ASIAN JOURNAL OF CIVIL ENGINEERING (BHRC) VOL. 17, NO. 5(2016)
PAGES 625-634

AXIAL AND ECCENTRIC COMPRESSION OF GFRP JACKETED STEEL TUBES

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Received: 12 October 2015; **Accepted:** 28 December 2015

ABSTRACT

This article discusses on the behavior of unwrapped and GFRP (Glass fiber reinforced polymer) wrapped hollow circular steel tubes under axial and eccentric compression (25 mm and 50mm). Finite element analyses through ANSYS were carried out on similar specimens. Comparisons of results proved that GFRP jacketing is an effective method for arresting elephant foot buckling in hollow steel tubes under both loading conditions. It also enhanced the stiffness, ultimate load and ductility of unwrapped tubes. More than two number of GFRP layers showed unfavorable inward buckling of tubes. Effective confinement was achieved by restricting the number of wrapped layers to two.

Keywords: Retrofitting; hollow circular steel tubes; GFRP sheet; epoxy; experiment analysis; numerical analysis (ANSYS).

1. INTRODUCTION

Due to increased and eccentric loads, the steel hollow sections get damaged. To rectify this problem there are two possible solutions to avoid the on-going deterioration and failure and to increase the strength and durability of columns. First one is replacement and another one is retrofitting. Full structure replacement has many disadvantages such as high cost for materials and labours, inconvenience due to interruption of the functions of structures. Therefore, it is better to repair or upgrade the structure by retrofitting. There are several methods adopted in retrofitting. Among different methods, the effective method to upgrade and rehabilitate the steel components is by using externally wrapped FRP composite system. This could be achieved by wrapping FRP sheets to steel tubes by using bonding agents such as epoxy. This work is carried out to control the radial buckling of hollow steel tubes.

Many studies were carried out on strengthening of steel tube using FRP. Numerical and experimental analysis on steel section along with FRP jacket were carried out and proved

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that provision of thin jacketing enhanced the ductility of the tube. It was concluded that when thickness of wrapping was increased beyond the limiting value, buckling of specimens occurred in inward direction. It was found that FRP confinement in steel tubes is effective in seismic retrofit as it leads to large increase in ductility [1, 2]. Experimental research on CFRP-composite concrete column on eccentric loading condition was performed and concluded that ultimate load decreased with increase in load eccentricity without any relation on lateral deformation. But wrapping proved to increase the ductility of the column [3, 4]. Experiments on CFRP bonded square hollow sections were conducted for wide range of slenderness ratios and concluded that optimum slenderness ratio of 2.5 showed increased axial load carrying capacity. It was found that wrapping delayed local bucking and provided effective resistance to elastic buckling deformations [5]. Axial compression test on 250 wrapped square, circular and rectangular columns were performed and concluded that diameter of columns did not show any significant difference in strength enhancement. But the effectiveness of confinement was significant in the case of square and rectangular than that of circular tubes [6]. Mechanical properties were studied through research conducted on square FRP tube. Burn out test indicated that ± 45^0 glass fiber reinforcement provides strong structural performance [7]. Experiments on recycled aggregate concrete columns confined with GFRP showed that there was considerable improvement in both strength and deformations [8]. Studies on different applications of FRP for external strengthening in civil constructions were carried out and the effectiveness of FRP system was confirmed for repair and retrofitting [9]. Experiments were carried out to analyse the stiffening effect of GFRP as tensile reinforcements and concluded that mean bond stresses decreased resulting in unfavourable bond slip behaviour [10].

From the knowledge gained from the past studies it was decided to apply similar wrapping technique for enhancing the structural performance of hollow circular tubes. The parameters considered for the study include different number of wrap layers and different loading conditions.

2. EXPERIMENTAL STUDY

2.1 Specimens

Twelve circular hollow tubes were tested. All the twelve tubes were cut from same hollow section to possess similar dimensions and material properties. The dimensions of the hollow tubes are as specified in Table 1.

Table 1: Specifications for the specimens

Specimen	Diameter (mm)	Height (mm)	Thickness (mm)
Hollow circular tube	152.4	300	4.5

Coupon test conducted on the specimens yielded the value of Young’s modulus, stress at yield point and tensile strength as 201.1 GPa, 310 MPa and 410 MPa respectively. Each layer of bidirectional glass fiber sheets had thickness of 0.6mm. The Young’s modulus and tensile strength mentioned by the manufacture for the sheet was 85 GPa and 2050 MPa respectively which confirms with BS-3749.

The hollow sections were divided into four groups of three tubes each. The group one (F0) was without any wrapping of fiber sheet. The second group of tubes wrapped with one layer of GFRP (F1). The third group of tubes (F2) was provided with double layers of GFRP and the fourth group of tubes were provided with three layers of GFRP (F3). Single tube from each group was subjected to axial loading 0_AX. The second and third tubes were tested for eccentric loading of 25 mm and 50 mm (25_ECC and 50_ECC respectively). Table 2 summarises the details of tested specimens.

Table 2: Details of specimens

Specimen ID	GFRP layers	Test load eccentricity (mm)
0_AX-F0	-	0
0_AX-F1	1-layer	0
0_AX-F2	2-layer	0
0_AX-F3	3-layer	0
25_ECC-F0	-	25
25_ECC-F1	1-layer	25
25_ECC-F2	2-layer	25
25_ECC-F3	3-layer	25
50_ECC-F0	-	50
50_ECC-F1	1-layer	50
50_ECC-F2	2-layer	50
50_ECC-F3	3-layer	50

The bonding of GFRP sheets was achieved with epoxy resin which is a combination of hardener and resin. The circumferential continuum of GFRP wrapping around the steel tube, was maintained through 75mm overlap. The surface of the steel tube was made smooth before wrapping.

2.2 Instrumentation and loading

The experiments were carried out in Universal Testing Machine (UTM) of 1000 kN ultimate load capacity with automated data acquisition system. The rate of load application was limited to 0.5 mm/min. Fig. 1 depicts the arrangements for carrying out the experiments.

The eccentric loading was achieved with the help of knife edges. The relative displacement of two loading plates was simultaneously recorded. Among eight specimens, four specimens were subjected to 25 mm eccentric load and remaining four was subjected to 50 mm eccentric load.

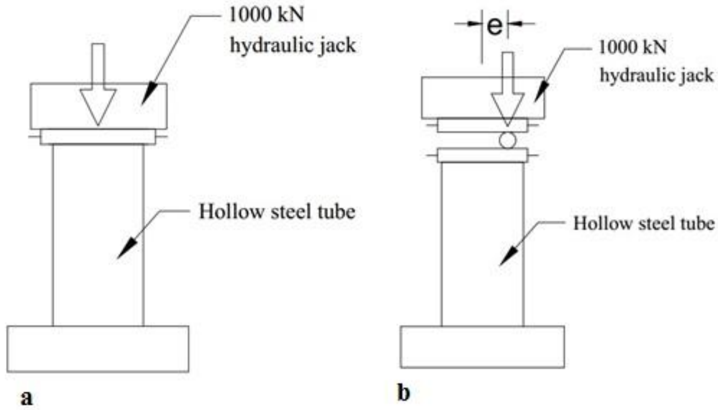


Figure 1. Arrangements for: (a) Axial loading (b) Eccentric loading

3. ANALYTICAL STUDY

3.1 Finite element modelling

To validate the experimental results, finite element models of FRP wrapped hollow circular columns were analysed using finite element package ANSYS. The meshing of the specimens was achieved through an eight noded structural shell element (shell93) well suited to model curved geometry. Each node has six degrees of freedom with three translations and three rotations. Shell 91 was the element used for modelling FRP wrapping. This element has eight nodes with translation in x, y and z directions. Numbering control was used to merge the common nodes between two elements.

The material properties of the specimens and the FRP were assigned based on the yield stress and elastic modulus obtained from experiments. The uniform mesh of 15 mm was adopted based on the mesh convergent study to provide more accurate results. Though the experimental setup resembled simply supported condition, fixed support was applied to both ends as per [1]. Bilinear isotropy and orthotropic properties were given as input for steel and fiber sheets respectively. Epoxy binder between the cylinder and the glass sheets was modelled as perfect bond. The load was distributed uniformly on all the nodes at the top of the steel tube. Fig. 2 shows the boundary conditions and the loading pattern on the model.

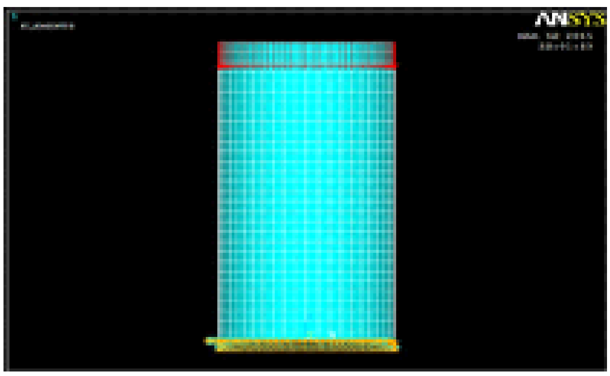


Figure 2. Loading and boundary condition for numerical model

4. RESULTS AND DISCUSSION

4.1 Experimental works

Among various imperfections during erection and construction, eccentricity in loading plays a major role. Four specimens were subjected to 25 mm eccentricity and the remaining specimens were subjected to 50 mm eccentricity. The failure modes of unwrapped specimens under the axial and eccentric loading conditions are as shown in Fig. 3(a) and Fig. 3(b) respectively.

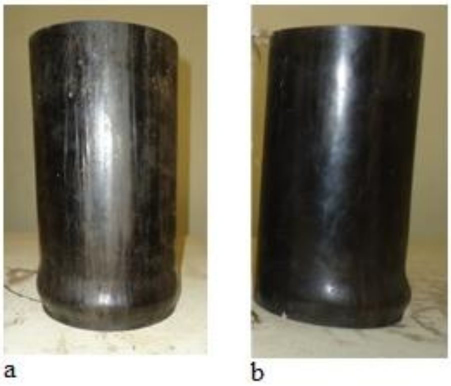


Figure 3. Failure of bare steel tubes under (a) Axial loading (b) Eccentric loading

Fig. 4 shows the load vs. axial shortening curve for 0_AX-F0 to 0_AX-F3. From the plot it was observed that FRP wrapped tube shows great enhancement in the tube ductility. In 0_AX-F1 the hoop tension along the circumference caused the rupture of the FRP wrap which resulted in radial buckling localised at the tube ends. In 0_AX-F2 the local buckling was controlled, whereas in 0_AX-F3, the failure mode was reversed to inward bucking near the mid height as shown in Fig 5. Therefore no local rupture was observed in FRP jacket.

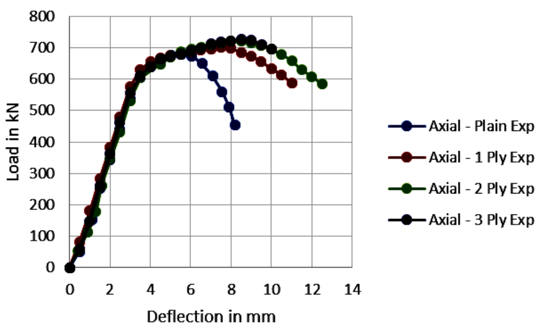


Figure 4. Load deflection curve for 0_AX

Figure 5. Failure of the sheet at ultimate load

It was found that for steel tubes, as the number of layers of wrapping was increased, the load deflection behaviour was improved considerably. But more than two layers lead to inward bucking away from the ends.

The load vs. axial shortening curves compared for specimens under 25 mm eccentric loading was as shown in Fig. 6. On testing the remaining four specimens for 50 mm eccentric loading, no significant enhancement in the load vs. axial shortening curve was noticed as shown in Fig. 7.

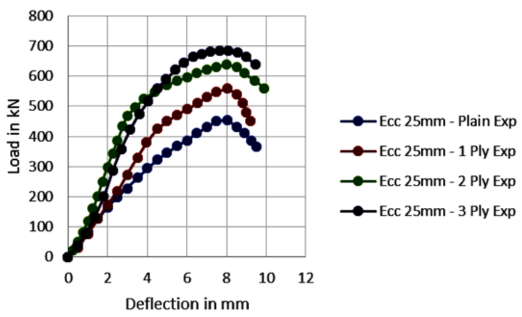


Figure 6. Load deflection curve for 25_ECC

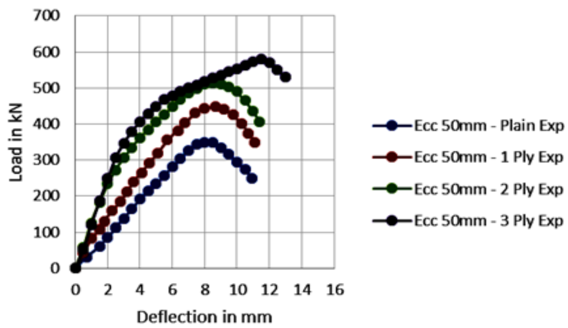


Figure 7. Load deflection curve for 50_ECC

4.1.1 Stiffness

The slope of load deflection plot gives the stiffness which is quantified by the amount of load required to produce unit deflection. The stiffness for different specimens are compared in Fig 8. Percentage increase of stiffness due to wrapping in 0_AX-F1 and 0_AX-F2 were 22.22% and 37.77% respectively compared to 0_AX-F0. But for 0_AX-F3 the increase was not significant with only about 17.77%. The eccentricity in loading do not allow for similar enhancement in stiffness. Percentage reduction in stiffness values for 25mm eccentric loading were 7.14%, 5.45%, 4.83% and 3.77% compared to their axial counterpart. Corresponding percentage reduction in stiffness values for 50mm eccentric loading were 33.33%, 40.33%, 40% and 39.62% respectively. Though the specifications for the specimens and no of layers remain similar, eccentricity more than 25mm in loading have brought down the stiffness considerably.

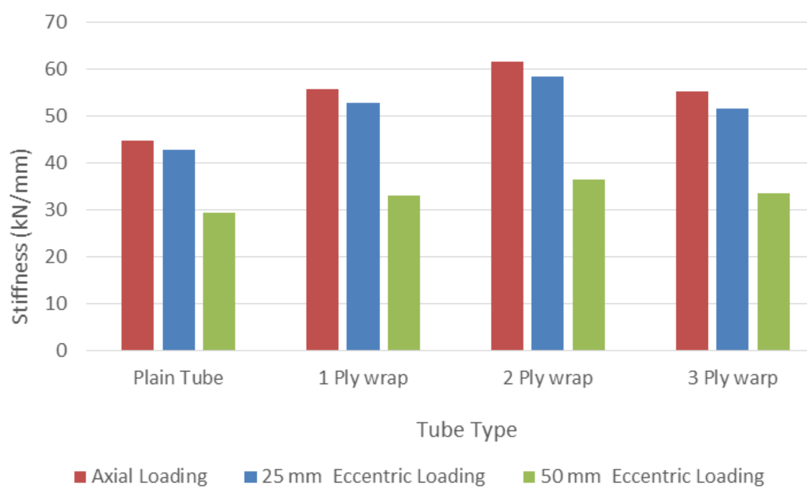


Figure 8. Comparison of stiffness

4.1.2 Energy absorption

The area enclosed under the load deflection curve is quantified as energy absorbed by the specimens. The energy absorption for different specimens are compared in Fig 9. Enhancement of energy absorption in 0_AX-F1 and 0_AX-F2 were 37.14% and 51.42% respectively compared to 0_AX-F0. 0_AX-F3 did not show significant improvement, with only about 45.71%. Eccentric loading condition leads to little improvement in energy absorption. Decline in energy absorption values for 25mm eccentric loading were calculated as 37.14%, 33.33%, 22.64% and 21.56% compared to their axial counterpart. Corresponding reduction for 50mm eccentric loading were 42.85%, 35.42%, 24.52% and 23.52% respectively.

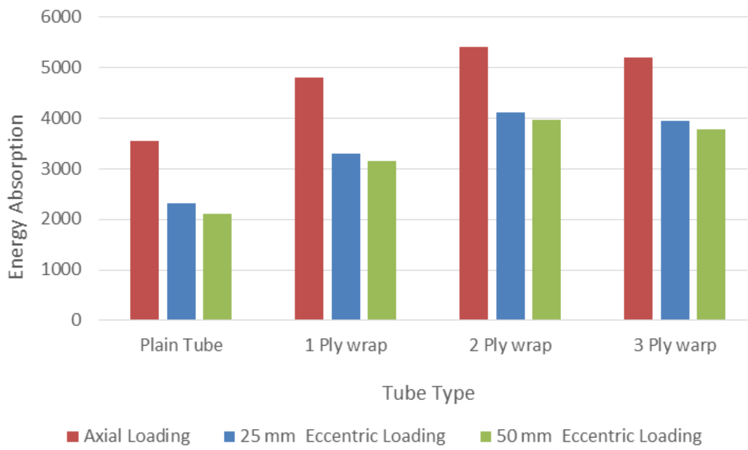


Figure 9. Comparison of energy absorption

4.1.3 Ductility ratio

Ratio of deflection at ultimate load to defection at yield load is quantified through the deflection ratio. Ductility was found to enhance as the number of layers of wrapping were increased as shown in Fig. 10.

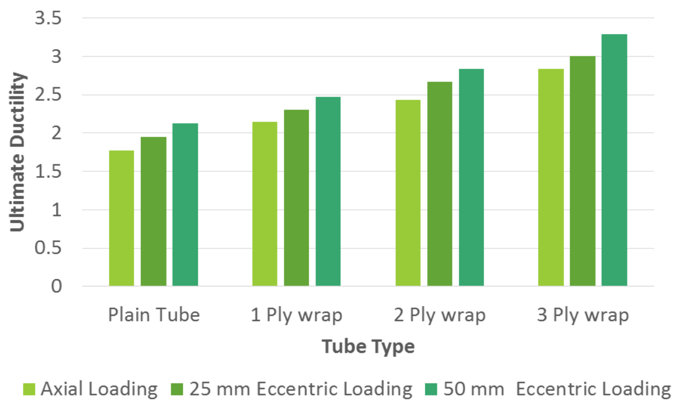
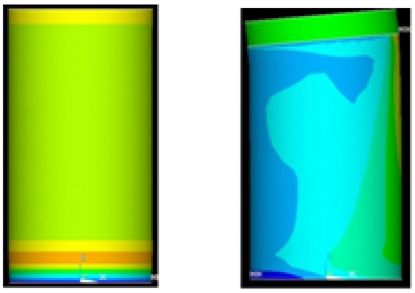


Figure 10. Comparison of ductility in tubes

Percentage increase in ductility for 0_AX-F1, 0_AX-F2 and 0_AX-F3 are 20%, 37.14% and 60% respectively compared to 0_AX-F0. Even though the eccentric loading reduced the ductility, considerable increase of 15.78%, 31.57% and 57.89% were noticed for 25mm eccentricity for 1 ply, 2 ply and 3 ply respectively. But increase in load eccentricity to 50mm, showed very little improvement of 9.09%, 27.27% and 45.45% correspondingly.

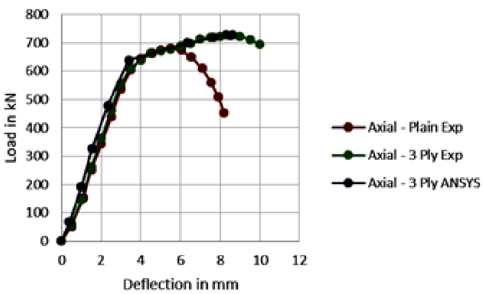
4.2 Numerical results

Both bare steel tube and wrapped tubes were modelled and analysed for different loading conditions. As the experimental results were in the form of load vs. axial shortening curves, similar results from finite element analysis were compared. The results obtained by numerical analysis were found to be agreed with the corresponding experimental results. The deflection contour was found to be similar to that obtained from the experimental study as shown in Fig. 11.

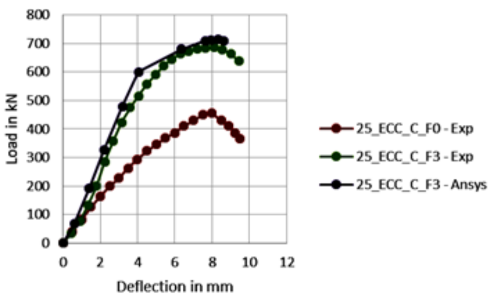


(a) Axial (b) Eccentric

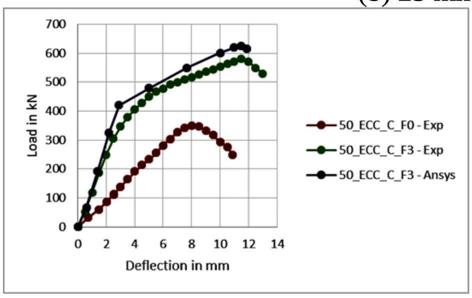
Figure 11. Failure modes of steel tubes - ANSYS



(a) Axial loading



(b) 25 mm eccentric loading



(c) 50mm eccentric loading

Figure 12. Comparison of load deflection curve

The load vs. displacement curve for axial loading and 25 mm and 50 mm eccentric loading were obtained through ANSYS and validations with experimental results are exhibited in Fig. 12 (a), Fig. 12(b) and Fig. 12(c) respectively.

From Fig 12 it was found that pattern of improvement in ultimate load, stiffness, energy absorption and ductility as observed in experimental works matched with the numerical results.

5. CONCLUSIONS

Present study was carried out on wrapped and unwrapped hollow steel tubes under axial and eccentric compression. Strengthening is achieved through glass fiber sheet with epoxy binder. The following conclusions are arrived from both experimental and numerical results.

- Good agreement exists between the loads vs. axial shortening curves obtained from experimental study with that of the curves obtained from numerical study.
- For both axial loading and minor eccentric loading, control of localised buckling along with percentage increase in stiffness and energy absorption are significant for strengthened specimens with two layers of wrapping.
- Whereas the percentage increase in stiffness and energy absorption is not significant for wrapped specimens subjected to high eccentric loading.
- Ductility is also improved through wrapping both for axial and eccentric loading.
- Increasing the number of wrap layers above two caused unfavourable inward buckling.
- The numerical model could be used for validating similar specimens under biaxial eccentricity.
- Study could be extended for square and rectangular hollow columns under eccentric load conditions.

Acknowledgements: The authors would like to express their gratitude to Vice chancellor of SASTRA University for providing the laboratory facilities in school of civil engineering to complete this research work successfully.

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