Experimental and Analytical Compression Behavior of Stiffened Concrete-filled Double-Skin Tubular Columns

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ABSTRACT

Concrete-filled double-skin tubular (CFDST) columns with concrete sandwiched between inner and outer steel tube skins form a modern column optimized for a high strength-to-weight ratio compared to traditional reinforced concrete (RC) or steel columns. The innovative addition of stiffened steel tubes with CFDST columns enhances their axial load-bearing capacity, ductility, and residual capacity by delaying or constraining localized deformations in the steel tubes. This study examines the comparative behavior of stiffened CFDST columns provided with flat rectangular stiffeners on the outer circular steel tube versus their unstiffened counterparts under centric compression loading. Detailed nonlinear finite element (FE) models were generated and validated against the test results. Experimental results showed the significant development of concrete confinement due to the presence of stiffeners, enhanced ductility, and residual axial load capacity in stiffened columns compared to unstiffened CFDSTs. The parametric variations on the stiffener width depicted enhancement in peak axial-load bearing capacity up to about 44% compared to unstiffened columns.

KEYWORDS

CFDST, stiffener, experimental study, finite element (FE).

INTRODUCTION

The steel tubular sections have been used frequently in the construction industry due to their higher tensile and compressive strengths. However local buckling in the form of inward and outward folding often prevents these sections from achieving the full sectional capacity. Hence the central hollow portion is filled with concrete to prevent or reduce the inward folding in steel tubular sections and these types of members are called concrete filled steel tubes (CFST). The axial compressive strength and axial deformation of CFST columns has been observed higher than the summation of individual sectional capacities of steel tubes and concrete core (Han et al., 2014; Schneider, 1998; Wei et al., 1995). The strength of concrete core is also enhanced in CFST columns, due to the restriction of concrete core expansion provided by the steel tube. The increased strength of concrete in CFST columns is called as confined strength of concrete and the phenomenon of restriction of concrete expansion is called confinement. Despite having increased confined strength of concrete core in CFST columns, the central region has been observed to be lesser confined in these columns (Schneider et al., 1998). As a result, in CFST columns, the central region has shown minimum contribution to the axial load-bearing capacity. Alternative to the CFST columns, the central region of concrete core is replaced with another concentric tube, which is kept as hollow, and the concrete is filled between the annulus of two steel tubes and the sections are called as concrete filled double skin tubular (CFDST) columns. The primary goal of providing a central tube in CFDST columns is to replace the weaker central concrete region and increase the sectional capacity of CFDST columns(Elchalakani et al. 2002; Hajjar 2000). From previous investigations, the axial compressive strength has been found to be significantly influenced by concrete confinement which is directly affected by the outer tube diameter (D_o) to outer tube thickness (t_o) ratio, $\frac{D_o}{t_o}$, yield strength of outer steel tube (f_{yo}), characteristic strength of concrete (f'_{co}) provided and concrete core thickness also known as hollowness ratio, expressed as $\chi = \frac{D_i}{D_o - 2t_o}$. The role of inner tube is to restrict the inner movement concrete core and hence the minimum criteria for inner tube thickness $t_i \geq \left(\frac{D_i f_{yo}}{D_o f_{yi}}\right) t_o$ has been provided by Han et al. (2010). The design model provided by (Han et al. 2001) to calculate the axial compressive strength of CFDST columns is based on the composite action outer steel tube and confined strength of concrete core. Similarly, the design model provided by (Hu et al. 2011) is based on the lateral pressure (f_l) provided by the outer steel tube. It is compelling that the loss of concrete confinement in CFDST columns corresponds to the failure of the outer tube due to local buckling. Consequently, various stiffening techniques have been adopted to strengthen the outer tubes of stiffened CFDST columns. The experimentally investigated end stiffened (stiffeners are provided locally at top and bottom only) CFDST columns exhibited up to 38% increase in axial compressive strength, and the failure has been observed due to the local buckling of outer tube and stiffeners, followed by concrete and inner steel tube failure (Alqawzai et al. 2020). The shear bolt stud outer tube stiffened circular CFDST columns also exhibited similar behaviour, with a 5% increase in axial compressive strength (Ayough et al. 2022). It has also been suggested that the strength of these stiffened CFDST columns can be further enhanced if the height of flat steel strips is increased and the number of shear bolt studs is increased. The experimental investigation of square CFDST columns provided with full-height steel stiffeners in outer tube stiffened exhibited a decrease in axial compressive strength due to loss of confinement in concrete (Wang et al. 2020). Contrary, finite element analysis (FEA) of circular outer tube stiffened CFDST columns with full height stiffeners has exhibited an increase in axial compressive strength as well as ductility (Ghannam et al., 2020; Hassan et al., 2023, 2021).

From the available literature, experimental investigation has been carried out for square outer tube stiffened CFDST columns only (Wang et al. 2020), and no such (experimental) investigation is available for stiffened circular CFDST columns. However, circular stiffened CFDST columns have been investigated through FEA only (Ghannam et al., 2020; Hassan et al., 2022, 2023). In the absence of an experimental study, the results of FEA have been validated using experimental results of unstiffened CFDST columns, which might not accurately reflect the behaviour of stiffened CFDST columns. In this study an experimental investigation has been carried out to investigate the behavior of outer tube stiffened CFDST columns. Further, finite element analysis using ABAQUS/CAE 6.14, software has been carried out to fully replicate the experimental behaviour.

RESEARCH SIGNIFICANCE

The outer tube significantly affects the confinement of concrete and the axial compressive strength of CFDST columns. It is pivotal to strengthen the outer tube in order to achieve higher axial compressive strength and enhanced ductility of CFDST columns. The primary objective of the present experimental study is to investigate the effectiveness of stiffeners in outer tubes. The significance of stiffeners to restrict the local buckling of the outer tube and confinement effect has been evaluated in the present study. Full-height flat steel stiffeners have been used to investigate the behaviour of these outer tube-stiffened CFDSTC columns.

RESEARCH METHODOLOGY

Circular outer and inner tubes have been adopted in unstiffened as well in stiffened CFDST columns, with D_o= 139 mm and D_i=60 mm, respectively. The yield strength of outer and inner tubes, from tensile coupon tests has been observed as, f_{yo}= 417.05 MPa and f_{yi}=492.91 MPa, respectively. Four steel stiffeners of width, w_s=25mm and yield strength of f_{yst}= 403.77 MPa, have been welded inside the outer tube using shielded metal arc welding approach, shown in Figure 1 (a). The thickness of outer tube, inner tube and steel stiffeners has been adopted as t_o = 3.5mm t_i=2.00 mm and t_{stf} = 2.8 mm, respectively. The concrete infill with a characteristic cylinder compressive strength of 31.05 MPa, has been used in the concrete core. The unstiffened CFDST columns have been prepared with the same outer tube, inner tube, and concrete core Figure 1 (b). Two specimens of unstiffened and stiffened CFDST columns with the height of 355 mm have been prepared in the present study and have been identified as U-139-I, U-139-II and 4S-139-I, 4S-139-II respectively.

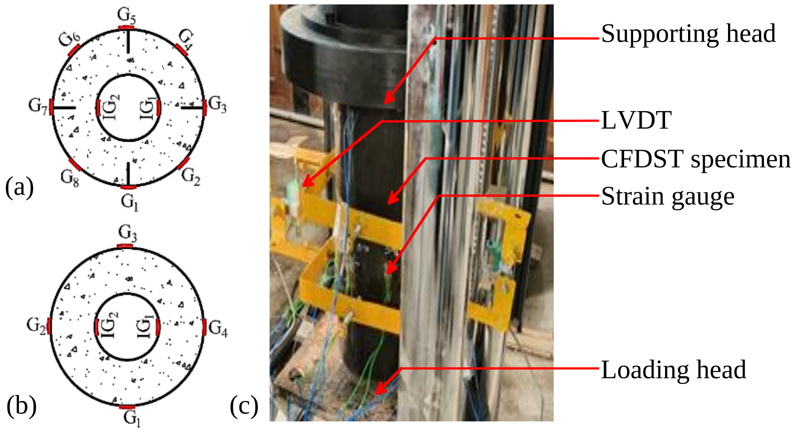

Figure 1. Experimental setup of outer tube stiffened CFDST columns: (a) 4S-139 (b) U-139 (c) Test setup

The hoop strain in outer tube and axial strain in inner tube has been measured with the help of strain gauges, provided at stiffened regions as well as in unstiffened regions as shown in Figure 1 (a) and (b). The axial strain in the outer tube has been measured with the help of a Linear Variable Differential Transformer (LVDTs), mounted at the mid-height of the specimen and 100 mm apart from each other as shown in Figure 1(c).

The finite element analysis has been carried out by using Abaqus CAE 6.14. The concrete elements have been modelled as 3-dimensional 8-noded brick elements whereas steel tubes and steel stiffeners have been modelled as 4-noded shell elements. The widely accepted constitutive model of confined concrete proposed by (Hu et al. 2011). has been adopted to model the concrete in CFDST columns. Concrete damage plasticity sub-option available in ABAQUS, has been used for present analysis to investigate the behaviour of concrete in tension and compression. For steel, the constitutive model proposed by (Tao et al. 2013) has been used. Surface-to-surface contact interaction with the Columb friction value of 0.3 has been employed between concrete surfaces and steel tube surfaces. From node-to-node mesh sensitivity analysis, the optimum mesh convergence has been observed at the 15mm global size of the element.

RESULTS AND DISCUSSIONS

All CFDST specimen exhibited local buckling failure in outer tubes with failure of concrete in these regions only. The behaviour of unstiffened CFDST columns U-139-I,II has been found consistent with the previous investigation of CFDST columns (without stiffeners) (Tao et al. 2004; Wang et al. 2019). Local Buckling has been observed at the top and bottom only (Highlighted with the ellipse in Figures) in the outer tubes after the peak loads are achieved in unstiffened CFDST columns as shown in Figure 2 (a). The local buckling in stiffened CFDST has been observed at multiple locations after peak loads, with larger axial deformation, which can be observed in Fig 1(a). It also compelling that the local buckling has been observed in unstiffened regions only, whereas no buckling is observed in the stiffened region. It is prudent that the stiffeners effectively restrict the local buckling of outer tubes in CFDST columns.

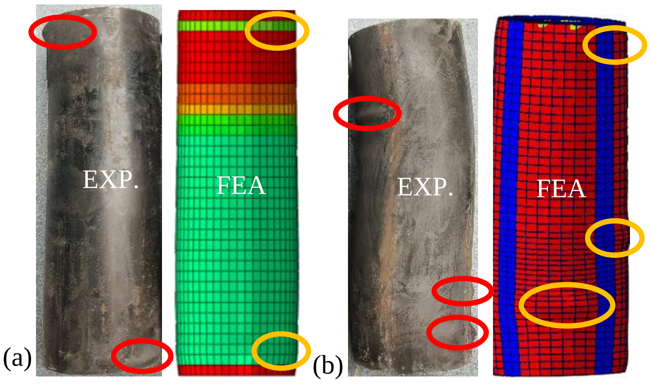

Figure 2. Comparison of Local buckling deformations: (a) U-139 (b) 4S-139

The local buckling in inner tube has not been observed in unstiffened CFDST columns, as the minimum criteria for inner tube thickness provided by (Han et al. 2010), holds true for these cases. In stiffened CFDST columns local buckling in inner tube has been observed with multiple inward folds, mimicking the outward folds of outer tube.

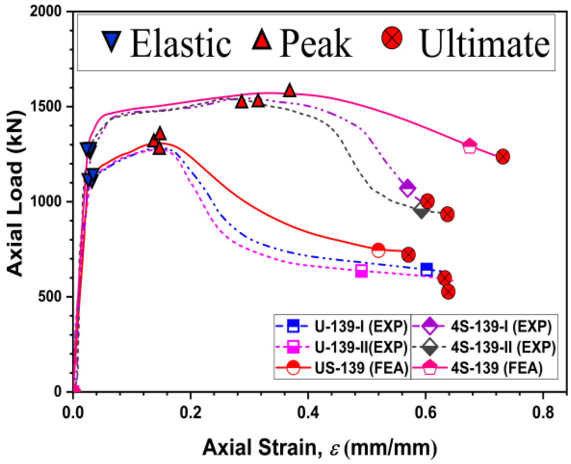

Figure 3. Axial Load-strain Characteristics.

The axial load-strain curves depicted an initial linear ascending branch when the steel and concrete elements are in the elastic stage. However, increased loads corresponding to the elastic stage have been observed in stiffened CFDST columns (1299 kN) as compared to unstiffened CFDST columns (1147 kN). The second nonlinear ascending has been observed steeper in unstiffened CFDST columns as compared to stiffened CFDST columns. The axial load and axial strain corresponding to the peak end of this stage have been observed higher in stiffened CFDST columns. The increase in Peak loads has been observed up to 20.17% in stiffened CFDST columns (1543 kN) as compared to unstiffened CFDST columns (1284 kN). The third descending nonlinear branch has been observed after the local buckling of outer tubes in all cases.

The ductility with respect to the strain (ε_{95}) when the load falls to 95% of the peak load and the strain ($\varepsilon_{75}= \varepsilon_y/75$) corresponding to the peak of the elastic stage has been observed significantly (126%) higher in stiffened CFDST columns (15.11) as compared to unstiffened CFDST columns (5.85). Similarly, the strength index (SI) with respect to the peak loads and summation of the individual sectional capacity of steel tubes, stiffeners and concrete core has been observed higher in stiffened CFDST columns. The increase in SI has been observed up to 27% in stiffened CFDST columns (SI=1.4) as compared to unstiffened CFDST columns (1.1).

The increase in axial load-carrying capacity and ductility has been attributed to the increase in the confined strength of concrete (fcc) in stiffened CFDST columns. The normalised confined concrete strength $\left(\frac{f_{cc}}{f_{co}^{'}}\right)$, provided in Figure 4 has been obtained by adopting the methodology of previous experimental investigation(Han et al. 2001; Zakir et al. 2021a; b; Zakir et al. 2022). The normalised confined concrete strength, $\frac{f_{cc}}{f_{co}^{'}}$ has been observed almost the same in unstiffened and stiffened CFDST columns however at peak loads 27.4% increase in $\frac{f_{cc}}{f_{co}^{'}}$ has been observed in stiffened CFDST columns $\left(\frac{f_{cc}}{f_{co}^{'}} = 1.81\right)$ as compared to unstiffened CFDST columns $\left(\frac{f_{cc}}{f_{co}^{'}} = 1.42\right)$. No residual confined concrete strength of concrete has been observed in unstiffened CFDST columns at the ultimate failure. However, in case of stiffened CFDST columns, up to $\frac{f_{cc}}{f_{co}^{'}} = 0.5$ has been observed as residual strength in concrete.

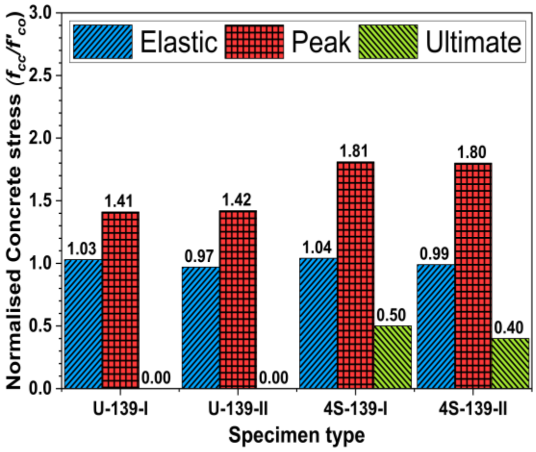

Figure 4. Comparison of normalized concrete strength.

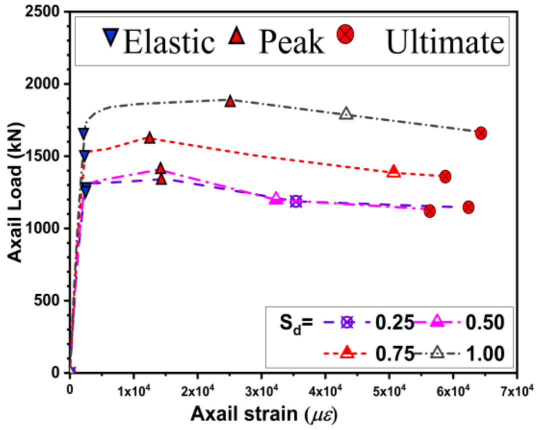

Figure 5. Axial load-strain curves of parametric study.

The current study is extended by the finite element analysis for parametric study by varying the stiffener width in 4S-139. The stiffener width (w_s) has been varied with respect to the concrete core depth, "d_c". A non-dimensional value, "$s_d = \frac{w_s}{d_c}$" representing the stiffener depth in the concrete core has been adopted to generalize the effect of stiffener depth in CFDST columns. The stiffener width has been adopted as 9mm, 18mm, 27mm and 36mm to achieve the values of s_d= 0.25d_c, 0.5d_c, 0.75d_c and 1.0d_c. The comparison of deformation shapes and axial load strain characteristics is shown in Figure 2 and Figure 3. From Figure 2, the deformations, and axial load-strain characteristics of FEA investigations are in good relation with the experimental (EXP.) results.

From the results of the parametric study, both an increase in load-carrying capacity as well as ductility has been observed with an increase in stiffener width as shown in Figure 5. The increase in strength has been observed from 6% to 44% when the stiffener width is increased from w_s=9mm to w_s=36 mm, which has been tabulated in Table 1. From these observations, a detailed investigation is suggested for stiffened CFDST columns, while varying the stiffener number and stiffener width in CFDST columns, with different outer tube diameters.

Table 1: Results of the parametric study

S.No.	Specimen	w_s	$s_d = \frac{w_s}{d_c}$	P_k	$\frac{P_{k,Stiff}}{P_{k,Unstiff}}$
1	U-139	0	0.00	1310	-
2	4S-139	9	0.25	1342	1.02
3	4S-139	18	0.5	1406	1.07
4	4S-139	27	0.75	1627	1.24
5	4S-139	36	1.00	1891	1.44

CONCLUSIONS

- Stiffened CFDST columns showed improved compressive behaviour compared to unstiffened columns, enhancement of about 20.17% in axial load-bearing strength, 126% in ductility, and 50% in residual strength were seen in this study.
- The experimental and analytical results showed reduced, delayed, and constrained local buckling deformations/foldings on the outer steel tube due to the presence of steel stiffeners. These localized foldings in steel tubes initiated the ultimate failure of CFDST columns under axial compression.
- Stiffener width showed a significant parametric influence on the performance of CFDST columns, indicating better composite action leading to higher load-carrying capacity (about 44 % in this study for variations of 25 % to 100 % of concrete core depth) compared to unstiffened tubular columns.

An extensive experimental study is currently being undertaken by the authors to investigate the performance of CFDST columns by varying stiffener characteristics, including variations of stiffener cross-sectional dimensions, number and their placements. Detailed analytical studies are to be performed in future to explore the benefits of stiffened CFDSTs compared to unstiffened counterparts.

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