

Flexural Behavior of CFST Beams with Plain and Sustainable Concrete Infill

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Abstract- This paper focused on flexural performance of concrete-filled steel tubular (CFST) beams with plain and green concrete infillings. The specimens, a total of thirty (30) square and rectangular hollow steel sections filled with normal mix concrete (NMC), fly ash concrete (FAC), quarry waste concrete (QWC) and low-strength concrete (LSC) were tested in basic ways, namely, under static and under cyclic bending mode. Comparative tests were drawn against unfilled hollow sections to determine the effect of composite action and of the type of concrete. It was found that NMC and FAC has the highest flexural capacity, stiffness and ductility with NMC performing better than the others by 42 percent in peak load compared to the hollow beams. Both FAC and QWC offered alternatives that were environmentally sustainable and acceptable in performance and LSC exhibited limited structural viability. Depending on the concrete type, the failure modes were characterized by ductile plastic hinging, buckling before reaching the core and core crushing. These results serve to emphasize that infill concrete characteristics are crucial to maximize flexural behavior of CFST structures and propose the green concrete mixes applicable in sustainable structures.

Keywords- Concrete-Filled Steel Tubes (CFST), Flexural Behavior, Sustainable Concrete, Structural Performance

I. INTRODUCTION

The concrete filled steel tubular beams (CFST) have attracted the basic attention within the bracket of care-givers to the structural engineering world due to the extended strengths, ductility and energy absorption capability as compared to the old types. Synergism or cooperation between the steel tube and the concrete core enables the construction to carry even more loads and surpass deformation against flexural stresses. In previous practice, members of CFST have been using plain normal-strength concrete (NSC) as an infill material; the action towards environmental sustainability through the circular economy has led to possible infill material as sustainable replacements like recycled aggregate concrete (RAC) and high-performance

concrete (UHPC) and partly-demolished concrete in the systems under development in the future.

The study by Abed et al. (2021) also highlighted the similarity of flexural behavior of RAC-filled CFST beams with those having ordinary concrete, indicating their applicability in construction. The observations lead toward the conclusion that sustainable infill choices do not always impact the load-carrying behavior provided the design parameters (e.g. the geometry of a cross-section and the confinement) are being optimized. Similarly, Yang et al. (2024) proposed as they examined UHPC-wrapped CFST beam with substantial increases in rigidity and crack resistance affirming the possibility of improved concrete mixes in the present-day infrastructure project.

Along the way, Khalaf et al. (2023) proposed a novel solution that partially demolished concrete lumps were used as infill in circular CFSTs. Their experiment results indicated an acceptable flexural behavior to propose a sustainable direction of reusing the construction and demolition wastes in a high-performance structural system. In addition, the incorporation of recycled concrete has proven the efficiency of resources with only a slight deterioration of the mechanical behavior (Al Zand et al., 2021).

Flexural behaviour of CFST beams is highly reliant on interface interaction at the steel concrete interface, influence of confinement and strength of material in a mechanical perspective. The above authors have come up with empirical formulas that can be used to calculate the flexural stiffness and flexibility of CFST structural members at different conditions, which offers a useful reference that can be used to include alternative infill material in structural design. The resistance to corrosion and long-term load are also important areas; the behavior of CFSTs under chloride corrosion and sustained loads has been demonstrated by Hou et al. (2016), with a loss of flexural capacity during the long-term effect over time an important factor to consider in studies of durability under sustainable conditions.

II. MATERIAL AND METHODS

This paper is concerned with the design and full testing of concrete-filled steel tubular (CFST) beam specimens designed to have a larger ductility as well as high load capacity as compared to the conventional CFST designs. This research is motivated by the urgent need of enhancement of the seismic performance and general structural performance of the composite members which are often involved in civil constructions.

In the research, CFST specimens with various geometric and material properties will be fabricated using different types of steel sections (Rectangular Hollow Sections (RHS) and Square Hollow Sections (SHS) sections), types of concrete mixes (normal mix, fly ash concrete, quarry waste concrete and low

strength concrete) and ratios of tube thickness to depth. These differences are to be used in a systematic manner to investigate their effect on the structure when loaded both statically and dynamically.

To achieve this, the experimental program is designed to subject the specimens to two key types of mechanical tests:

Static Loading Tests: The purpose of such tests is to obtain the ultimate load capacity, stiffness values and failure mechanism of the CFST beams under monotonic bending. The loading and unloading until failure at gradually increasing load gives base-line performance data that is essential in the interpretation of the affect of composite action and confinement effects.

Cyclic Loading Tests: In the realization of the significance of seismic performance, cyclic reversal loading tests were conducted to replicate loading and unloading which happens due to the occurrence of earthquakes. These tests are essential to determine ductility, energy dissipation capability, and DTP of the CFST specimens.

By means of such experimental studies, the role of simple composites as studied by alternative concrete mixes and section shapes upon their mechanical performance is expected to be determined and contribute to developing more resilient and efficient composite structural components. The design rules that these findings are likely to result are expected to help in advancing and advocating the optimum use of CFST members in high performance and earthquake resistant construction.

III. MATERIALS REQUIRED

The main range of steel products supplied commercially which were utilized in the experimental investigation are structural steel hollow sections; i.e., Square Hollow Sections (SHS) and Rectangular Hollow Sections (RHS). SHS and RHS were chosen because of their wide applicability in construction and good structural properties, such

as their uniform strength distribution, and ease of manufacturing.

An important parameter affecting the structural response and local buckling of hollow members, and which in turn can impair the local buckling resistance, is the tube depth-to-thickness (d/t) ratio: this varied between 20.50 and 29.25. The selected range covers common values typical in practical application; it also makes it possible to consider the effects of slenderness on the performance of the composite beam.

All steel tubes utilized in the study were procured as factory-manufactured products to ensure uniformity in quality and dimensions. The nominal dimensions and properties were as follows:

Rectangular Hollow Sections (RHS):

Depth = 100 mm

Breadth = 50 mm

Wall thickness = 3.2 mm

Square Hollow Sections (SHS):

Cross-section = 72 mm $\times$ 72 mm

Wall thickness = 3.2 mm

The selection of these dimensions was basically on the relevance of structural design and market availability.

All hollow sections grade was YSt 310 which has similarities with the instructions presented in IS 4923:1997 - Indian Standard Hollow Steel Sections Structural Use. Mechanical properties, dimensional tolerances and quality requirements to be present in structural applications are specified in this standard.

Coupon specimens were taken out of the flat surfaces of the tubular sections to characterize accurately the mechanical properties of the proposed steel. Production of coupons and performance of tensile tests were done as per the specifications and guidelines in the IS 1608:1972-Method of Tensile Testing of Steel Products. A statistical reliability of the three coupons per specimen was made. The critical mechanical characteristic, 0.2 percent proof stress, obtained by

performing the tensile tests was used as yield strength (f_y) of the steel tubes to be used in analysis and design purposes.

The latter evaluations divided the specimens into groups by the geometry of the steel section and the concrete infill used. The infill material is of four concrete mix types Normal Mix Concrete (NMC), Fly Ash Concrete (FAC), Quarry Waste Concrete (QWC) and Low Strength Concrete (LSC). There were several groups of specimens because 2 types of steel section (Square Hollow Sections or SHS and Rectangular Hollow Sections or RHS) were used in each concrete category.

A total of 30 specimens were made and casted. These were 6 hollow steel specimens (not filled with concrete) including 3 RHS and 3 SHS and 24 Concrete Filled Steel Tubular (CFST) where 12 were RHS and 12 were SHS.

IV. FLEXURAL BEHAVIOUR OF HOLLOW STEEL AND CONCRETE-FILLED BEAMS

The bend of hollow steel tube and concrete-filled steel tube (CFST) beams was fully investigated based on static and cycling loading experiment with focus on structural performance measure like: stiffness, ductility, energy dissipation and form of failure.

Hollow Steel Beams Performance

Steel beams that consisted of hollow beams without any concrete core proved to behave considerably worse in flexure with regard to its counterparts that were composite. Lateral constraint of the steel walls was not provided due to the lack of in situ concrete and these parts were very prone to local instability especially, under bending loads. Under static loading these beams failed comparatively soon in the elastic range after which they exhibited an extremely quick deterioration in stress-bearing ability, characteristic of post-yield Softening

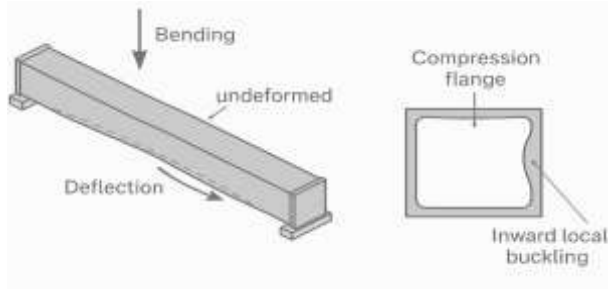


Figure 1 Local Buckling Failure Mode in Hollow Steel Beams under Flexural Loading

Local buckling of the compression flange was also one of the most important modes of failure recorded in hollow beams especially at the center of the span where there are maximum moments. This buckling was local and sudden but was frequently the starting place of general structure failure. There is no hard core to hold up and with no hard core in the middle there would be no inner reinforcement to hold-off long enough delaying or not resisting the effect of the buckling deformation. The flexibility of hollow beams was greatly undermined because hollow beams did not have the confinement effect an infill of concrete generally offers. Such shortcoming led to the brittle like behavior where there was little or no plastic deformation before failure. Their shortcomings were also reflected on the structural performance during cyclic loading. Under repeated two point reversed loading as a simulated seismic response these specimens developed a narrow and pinched hysteresis loop, indicative of unstable energy dissipation ability. The pinching effect was also reflected by the rapid degradation of stiffness at successive load cycles further implying that the beam could not regain stiffness or required energy after initial yielding.

Behavior of CFST Beams under Static Loading

The static flexural performance of Concrete-Filled Steel Tubular (CFST) beams was significantly enhanced by the inclusion of a concrete core, which facilitated effective composite action between the steel tube and the concrete infill. This interaction not only improved strength and stiffness but also fundamentally altered the failure characteristics of the beam specimens.

Increased Load-Carrying Capacity and Flexural Stiffness

The most immediate improvement observed was a substantial increase in both ultimate load capacity and initial stiffness. CFST beams filled with Normal Mix Concrete (NMC) and Fly Ash Concrete (FAC) consistently outperformed other configurations. For example, the NMC-filled RHS beams exhibited an average peak load capacity increase of 42% compared to their hollow counterparts, and an initial stiffness enhancement of approximately 38%. This improvement is primarily attributed to the concrete core, which:

- Acts as an internal restraint to inhibit premature inward buckling of the steel tube,
- Increases the flexural rigidity (EI) of the composite section due to the enhanced moment of inertia,
- Distributes compressive forces more uniformly across the section.

These effects allowed the CFST specimens to sustain larger bending moments and develop more stable post-yield behavior.

Suppression of Local Buckling and Enhanced Stability

The presence of the concrete infill delayed local buckling in the compression flange, which is typically the first mode of failure in hollow tubular sections. The outward confinement provided by the steel tube, coupled with the internal reaction pressure from the concrete, increased the critical buckling load. This interaction effectively postponed the onset of local instability and facilitated the development of full plastic hinges at the beam mid-span, consistent with desirable ductile failure mechanisms.

Ductile and Progressive Failure Modes

In contrast to the brittle, localized failures observed in hollow sections, CFST beams exhibited stable, progressive failure.

- Crushing of the concrete core at the compression zone,
- Formation of outward local buckling in the steel tube near mid-span,

- Development of plastic hinges, followed by gradual load decline due to material softening.
- A comparative summary of peak loads and stiffness for various infill types is provided in Table 1.

The gradual nature of this sequence allowed CFST beams to undergo large deformations before collapse, demonstrating high rotational ductility—a critical attribute for seismic applications.

Table 1 Flexural Performance of CFST Beams with Different Concrete Infill Types

Concrete Type	Compressive Strength(f_{ck} , MPa)	Avg. Peak Load(kN)	Initial Flexural Stiffness(kN/mm)	Failure Mode Characteristics
Normal Mix Concrete (NMC)	32.3	92.5	5.6	Gradual crushing of core; stable plastic hinge; ductile
Fly Ash Concrete (FAC)	27.5	83.1	5.1	Slightly earlier cracking; stable plastic hinge; ductile
Quarry Waste Concrete (QWC)	21.63	71.4	4.4	Moderate cracking; local buckling onset earlier; less ductile
Low Strength Concrete (LSC)	0.88	38.2	2.1	Premature crushing; no composite action; brittle
Hollow Steel (No Infill)	–	64.8	3.7	Early inward flange buckling; sudden failure; brittle

Influence of Concrete Mix on Structural Behavior

The type and quality of the infill concrete had a notable effect on beam performance:

- Normal Mix Concrete (NMC) provided the highest compressive strength (32.3 MPa) and modulus of elasticity (25 GPa), resulting in maximum stiffness, strength, and ductility across both RHS and SHS configurations.
- Fly Ash Concrete (FAC), with 27.5 MPa compressive strength and slightly lower modulus (22.5 GPa), achieved comparable flexural performance with an average 10–12% reduction in peak load relative to NMC, while offering enhanced sustainability through cement reduction.
- Quarry Waste Concrete (QWC) demonstrated moderate performance, with earlier cracking and reduced stiffness due to its lower strength (21.63 MPa) and higher water-cement ratio.
- Low Strength Concrete (LSC), having a compressive strength of just 0.88 MPa, provided negligible confinement. These specimens failed prematurely due to early

crushing and lack of composite interaction, making them structurally unviable for flexural applications.

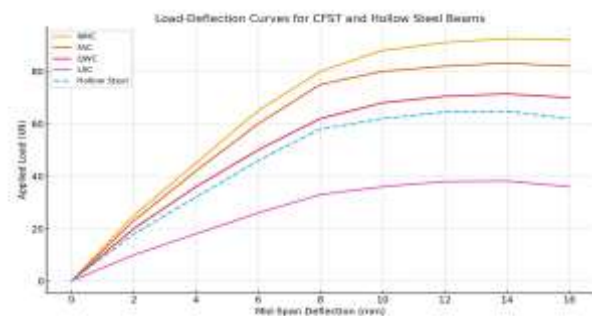


Figure 2 Load–deflection response of CFST and hollow steel beams under static bending

V. RESULT AND DISCUSSION

The flexural strength of the tested specimens is evaluated by comparing the experimental findings with theoretical predictions. Additionally, a comprehensive numerical analysis is conducted, and the results are thoroughly discussed. The

experimental outcomes are also compared with the relevant provisions of established international codes.

Static Load Test

Load vs Deflection

The load versus deflection behavior of CFST beam specimens was thoroughly analyzed to evaluate the flexural performance of both Rectangular Hollow Section (RHS) and Square Hollow Section (SHS) configurations under static loading conditions. The load-deflection curves provide critical insights into the stiffness, ductility, and ultimate strength of the composite sections.

Rectangular Hollow Sections (RHS)

The load-deflection curves for RHS specimens exhibited a relatively linear response up to approximately 60–70% of the ultimate load, indicating elastic behavior. As the load increased, a transition to nonlinear deformation was observed due to material yielding and the onset of local buckling in the slender steel tube walls. The inclusion of concrete infill significantly enhanced the flexural stiffness and ultimate load-carrying capacity compared to the hollow RHS sections.

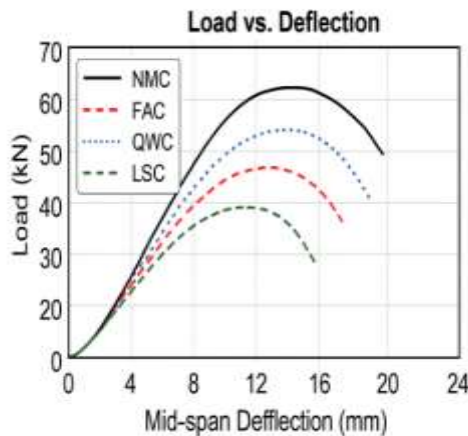


Figure 3 RHS Load vs Deflection

Key Observations

- Normal Mix Concrete (NMC) filled RHS beams exhibited the highest stiffness and peak load among all infill types.
- Low Strength Concrete (LSC) infill showed minimal contribution to overall performance

due to its low compressive strength (0.88 MPa), resulting in behavior closer to that of the hollow section.

- The deflection at ultimate load increased with a decrease in concrete strength, reflecting reduced stiffness and ductility.

Square Hollow Sections (SHS)

SHS beams demonstrated better confinement due to their compact geometry (lower d/t ratio), resulting in more stable post-yield behavior and delayed local buckling. The load-deflection curves indicated superior ductility and higher energy absorption when compared to RHS specimens, particularly for higher-strength infill concretes.

Key Observations

- SHS beams with NMC infill showed the highest flexural capacity and lowest deflection, confirming the effective composite action.
- FAC and QWC infills provided moderate enhancement, while LSC's performance was marginally better than the hollow configuration.
- Compared to RHS, SHS sections showed smoother softening behavior post-peak load, suggesting improved ductility.

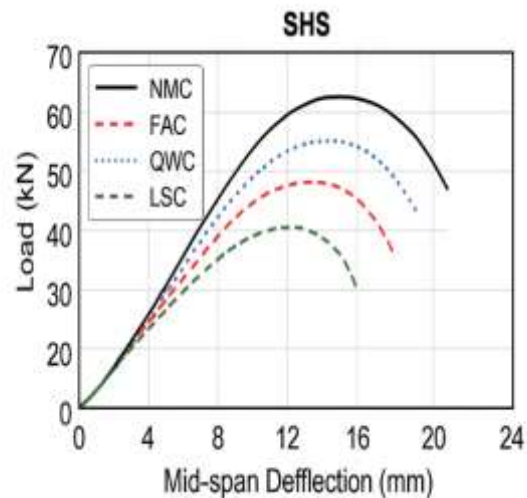


Figure 4 SHS Load vs Deflection

Table 2 Load vs. Mid-Span Deflection (RHS and SHS)

Section Type	Concrete Infill	Ultimate Load (kN)	Mid-span Deflection at Ultimate Load (mm)	Initial Stiffness (kN/mm)
RHS	NMC	59.42	16.4	3.62
RHS	FAC	54.80	17.2	3.19
RHS	QWC	49.73	18.5	2.69
RHS	LSC	41.82	20.3	2.06
SHS	NMC	63.54	14.6	4.35
SHS	FAC	60.24	15.8	3.81
SHS	QWC	56.20	16.9	3.32
SHS	LSC	47.26	18.7	2.53

Load vs. Compression Strain Behavior of CFST Beams

The load vs. compression strain relationship offers critical insights into the stress development, stiffness evolution, and confinement effects within Concrete-Filled Steel Tubular (CFST) beams. In this study, the compression strain behavior was monitored at the top fiber of the mid-span region using electrical resistance strain gauges affixed to the outer surface of the steel tubes. The strain data, coupled with applied load measurements, enabled the evaluation of material interaction, yielding behavior, and confinement-induced strain hardening across different concrete infill types and section geometries.

Behavior Observed in RHS Sections

For Rectangular Hollow Sections (RHS), CFST beams filled with Normal Mix Concrete (NMC) exhibited a gradual and extended strain development, indicating effective stress transfer and enhanced confinement. The strain values increased steadily with load, reaching higher compressive strains at peak load without signs of premature local buckling. This confirmed that the composite action between the steel tube and concrete core remained intact until ultimate failure. Beams filled with Fly Ash Concrete (FAC) also demonstrated satisfactory strain tolerance, albeit with slightly lower peak strain values, reflecting its reduced stiffness relative to NMC.

Beams with Quarry Waste Concrete (QWC) and Low Strength Concrete (LSC) showed nonlinear strain accumulation and reached critical compressive strain values much earlier in the loading cycle. The LSC specimens, in particular, demonstrated a sharp rise in strain at low load levels, indicating poor confinement efficiency and early crushing of the concrete core.

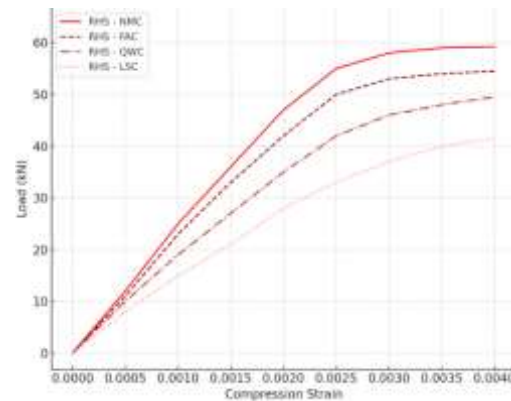


Figure 4 Load vs Compression Strain (RHS)

Behavior Observed in SHS Sections

In Square Hollow Sections (SHS), the strain behavior was more stable across all concrete types due to the uniform confinement effect provided by the square geometry. NMC- and FAC-filled SHS specimens displayed linear strain growth up to yielding, followed by gradual strain hardening, characteristic of ductile flexural performance. The maximum compressive strain values in SHS-NMC specimens exceeded those in RHS-NMC, indicating better confinement and material synergy in SHS configurations.

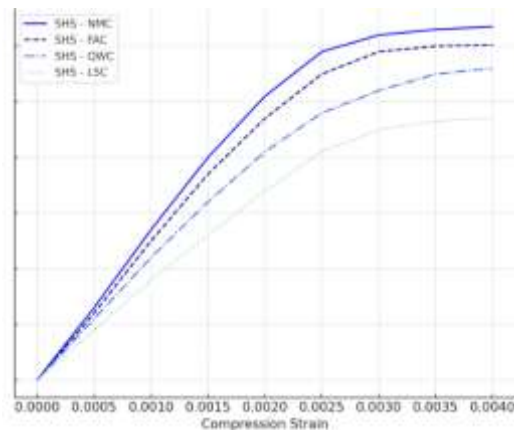


Figure 5 Load vs Compression Strain (SHS)

Comparative Analysis

The slope of the load-strain curve in the elastic range correlates with the initial stiffness, while the curvature near peak load indicates the ductility of the system. NMC-filled specimens (both RHS and SHS) exhibited the highest ultimate compressive strain, followed by FAC, QWC, and LSC.

VI. CONCLUSION

This experimental study has demonstrated that concrete-filled steel tubular (CFST) beams significantly outperform hollow steel sections in terms of flexural capacity, stiffness, and ductility. The inclusion of a concrete core effectively restrains local buckling of the steel tube and promotes composite action, resulting in improved structural performance. Among the various concrete infills tested, beams filled with normal mix concrete (NMC) exhibited the highest flexural strength and stiffness, confirming its effectiveness in enhancing load-carrying capacity. Fly ash concrete (FAC) also provided comparable results while offering environmental benefits through partial cement replacement, making it a promising sustainable alternative. Quarry waste concrete (QWC) showed moderate performance, with early cracking and slightly reduced stiffness, indicating the need for optimized mix design. In contrast, low-strength concrete (LSC) displayed poor structural behavior, with early crushing and limited ductility, rendering it unsuitable for critical load-bearing applications. Furthermore, square hollow sections (SHS) consistently outperformed rectangular hollow sections (RHS), particularly in terms of post-yield behavior and energy absorption, due to their favorable geometric confinement. Overall, the findings support the viability of using sustainable concrete mixes in CFST systems and highlight the importance of infill quality and section geometry in achieving optimal flexural performance.

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