Experimental Investigation of Concrete-filled Steel Tube Beams with Transverse Openings

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ABSTRACT

Modern building construction requires numerous pipes and ducts for services like air conditioning and electricity, often accommodated by web openings in beams. This study investigates the structural performance of Concrete-Filled Steel Tube (CFST) beams with transverse openings, which can affect their load-carrying capacity and behavior. Eight CFST beams and four Hollow Steel Tube (HST) beams were tested under two concentrated loads, including four CFST and two HST beams with transverse openings. The present research examines how openings impact load capacity, failure modes, ductility, strain, and Energy Absorption (EA) across varying cross-sections and Depth-to-thickness (D/t) ratios. The results show that transverse openings significantly affect CFST beams more than HST beams. The load-carrying capacity of CFST beams was reduced by up to 18.6%, while HST beams exhibited reductions of only up to 3.77%. Ductility and EA followed similar trends, with CFST beams experiencing reductions of up to 20% in ductility and 30.7% in EA. The HST beams showed relatively minor decreases of 2.54% in ductility and 14.1% in EA. The failure of CFST beams with openings was characterized by steel rupture through the openings. The effect of openings increased with higher D/t ratios. Despite the reductions caused by the openings, the overall enhancement in all studied aspects provided by the concrete filling in CFST beams with transverse openings remained significant.

Keywords-CFST; composite beams; confinement; openings

I. INTRODUCTION

Composite structures offer better and more cost-effective solutions compared to using individual materials separately. A composite material is formed by combining two or more distinct materials, creating a unique substance that provides several benefits compared to individual materials [1]. CFSTs are composite elements created by filling an HST with concrete to enhance its mechanical properties. This integration takes advantage of the concrete's high compressive strength and the steel's superior flexural strength, resulting in a structure with improved deformation resistance [2]. By filling the steel tube with concrete, the structure's resistance to global buckling is improved, and local buckling is minimized. This confinement effect also enhances the concrete compressive strength [3, 4]. CFST columns are extensively adopted in high-rise buildings, bridges, railway decks, and seismic-resistant structures. They are also used for supporting storage tanks due to their high load-bearing capacity, superior ductility, and exceptional fire resistance [5-7]. Recent studies on CFST members subjected to pure bending reveal that CFST beams provide better characteristics compared to HSTs, including enhanced ductility, stiffness, fire resistance, flexural strength, and EA [8-10]. Additionally, CFSTs enable rapid construction by eliminating the need for reinforcement and traditional formwork required in reinforced concrete structures, allowing for efficient filling and forming. Concrete-filled steel structures offer an optimal solution in scenarios involving long-span structural members with constrained cross-sectional dimensions, particularly when seismic forces, oscillations, or vibrations are a subject of concern [11].

A network of pipes and ducts is often necessary to accommodate essential utilities, including electricity, telephony, water supply, sewage, and air conditioning. These utilities are typically positioned beneath the floor, and covering them with a suspended ceiling can result in additional unused space on each floor. Incorporating openings in beams has become a practical and cost-effective design solution to minimize the need for suspended ceilings and reduce construction costs, especially in multi-story buildings. These openings can take various shapes, including circular, rectangular, or irregular configurations [12-14]. However, introducing web openings in beams creates structural discontinuities that result in stress concentration zones around the perforations. These discontinuities can adversely affect beam performance, leading to reduced stiffness, increased deflection, and lower load-bearing capacity. Therefore, careful attention must be given to the design and detailing of web openings to maintain structural integrity and ensure optimal performance [15-17]. Previous studies have investigated how transverse openings impact steel beams, reinforced concrete beams, and composite beams. According to [18, 19], circular openings in steel beams are more effective than square or rectangular ones. Additionally, openings up to 75% of the beam's depth are effective. In contrast, authors in [20] found that in concrete beams, openings with a diameter up to 0.25 times the beam's depth reduce its strength by about 20% if no reinforcement is provided around the opening. Authors in [21, 22] observed that incorporating web openings in composite steel-concrete beams negatively impacts their load-bearing and deformation capacities, resulting in reduced strength and stiffness. The current study investigates the effect of transverse openings on CFST beams and compares it with the impact of openings of the same size on HST beams. A full-scale testing of composite beams is complex and expensive. To better understand their behavior, 12 scaled-down samples were used as a practical alternative. The experimental program was designed with simply supported beams subjected to two concentrated loads. Strain gauges and displacement transducers were employed to capture detailed data during the tests. These measurements were then analyzed to evaluate the structural behavior of CFST beams.

II. EXPERIMENTAL PROGRAM

A. Specimen Details

In the present study, a total of twelve scale-down beam specimens were prepared and tested, namely eight CFST beams and four HST beams, as detailed in Table I. Each beam measured 1400 mm in length and had a clear span of 1200 mm. Four of the CFST beams and two of the HST beams had transverse openings of 40 mm in diameter in order to study these openings' effect on CFST beams compared to that on HST beams. Each of these beams had three transverse openings: one at the center and two located 250 mm to the right and left of the center. Both ends of the CFST beams were welded with 2 mm thick steel plates. The bottom end was sealed, while the top was left open for casting the concrete. The steel tube was positioned vertically when the concrete core was cast inside to form the composite beam, as shown in Figure 1. In Table I, the letter (O) denotes the presence of transverse openings, while (S) and (R) indicate square and rectangular cross-sections, respectively. Numbers 2 and 3 represent the nominal thicknesses of the steel tubes.

TABLE I. SPECIMENS DETAILS

Beam ID				Cross-Section mm	Thickness mm
HST-2S	HSTO-2S	CFST-2S	CFSTO-2S	100×100	1.5
HST-3S	HSTO-3S	CFST-3S	CFSTO-3S	100×100	2.4
CFST-2R		CFSTO-2R		50×100	1.4
CFST-3R		CFSTO-3R		50×100	2.2

Fig. 1. The casting process of CFST.

TABLE II. PROPORTIONS FOR THE CONCRETE MIX

Cement (kg/m^3)	Sand (kg/m^3)	Gravel (kg/m^3)	Superplasticizer (kg/m^3)	Fine pozzolanic (kg/m^3)	W/C ratio
361	877	931	5	36	0.50

B. Material Properties

Self-Compacting Concrete (SCC) was used to ensure that the steel tubes were filled perfectly with concrete. The concrete mix proportions are provided in Table II. The compressive strength of the concrete was determined at an age of 28 days using two concrete cylinders, each with a diameter of 150 mm and a length of 300 mm. Based on the procedures followed in [23], the cylinders were filled with SCC that had a slump flow of about 700 mm and an L-box ratio of 0.91. The average compressive strength of the concrete was 31.7 MPa.

A steel coupon was cut and tested in tension for each steel tube to determine the mechanical properties of the material [24]. Figure 2 illustrates the test process, while Table III summarizes the yield strength (f_y) and ultimate strength (f_u) for these sections.

Fig. 2. Material test for the steel.

TABLE III. MECHANICAL PROPERTIES FOR STEEL

<table>
<tr><th>Section</th><th>f_y (MPa)</th><th>f_u (MPa)</th><th colspan="3" rowspan="2">Specification Limits Based on [25]</th></tr>
<tr><td>100×100×3</td><td>361.8</td><td>458.0</td></tr>
<tr><td>100×100×2</td><td>356.5</td><td>451.3</td><td>Grade</td><td>f_y (MPa)</td><td>f_u (MPa)</td></tr>
<tr><td>50×100×3</td><td>425.3</td><td>538.4</td><td>50</td><td>Min. 345</td><td>450-690</td></tr>
<tr><td>50×100×2</td><td>478.5</td><td>605.7</td><td>55</td><td>Min. 380</td><td>485-690</td></tr>
</table>

C. Test Setup and Loading Procedure

Testing was performed on CFST and HST specimens over a 1200 mm clear span, with the load having been applied symmetrically, resulting in a 625 mm pure moment region. The vertical deflection of the beam was recorded using a Linear Variable Displacement Transducer (LVDT) positioned at the midspan. As illustrated in Figure 3, a 50-ton load cell was placed midway between the concentrated loads. Two strain gauges were installed in the mid-span region, one on the top flange and the other on the bottom flange of the steel tube section. For beams that included transverse openings, an additional strain gauge was installed directly below the center of the opening. This third gauge was crucial for capturing the localized strain concentrations around the opening.

(a)

(b)

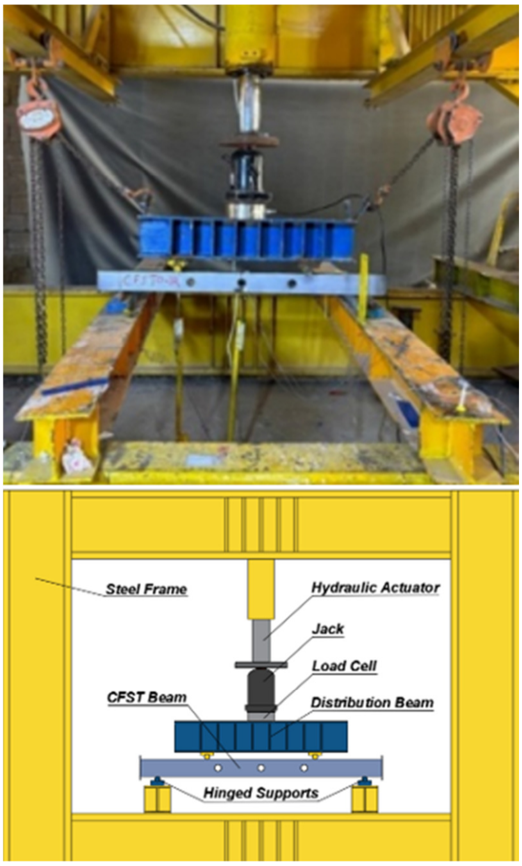

Fig. 3. Test setups: (a) experimental setup in the laboratory, (b) schematic representation of the setup.

III. RESULTS AND DISCUSSION

A. Load-Carrying Capacity

The incorporation of concrete into the HST significantly enhanced the load-carrying capacity of the beams. As demonstrated in Figure 4, the load-carrying capacity increased notably, rising from 21.19 kN for HST-3S to 49.83 kN for CFST-3S, representing an 135.1% improvement. Similarly, the load increased from 9.54 kN for HST-2S to 30.96 kN for CFST-2S, corresponding to a remarkable 224.5% improvement. These substantial increases in load-carrying capacity are a result of the composite action between the concrete infill and the steel tube. The concrete core provides additional compressive strength and delays local buckling, while the confinement by the steel to the concrete enhances its performance under load. However, the introduction of transverse openings in the beams led to reductions in load-carrying capacity, with this effect being more pronounced in the CFST beams compared to the HST beams. For CFST beams, the reductions were 11.5%, 18.6%, 11.8%, and 10.5% for CFST-3S, CFST-2S, CFST-3R, and CFST-2R, respectively. In contrast, the HST beams experienced much smaller reductions of only 0.14% for HST-3S and 3.77% for HST-2S. Despite the reductions caused by the transverse openings, the CFSTs still demonstrated substantial improvements over their hollow counterparts. The incorporation of concrete resulted in increases of 108.4% and 174.5% for HSTO-3S and HSTO-2S, respectively. These results indicate that even with the presence of openings, the addition of concrete infill provides significant structural benefits. From the load-displacement curves it can be observed that the initial stiffness, represented by the slope of the linear portion of the curve before yielding, remained nearly the same for beams with and without openings. This denotes that the openings have a minimal impact on the elastic behavior of the beams and little effect on the beam deflection at service load levels.

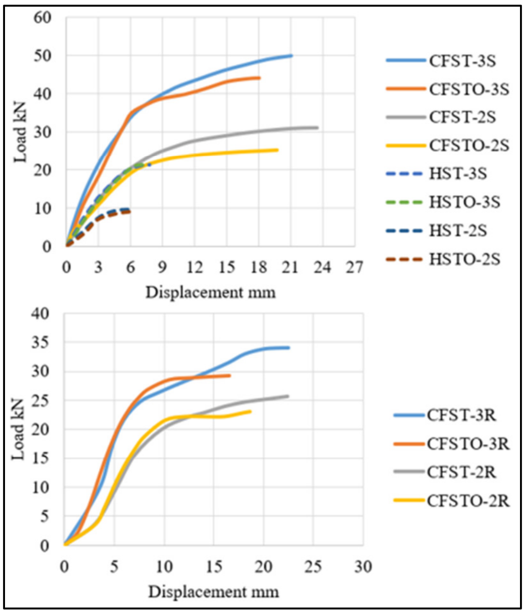

Fig. 4. Load-displacement curves.

B. Failure Modes

All specimens were subjected to loads exceeding their strength capacities to investigate extreme failure performance. The HST specimens, with or without transverse openings, exhibited inward buckling failure, specifically under the concentrated loads, as shown in Figure 5a. The CFST specimens without openings demonstrated typical failure modes, with deflection curves following a half-sine wave pattern during the loading process. In each filled specimen, at the top flange of the tube, outward buckling failure occurred near the concentrated loads, as portrayed in Figure 5b. The steel tube's inward buckling was effectively prevented due to the concrete infill. The type of buckling failure observed under concentrated loads is unlikely to occur when these beams are used in conventional floor systems, as they typically experience uniformly distributed loads instead. The CFST beams with transverse openings experienced a rupture in the steel tube beneath the openings, as illustrated in Figure 5c. This failure mode suggests that the presence of openings creates stress concentrations, potentially causing localized failures under extreme loading conditions. An exception to this pattern was observed in the CFSTO-2S specimen, where outward buckling occurred directly above the opening, as depicted in Figure 5d. Additionally, as displayed in Figure 5e, concrete cracks were observed through the openings on the tension side. Figure 5f shows all the specimens after they reached their extreme failure limits during testing.

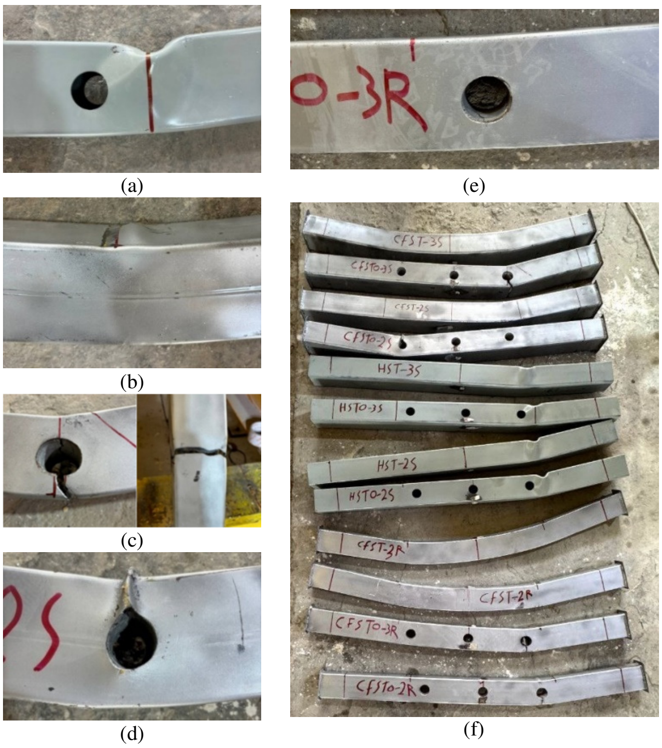

Fig. 5. Failure modes of HST and CFST specimens: (a) Inward buckling in HST specimens, (b) outward buckling in CFST specimens, (c) rupture in CFST beams with openings, (d) buckling above the opening in CFSTO-2S, (e) concrete cracks at the tension zone, (f) all specimens at failure.

C. Ductility

Figure 5 presents the tested specimens, where it is evident that the CFST beams experienced considerably larger deformations compared to the HST beams. Ductility, defined as a beam's capacity to undergo inelastic deformation while maintaining its load-carrying capacity before failure [26], was notably different between the two beam types. As illustrated in Figure 4, CFST beams demonstrated an extensive nonlinear response region before failure, whereas HST beams failed almost immediately upon reaching their yield point. The ductility index (μ) is defined as the ultimate deformation to yield deformation ratio, given by:

$$\text{Ductility Index} = \frac{\Delta_u}{\Delta_y} \quad (1)$$

where Δ_u indicates the beam deflection at ultimate load and Δ_y refers to the deflection at yielding. Figure 6 depicts the ductility indices of all specimens. The results demonstrate significant enhancement in ductility, with increases of 187.1% and 82.1% for CFST-3S and CFST-2S, respectively, when compared to their hollow counterparts, HST-3S and HST-2S. This improvement can be attributed to the slenderer sections being more susceptible to buckling. Consequently, the core concrete delayed local buckling, resulting in increased ductility compared to the HST specimens. The effect of transverse openings on ductility was particularly pronounced in the CFST specimens, with decreases of 12.4%, 17.3%, 9.46%, and 20% for CFST-3S, CFST-2S, CFST-3R, and CFST-2R, respectively. In contrast, the impact was minimal on the HST specimens, showing decreases of 2.54% and 1.52% for HST-3S and HST-2S, respectively. Although the ductility decreased due to transverse openings, the concrete-filled specimens still maintained significantly higher ductility levels, with CFSTO-3S and CFSTO-2S exhibiting values of 157.4% and 52.9% higher than those of their hollow counterparts, HSTO-3S and HSTO-2S, respectively.

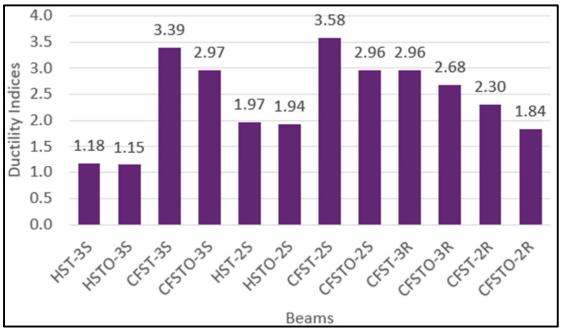

Fig. 6. Ductility indices of the beams.

D. Mid-Span Load-Strain Relationships

Mid-span strains in the beams were measured at the top flange, bottom flange, and beneath the opening for each load increment, as presented in the load-strain curves in Figure 7. In these curves, a negative sign denotes compressive strain, while a positive sign indicates tensile strain. For the HST specimens, the strain distribution remains essentially linear and stays below the yield strain due to local buckling failure. Both compressive and tension strains are nearly equal, and the transverse openings have no considerable effect on the strain distribution, where the openings do not create substantial stress concentrations or alter the overall load distribution pattern. This behavior is consistent across all tested HST specimens. In contrast, the strain distribution in CFST specimens initially follows a linear pattern, followed by a curve after the yield point. This post-yield nonlinear behavior post-yield indicates that the concrete filling allows the beam to sustain loads beyond the yield point of the steel tube, and results in plastic deformation.

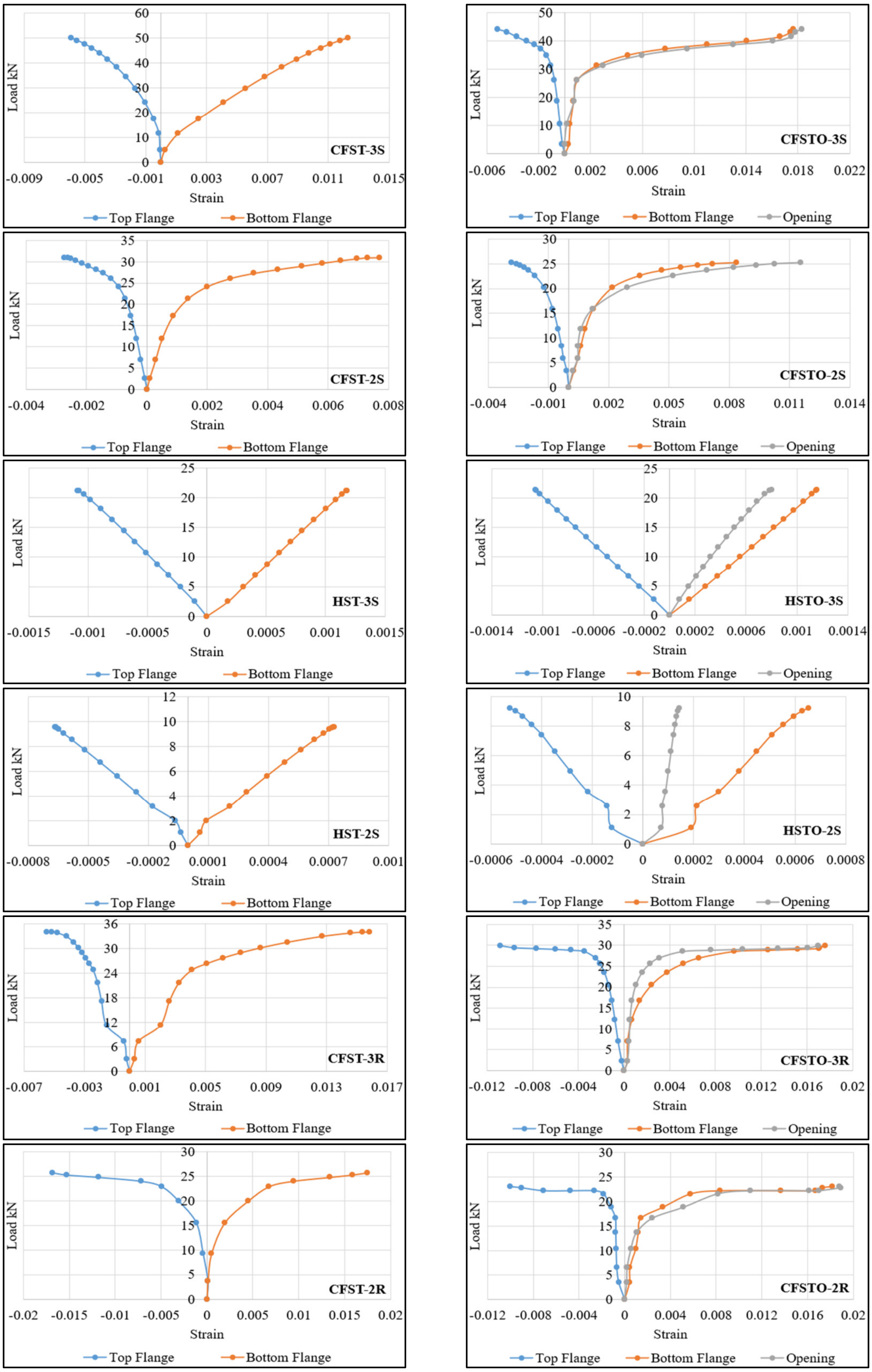

Fig. 7. Load-strain curves at mid-span.

The effect of the openings is most significant on the tension side, where the strain values are significantly higher compared to the beams without openings. Although the strain beneath the openings is not located at the extreme fiber, it matches or exceeds the strain observed on the tension side of the CFST specimens. This observation is particularly important, as it indicates that the areas surrounding the openings in CFST beams act as critical zones that could influence the beam's overall structural strength and performance. The higher strains in these areas could lead to localized yielding or failure initiation.

E. Energy Absorption (EA)

Evaluating the EA capacity is important for assessing the load capacity of the structure. When a structural system is subjected to environmental and unusual loads, ductility alone may be insufficient to ensure safety. EA reflects the structural strength under unexpected loads [27]. The load-displacement curves in Figure 4 were analyzed to calculate the EA, represented by the area under the curves. The estimated EA values are presented in Figure 8. Compared to HST beams, CFST beams demonstrate a significantly greater capacity for energy dissipation. The increase in EA is 680%, rising from 0.10 kJ for HST-3S to 0.78 kJ for CFST-3S, and 1300%, increasing from 0.04 kJ for HST-2S to 0.56 kJ for CFST-2S. Although this enhancement in EA is notable for CFST beams, the effect of transverse openings is more pronounced than in HST beams. The reduction in EA was 23.1%, 30.6%, 14.8%, and 23.1% for CFST-3S, CFST-2S, CFST-3R, and CFST-2R, respectively, compared to a reduction of 8% and 10% for HST-3S and HST-2S, respectively. While transverse openings reduce EA, the values for CFSTO beams remain significantly higher than those of HSTO beams. For example, the EA of CFSTO-3S surpassed that of HSTO-3S by 552%, and CFSTO-2S exceeded HSTO-2S by 1183%.

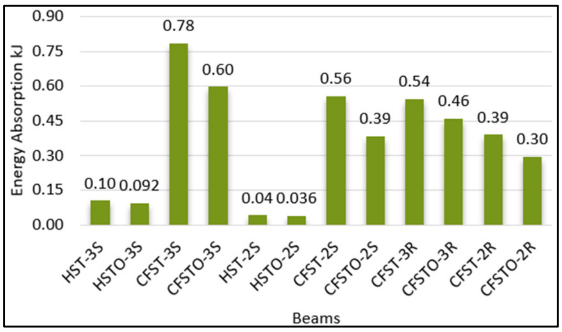

Fig. 8. EA of the beams.

F. Transverse Openings and Beam Geometry

Although CFST beam behavior is affected by different geometric configurations, the influence of transverse openings on these beams also varies with the geometry. This study investigates how variations in shape and dimensions affect the impact of transverse openings on the performance and structural properties of CFST beams. With a decreasing D/t ratio, both HST and CFST beams exhibit improved load-carrying capacity, which also lessens the impact of the openings on beam behavior. Figure 9 demonstrates that the decrease in load-carrying capacity becomes more pronounced as the D/t ratio increases. Even though greater D/t ratios typically lead to lower load-carrying capacity, the enhancement provided by the concrete filling becomes more pronounced at higher D/t ratios, with improvements of 135.1% and 224.5% being observed for ratios of 41.7 and 66.7, respectively. When transverse openings are present, the improvements for the same ratios are 108.4% and 174.5%.

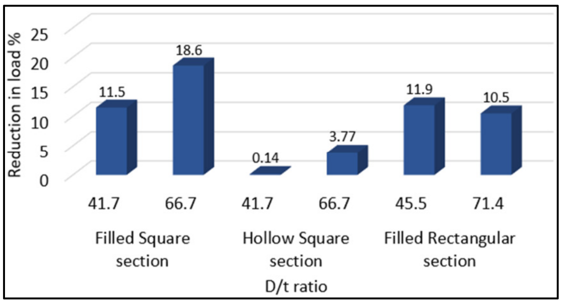

Fig. 9. Impact of openings on load-carrying capacity across different D/t ratios.

A similar trend was noted in ductility, where the reduction due to transverse openings became more pronounced at higher D/t ratios, for both hollow and filled beams, as depicted in Figure 10. The impact of the D/t ratio on ductility was more significant than its effect on the load-carrying capacity.

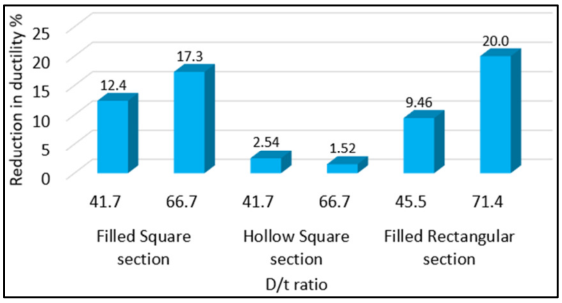

Fig. 10. Impact of openings on ductility across different D/t ratios.

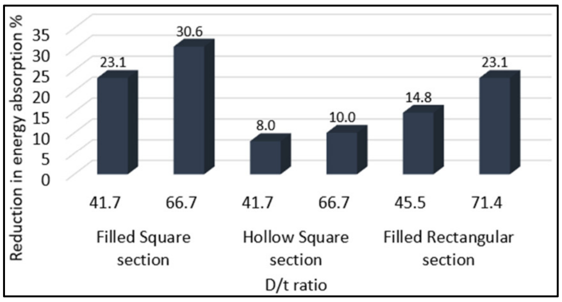

Fig. 11. Impact of openings on EA across different D/t ratios.

The reduction in EA due to transverse openings in HST beams was slightly influenced by the D/t ratio, in contrast to the CFST beams, where the impact was much more significant. Figure 11 illustrates this variation, showing a 30.6% reduction at a D/t ratio of 66.7 compared to a reduction of 23.1% at a D/t ratio of 41.7 in filled square sections, and a 23.1% decrease at a D/t ratio of 71.4 compared to a decrease of 14.8% at a D/t ratio of 45.5 in filled rectangular sections.

IV. CONCLUSIONS

This study investigated the impact of transverse openings on Concrete-Filled Steel Tube (CFST) beams, with a focus on their load-carrying capacity, failure modes, strain behavior, ductility, Energy Absorption (EA), and geometric characteristics. This research contributes novel insights into the behavior of CFST beams with transverse openings, addressing a critical gap in understanding their performance. While previous studies have demonstrated the advantages of solid CFST beams, the introduction of transverse openings presents unique challenges by significantly altering their structural behavior. The findings reveal that although the effects of transverse openings are more pronounced in CFST beams than in Hollow Steel Tube (HST) beams, the concrete infill continues to provide significant advantages. This enables CFST beams to maintain superior strength, ductility, and EA compared to their hollow counterparts. The findings of this study are summarized as follows:

- The stiffness of the CFST beams was substantially greater than that of the HST beams, demonstrating the significant contribution of the concrete infill. Furthermore, the presence of transverse openings had a negligible impact on the overall stiffness.
- Filling the HSTs with concrete significantly enhances the load-carrying capacity although the presence of transverse openings reduces this capacity more in CFST beams compared to HST beams. Despite these reductions, concrete still provides substantial improvements in the load-carrying capacity.
- The failure modes varied significantly between the HST specimens and CFST specimens, with HSTs exhibiting inward buckling under concentrated loads, while the CFST specimens displayed outward buckling and prevented inward failure. In the presence of transverse openings, CFST beams experienced ruptures beneath the openings, while the HST beams' failure modes were not significantly affected.
- CFSTs demonstrated superior ductility compared to HSTs, showing significant improvements. While transverse openings reduced ductility, particularly in CFST specimens, the concrete-filled specimens still maintained substantially higher ductility than their hollow counterparts. This enhanced ductility is attributed to the concrete infill's ability to delay local buckling, especially in slenderer sections.
- The strain behavior varied significantly between HST and CFST specimens. HST specimens maintained a linear strain distribution below yield strain due to local buckling, with almost no impact from openings being observed. In contrast, CFST specimens initially showed linear strain followed by a curved pattern post-yield, with openings notably affecting strain distribution, particularly on the tension side, and strains beneath the openings were comparable to or exceeded the tension side values.
- CFST beams demonstrate improved EA compared to HST beams, exhibiting considerable improvements. Although transverse openings diminish EA in CFST beams, they still significantly exceed the performance of HST beams. This indicates that CFST beams have an enhanced ability to dissipate energy under extreme loading conditions.
- The Depth-to-thickness (D/t) ratio significantly influences CFST beam performance, as lower ratios lead to better load capacity and reduced impact from transverse openings. While higher D/t ratios generally decrease load capacity, the enhancement from concrete filling becomes greater with larger D/t ratios. However, these higher ratios also make the beams more susceptible to performance reductions from transverse openings, particularly in terms of ductility and EA with CFST beams being more affected than HST beams.

REFERENCES

[1] M. H. Mohsen and S. N. Mohammed, "The Effective Width in Composite Steel-Concrete Beams at Ultimate Loads," *Journal of Engineering*, vol. 20, no. 08, pp. 1–17, Aug. 2014, https://doi.org/10.31026/j.eng.2014.08.01.

[2] D. Chen, V. Montano, L. Huo, S. Fan, and G. Song, "Detection of subsurface voids in concrete-filled steel tubular (CFST) structure using percussion approach," *Construction and Building Materials*, vol. 262, Nov. 2020, Art. no. 119761, https://doi.org/10.1016/j.conbuildmat.2020.119761.

[3] Z.-L. Du, Y.-P. Liu, J.-W. He, and S.-L. Chan, "Direct analysis method for noncompact and slender concrete-filled steel tube members," *Thin-Walled Structures*, vol. 135, pp. 173–184, Feb. 2019, https://doi.org/10.1016/j.tws.2018.11.007.

[4] S. Guler and D. Yavuz, "Post-cracking behavior of hybrid fiber-reinforced concrete-filled steel tube beams," *Construction and Building Materials*, vol. 205, pp. 285–305, Apr. 2019, https://doi.org/10.1016/j.conbuildmat.2019.01.192.

[5] A. N. Hassooni and S. R. Al-Zaidee, "Rehabilitation of Composite Column Subjected to Axial Load," *Civil Engineering Journal*, vol. 8, no. 3, pp. 595–611, Mar. 2022, https://doi.org/10.28991/CEJ-2022-08-03-013.

[6] G.-C. Li, B.-W. Chen, Z.-J. Yang, Y.-P. Liu, and Y.-H. Feng, "Experimental and numerical behavior of eccentrically loaded square concrete-filled steel tubular long columns made of high-strength steel and concrete," *Thin-Walled Structures*, vol. 159, Feb. 2021, Art. no. 107289, https://doi.org/10.1016/j.tws.2020.107289.

[7] A. N. Hassooni and S. R. A. Zaidee, "Behavior and Strength of Composite Columns under the Impact of Uniaxial Compression Loading," *Engineering, Technology & Applied Science Research*, vol. 12, no. 4, pp. 8843–8849, Aug. 2022, https://doi.org/10.48084/etasr.4753.

[8] W. F. Zhang, L. Gardner, M. A. Wadee, K. S. Chen, and W. Y. Zhao, "On the uniform torsional rigidity of square concrete-filled steel tubular (CFST) sections," *Structures*, vol. 43, pp. 249–256, Sep. 2022, https://doi.org/10.1016/j.istruc.2022.06.046.

[9] A. Alghossoon and A. Varma, "Rectangular filled composite members made from high strength materials: Behavior and design of columns and beams," *Thin-Walled Structures*, vol. 185, Apr. 2023, Art. no. 110641, https://doi.org/10.1016/j.tws.2023.110641.

[10] M. Alqarni, A. Noman, and M. A. Bashir, "Numerical Simulation and Parametric Study on the Moment Capacity of Composite Beam," *Computational Engineering and Physical Modeling*, vol. 2, no. 3, pp. 16–26, Jul. 2019, https://doi.org/10.22115/cepm.2019.199497.1069.

[11] A. Al-Nini *et al.*, "Flexural Behavior of Double-Skin Steel Tube Beams Filled with Fiber-Reinforced Cementitious Composite and Strengthened

with CFRP Sheets," *Materials*, vol. 13, no. 14, Jan. 2020, Art. no. 3064, https://doi.org/10.3390/ma13143064.

[12] F. El Ame, J. N. Mwero, and C. K. Kabubo, "Openings Effect on the Performance of Reinforced Concrete Beams Loaded in Bending and Shear," *Engineering, Technology & Applied Science Research*, vol. 10, no. 2, pp. 5352–5360, Apr. 2020, https://doi.org/10.48084/etasr.3317.

[13] A. Al-Rifaie, A. S. Al-Husainy, T. Al-Mansoori, and A. Shubbar, "Flexural impact resistance of steel beams with rectangular web openings," *Case Studies in Construction Materials*, vol. 14, Jun. 2021, Art. no. e00509, https://doi.org/10.1016/j.cscm.2021.e00509.

[14] L. T. Hussein and R. M. Abbas, "A Semi-Empirical Equation based on the Strut-and-Tie Model for the Shear Strength Prediction of Deep Beams with Multiple Large Web Openings," *Engineering, Technology & Applied Science Research*, vol. 12, no. 2, pp. 8289–8295, Apr. 2022, https://doi.org/10.48084/etasr.4743.

[15] M. Classen, W. Kurz, M. Schäfer, and J. Hegger, "A mechanical design model for steel and concrete composite members with web openings," *Engineering Structures*, vol. 197, Oct. 2019, Art. no. 109417, https://doi.org/10.1016/j.engstruct.2019.109417.

[16] "Strengthening of RC Beams with Large Openings in Shear by CFRP Laminates: Test Results," in *International Conference on Civil, Offshore, & Environmental Engineering (ICCOEE 2012)*, KLCC, Kuala Lumpur, Jun. 2012.

[17] H. M. Mahdi and R. M. Abbas, "Effect of Openings on the Torsional Behavior of SCC Box Beams Under Monotonic and Repeated Loading," *Civil Engineering Journal*, vol. 9, no. 9, pp. 2300–2314, Sep. 2023, https://doi.org/10.28991/CEJ-2023-09-09-015.

[18] S. G. Morkhade and L. M. Gupta, "An experimental and parametric study on steel beams with web openings," *International Journal of Advanced Structural Engineering (IJASE)*, vol. 7, no. 3, pp. 249–260, Sep. 2015, https://doi.org/10.1007/s40091-015-0095-4.

[19] S. G. Morkhade and L. M. Gupta, "Experimental investigation for failure analysis of steel beams with web openings," *Steel and Composite Structures*, vol. 23, no. 6, pp. 647–656, Jan. 2017, https://doi.org/10.12989/scs.2017.23.6.647.

[20] L. Jen Hua, H. S. Tang, W. K. Leong, and H. T. Sia, "Behaviour of Reinforced Concrete Beams With Circular Transverse Openings Under Static Loads," *JOURNAL OF SCIENCE AND APPLIED ENGINEERING*, vol. 3, no. 1, pp. 1-16, May 2020, https://doi.org/10.31328/jsae.v3i1.1288.

[21] H. Du, X. Hu, D. Shi, and B. Fang, "Effect of reinforcement on the strength of the web opening in steel-concrete composite beam," *Engineering Structures*, vol. 235, May 2021, Art. no. 112038, https://doi.org/10.1016/j.engstruct.2021.112038.

[22] S. Mastan, S. Anandh, and S. Sindhu Nachiar, "Numerical method and validation using ANN of composite steel-concrete beam for optimized geometry and emplacement of web opening," *Asian Journal of Civil Engineering*, vol. 25, no. 2, pp. 1539–1559, Feb. 2024, https://doi.org/10.1007/s42107-023-00860-6.

[23] *Standard Practice for Fabricating Test Specimens with Self-Consolidating Concrete*, vol. 04.02. ASTM International, 2023.

[24] *Standard Test Methods and Definitions for Mechanical Testing of Steel Products*. ASTM International, 2019.

[25] *Standard Specification for High-Strength Carbon-Manganese Steel of Structural Quality*, vol. 01.04. ASTM International, 2019.

[26] F. Wu, Y. Zeng, B. Li, and X. Lyu, "Experimental Investigation of Flexural Behavior of Ultra-High-Performance Concrete with Coarse Aggregate-Filled Steel Tubes," *Materials*, vol. 14, no. 21, Jan. 2021, Art. no. 6354, https://doi.org/10.3390/ma14216354.

[27] A. N. Hanoon *et al.*, "Sawdust-Based Concrete Composite-Filled Steel Tube Beams: An Experimental and Analytical Investigation," *Journal of Composites Science*, vol. 7, no. 6, Jun. 2023, Art. no. 256, https://doi.org/10.3390/jcs7060256.