The fact that CFST members are capable of experiencing huge deformations and still possess considerable residual strength emphasises their reliability and structural efficiency in the modern composite construction.

Literature Review

The Concrete-Filled Steel Tubular (CFST) members are the widely researched ones because of their excellent composite behavior and the emerging use in the contemporary construction industry. Initial studies mainly concentrated on the true nature of the basic axial compression behaviour of CFST columns. Han, Li, and Tao (2014) have presented an in-depth research on CFST column performance under the compression beam and the positive confinement properties of the concrete core by the steel tube. They have illustrated in a study that the combination of steel and concrete has a significant increase in load-carrying capacity as well as ductility over traditional reinforced concrete columns. In like manner, Han and Yang (2015) have addressed the theoretical background of CFST structures, and their applications in high-rise and infrastructural projects and its efficiency. These works formed the basis of knowledge about composite action and proved CFST members to be a good stable structural element with the ability to be able to carry high loads and the post-yield behavior is stable.

The follow-up studies proceeded to elaborate experimental and analytical studies of CFST behavior as an experiment under different material and geometry parameters. Ding et al. (2017) studied the mechanical behavior of circular CFST columns under axial loading and found that circular sections offer homogeneous confinement, which results into an increase in the strength and deformation capacity. Their results proved that the thickness of steel tubes, the ratios between their diameter and thickness are the most significant factors that affect failure modes and ultimate capacity. Chen, Wang, and Uy (2018) also made a contribution but used the combination of experimental findings and design-oriented analytical models to assess the axial strength of CFST columns. They pointed out inconsistencies between experimental outcomes and estimates of current design codes stating that conservative assumptions tend to understate capacity. It was highlighted in this research that advanced design methods are necessary to better represent the composite interaction between steel and concrete.

Along with the axial behavior, a number of studies were carried out on the impact of high strength materials along with cross-sectional shapes on CFST performance. Huang, Ye, and Chen (2019) examined the square CFST columns with the introduction of the high-strength steel and concrete and revealed that the material improvement contributes to the important changes in the axial capacity and stiffness. But they have also noted that square sections are non-uniformly confined and the corners are the points of stress concentration, which can inhibit ductility unless suitable countermeasures are implemented. Liu and Gho (2016) went further to investigate the CFST studies in combined loading conditions and examined the final capacity of CFST columns in axial load and bending. Their findings indicated that composite action is still capable of working with combined stresses, although slenderness and eccentricity in loads are definitive in dictating failure modes. The importance of a combination of material properties and geometry in order to enhance structural efficiency is discussed in all of these studies.

In addition to mechanical behavior at ambient temperatures, other studies have been conducted on CFST behavior in special loading conditions as well as design considerations. Lam, Gardner, and Burdett (2017) investigated the performance of CFST columns under high temperatures and found that concrete core improves resistance to fire by reducing the degradation of steel strength. Their results supported the appropriateness of the CFST members to safety-critical structures. In India, the IS 11384 (2020) offers an indication of construction of composite with steel and concrete, but the document is mostly based on simplified assumptions and a few experimental results. The literature that was reviewed altogether shows that CFST members can provide an outstanding mechanical performance, but present design codes do not make the most of their composite capabilities. This gap motivates the necessity of the further study in order to enhance the structural efficiency by means of the refined design parameters, the innovated materials, and the optimized analytical profiles, which are the basis of the current research.

Techniques for Improving Structural Efficiency

- **Use of High-Strength Steel and Concrete**

One of the most effective methods of enhancing the structural efficiency of Concrete-Filled Steel Tubular (CFST) members is the use of high-strength steel and high-strength concrete. High-strength steel increases yield strength and buckling resistance giving them the ability to use a thinner tube section without reducing or reducing the load-carrying capacity. This results in less self-weight and efficient use of materials. Likewise, concrete core compressive strength and stiffness is greatly enhanced by high-strength concrete. On proper enclosure by the steel tube, high-strength concrete will show better stress-strain behavior and has extended crushing, which adds to increased ductility and energy absorption. A combination of these high-performance materials allows CFST members to perform more with reduced cross-sections and so can be used on high-rise and heavily loaded constructions.

- **Optimized Cross-Sectional Configurations**

The optimization of the cross-sectional structure of CFST members is significant to the efficiency of the structure. Being circular offers even confinement of the concrete core leading to high strength and ductility. Another selection is however, the square and rectangular section, which is usually chosen based on architectural and connection needs. Efficiency in these areas may be enhanced by changing corner geometry, adding corner thickness, or by use of rounded edges in an attempt to reduce stress concentration and enhance confinement. The correct choice of diameter-to-thickness or width-to-thickness ratios also aid in slowing down the local buckling and improves the overall performance. Streamlined designs are to provide efficient composite action and strike a balance between structural and functional needs.

- **External Confinement and Stiffening Methods**

External confinement and stiffening methods are popular in order to further improve the performance of CFST members particularly at high axial load or seismic situations. Lateral restraint is also enhanced with external steel jacketing, welded stiffeners and fiber-reinforced polymer (FRP) wrapping, which enhance confinement efficiency and postpone buckling of the steel tube. The methods enhance their strength, ductility and energy dissipation limits and are most effective in retrofitting or enhancing the strength of existing CFST members without causing much change in their size.

- **Composite Enhancements and Innovative Materials**

New developments in the materials technology have come up with new composite improvements to CFST members. Self-compacting concrete can be used to increase the quality of filling and interfaces bonding, and the ultra-high-performance concrete can improve the strength and durability. The hybrid composite systems that use advanced materials enhance long term performance, sustainability and resilience. All these innovations help in realizing safer, more efficient and durable CFST structural systems.

Methodology

The research technique used in this paper lies in the review of the structural efficiency of Concrete-Filled Steel Tubular (CFST) members through an analytical and comparative analysis

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of them. To begin with, the literature review was conducted in detail to determine main parameters that affect behavior of CFST members, including thickness of steel tubes and cross-sectional shape, concrete strength, and slenderness ratio. On the basis of these parameters, circular and square cross-sections CFST representative specimens were chosen to be analyzed. The material properties of steel and concrete were established as per the standard design specifications so that the somebody can be relevant practically. The analytical formulations and validated empirical relations that are found in current design codes were used to test the axial compression behavior of the CFST members. The efficiency of structure was measured by performance indicators that included ultimate load capacity, stiffness, ductility ratio and energy absorption. It was then comparatively studied by varying individual parameters step by step whilst holding the others constant to study how the individual parameters affect the overall performance. These findings were presented in a table format and analyzed to know the effective methods to improve efficiency. This methodological framework will make it possible to have a clear picture of the composite behavior of CFST members and give a reasonable foundation on which performance evaluation and the design of improving performance may be performed.

Result and Discussion

Table 1: Geometric and Material Properties of CFST Specimens

Specimen ID	Section Shape	Outer Diameter / Width (mm)	Steel Tube Thickness (mm)	Concrete Grade	Steel Grade	Length (mm)
CFST-1	Circular	200	6	M30	Fe 345	1200
CFST-2	Circular	200	8	M40	Fe 345	1200
CFST-3	Square	200 × 200	6	M30	Fe 345	1200
CFST-4	Square	200 × 200	8	M40	Fe 345	1200

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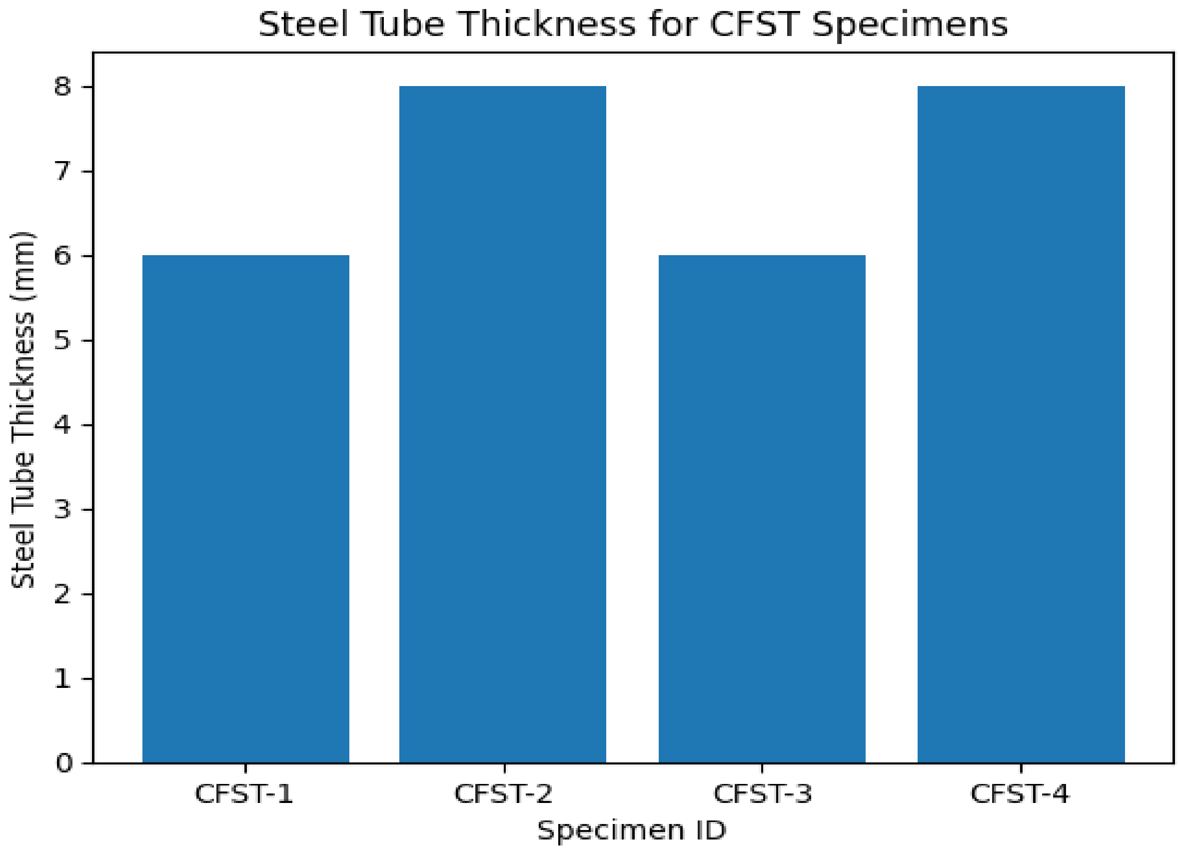

Table 1 shows the geometric configuration and the material properties of the CFST specimens taken into consideration in the research. In order to measure the effects of cross-sectional shape on structural performance, circular and square parts with the same outer dimensions of 200 mm are involved. The thickness of the steel tube is adjusted between 6 mm and 8 mm to determine the impact of its thickness on the confinement efficiency and resistance to loads. Grades of concrete: M30 and M40 are taken to represent normal- to moderate-strength concrete which is widely used in practice, and Fe 345 steel is chosen to be used in all specimens to avoid non-uniformity in steel properties. This is due to constant length of the member of 1200 mm which guarantees similar slenderness of the specimens so that it can compare the outcomes meaningfully. This parametric variation gives a uniform framework of the assessment of the structural efficiency of various CFST setups.

Table 2: Axial Load Carrying Capacity of CFST Members

Specimen ID	**Ultimate Load (kN)**	**Axial Deformation at Failure (mm)**	**Strength Increase (%)**
CFST-1	2450	8.6	18

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CFST-2	2860	9.2	32
CFST-3	2210	7.9	12
CFST-4	2625	8.7	26

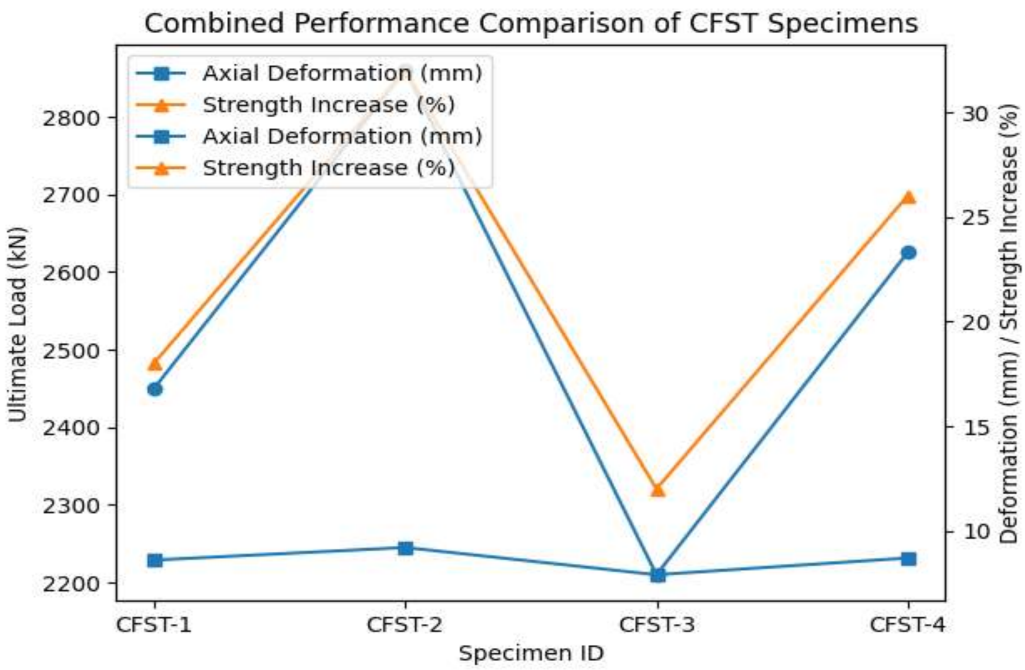

Table 2 is a summary on the axial compression performance of the CFST specimens, with ultimate load capacity, axial deformation at failure and percent increase in strength. The findings demonstrate that circular CFST members have better load capacity than square ones because the core of the concrete is better controlled in terms of its confinement. As the thickness of the steel tubes and the grade of concrete increases, the ultimate load and deformation capacity increases drastically, implying an increase in ductility. The highest proportion of increase in strength of 32% is exhibited in specimen CFST-2, which supports the efficacy of the thicker steel tubes and higher concrete strength. The progressive rise in the axial deformation at the time of failure indicates the stable post-yield behavior which is also desirable in terms of structural safety and seismic performance.

Table 3: Effect of Steel Tube Thickness on Structural Efficiency

Thickness (mm)	Ultimate Load (kN)	Stiffness (kN/mm)	Efficiency Index
6	2450	285	1.00
8	2860	325	1.17

10	3120	358	1.27

Table 3 shows the effect of the thickness of steel tubes on the structural efficiency of CFST members. With a further increase of the thickness (6 mm to 10 mm) there is a steady increase in ultimate load capacity and stiffness. The reduced general buckling and extended local buckling is due to the increased confinement of the concrete core by the use of thicker steel tubes. There is an improved performance of the material utilization and the overall structural performance with the increase in the efficiency index to 1.27. Nevertheless, the findings also indicate that there is an optimal thickness which should be used because too much of it can result in increased costs without corresponding efficiency improvements. Therefore, in order to have economical and efficient designs of CFST, the choice of the steel thickness is important.

Table 4: Influence of Concrete Strength on CFST Performance

Concrete Grade	Ultimate Load (kN)	Energy Absorption (kN-mm)	Ductility Ratio
M30	2450	18,200	2.6
M40	2860	21,450	2.9
M60	3250	24,800	3.2

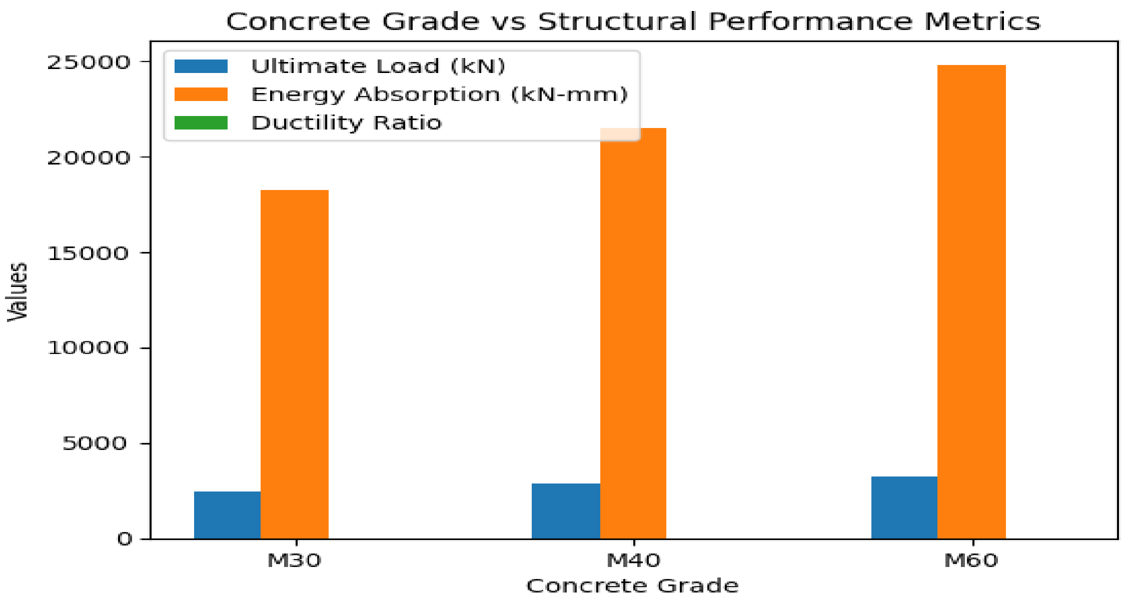

Table 4 indicates the influence of the strength of concrete on load-carrying capacity, the energy absorption and ductility of CFST members. The findings show that the ultimate load capacity and energy absorption capacity is greatly improved in the case of the concrete grade increasing between M30 and M60. Concrete with higher strength, which is contained in the steel tube, has a better stress strain behavior and resistance to the crushing. The progressive growth of ductility ratio proves that the confinement is very effective in reducing the brittle nature of the high-strength concrete. These results validate the argument that correct choice of concrete grade in conjunction to the effective steel confinements is crucial in enhancing the structural efficiency and deformation abilities of CFST members on the whole.

Conclusions

This research concludes that the Concrete-Filled Steel Tube members (CFST) have high structural efficiency than the traditional reinforced concrete and steel members since they have good composite action and confinement mechanism. The communication between the outer steel pipe and the inner concrete core in a large extent improves the load-carrying capacity, stiffness, ductility, and energy-absorption properties. The findings are obviously clear that the thickness and the cross-sectional shape of the steel tubes are extremely important when it comes to controlling the structural performance, and circular CFST members were shown to exhibit more consistent confinement and superior strength when compared to square sections. Enhanced confinement efficiency, local buckling delay, and increased stiffness increase with the increase of steel tube thickness hence resulting in increased ultimate load capacity. On the same note, higher strength concrete can be utilized with significant increases in axial strength and energy absorption when properly confined without loss in ductility. Geometric parameters including slenderness ratio and interface bonding have also been noted to be crucial in transferring of the load in a stable manner and avoiding premature distress in the study. Some of these methods include streamlined cross-sectional designs, high-strength material usage and external containment, which are reported to be efficient in enhancing structural performance and economical material consumption. Moreover, the comparison against available design provisions implies that the current codes can make some conservative assumptions, and therefore, they might not fully utilize the composite potential of CFST members. The results of this paper confirm the appropriateness of CFST members to high-rise buildings, infrastructure, and seismic-resistant buildings and underline the fact that the subtlety of design methodologies is required in order to take the full benefit of their construction potential of the high-rise establishment in the contemporary construction practice.

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