EFFECTS OF TENSION AND COMPRESSION LOADS ON THE FRP WRAPPED STEEL TUBES

Asghar Vatani Oskouei
[a]Department of Civil Engineering, Shahid Rajaee Teacher Training University
E-mail: asvatani@gmail.com

Laya Zahedi
Islamic Azad University, Science and Research Branch, Sirjan, Iran.
Telephone: +98-21-22970021; Fax: +98-21-22970021
E-mail: laya60zahedi@gmail.com

Abstract

Steel tubes are the most applicable members in jacket types of offshore structures. Under many load conditions, deterioration may be occurred in lots of these elements, so rehabilitation and retrofitting of them is an important matter for service ability of these types of marine structures. In this study, strengthening of steel tubes with FRP laminates are investigated by numerical approach. Also, a parametric study is carried out on the tensile and compressive axial force of the tube and the effects of these parameters were investigated closely. For this purpose, the ABAQUS finite element software was used. In the finite element model, the monotonic loading of four-point bending with quasi-static method was applied. Results was shown that FRP laminates, will be improved the mechanical behavior of steel tubes such as strength and stiffness. In the analysis, the failure mode was in the load and support location.

Keywords: FRP Laminates, FEM analysis, Marine Structures, Tubular members, Offshores

Introduction

Over the past decade, fiber-reinforced polymer (FRP) composites have been widely used in the strengthening of concrete structures [1,2]. More recently, the use of FRP to strengthen metallic structures has also attracted a significant amount of attention [3], but this work has generally been limited to the strengthening of metallic beams by the bonding of FRP laminates. The present paper is concerned with the performance enhancement of circular hollow steel tubes with FRP laminates.

Circular hollow steel tubes are widely used as members of offshore and a common failure mode of such tubes when subjected to axial compression and bending.

There are increasing research efforts concerning the application of FRP to steel structures with very promising results. High stiffness fibers, such as carbon fibers, can effectively enhance the mechanical properties of steel structures such as strength and stiffness; additionally, composites could also enhance the fatigue life of steel.

The primary application of existing research on FRP to steel composites is for the repair of bridges. One of the first known studies on this topic involved the use of CFRP laminates to repair steel-concrete composite bridge sections [4]. Six composite beams were tested in a four-point bending set-up. The resulting average increase in bending strength of the beams varied from 12% to 50%. The increase in stiffness was small, but the failure mode was generally ductile with large deformations.

Another study of the rehabilitation of deteriorated steel bridge members [5] covered two major matters concerning the use of composites for rehabilitating steel girders: its effectiveness and its durability.

Miller et al. [6] tested two full-scale steel-CFRP composite girders under fatigue loading at a stress range of 34 MPa for 10 million cycles. An examination of the specimens concluded that the retrofit had good fatigue resistance. Afterwards, in a field application, a slab-on-girder bridge with high truck traffic had CFRP plates bonded to the outer face of the tension flange of one girder, over the full length of the girder. Static results indicated an increase in stiffness of 12%, whilst the girder continued to be monitored to study the long term effects on the bond durability of the CFRP under fatigue and freeze-thaw conditions.

In another study [7, 8], the effectiveness of applying CFRP plates to the tension flange of intact and damaged steel-concrete large-scale composite girders for strengthening and repair was investigated. Three undamaged girders were retrofitted with layers of CFRP laminate plates [7] and ultimate four-point bending strength increases between 44% and 76% were reported. The tension flanges of three other beams were cut to simulate localized damage [8] and then repaired by bonding a similar number of CFRP laminate plates to the bottom flange. The strength increase of the repaired specimens ranged from 20% to 80% and the stiffness of the damaged specimens was recovered by an average of 93%. It was noted also that, for both the undamaged and damaged retrofitted girders, the efficiency of the CFRP plates at failure decreased as the number of layers increased.

In a more recent study by Al-Saidy et al. [9], steel beams were damaged deliberately at their tension flange and repaired with CFRP plates. Pultruded CFRP plates with unidirectional fibers were attached either to the tension flange or to the lower area of the beam web, and the beams were tested in four-point bending. It was concluded that the strengths of the damaged beams were fully restored to their undamaged states, with gains in strength ranging between 6% and 54%; however, the stiffness could only be partially restored to 50% of the undamaged value.

The feasibility of using new types of high modulus CFRP materials to increase the strength and stiffness of both steel monopoles and steel-concrete composite girders has been performed in another study [10]. Three monopoles were strengthened using several configurations of CFRPs and tested as cantilevers. The monopoles were welded to a thick baseplate and had a uniformly tapered dodecagonal cross-section. Strengthening was performed using either composite sheets or strips of CFRP laminates, with transversely oriented sheets placed on top to avoid delamination of the longitudinal sheets. In both cases, the composites were anchored to the baseplate by several mechanical fasteners. As a result, the stiffness increase ranged from 17% to 53% which demonstrated the adequacy of the employed strengthening method.

As part of the same study [10], steel-concrete composite girders were fabricated and CFRP strips were bonded side by side at the center of the girder. The beams were tested in four-point bending and the results indicated a girder stiffness increase of 12% whilst the strength increase was 42%.

Finally, two innovative in situ applications of composite materials in the construction field in the United Kingdom have been described by Garden [11]. One application consisted of the rehabilitation of cast iron beams using pultruded CFRP bonded to their tension flanges. The beams were part of a garage structure beneath a residential development and needed to be strengthened to compensate for lost flexural capacity due to corrosion and to allow for future load increases. The other CFRP-to-metal field application described by Garden [11] consisted of the rehabilitation of curved steel beams using laminates. The beams were part of a structural frame of a historic building dating back to 1903 and needed to be strengthened because of loss of flexural capacity due to corrosion damage and to accommodate an anticipated increase in floor loading. In both applications, composites showed very good potential for use in the rehabilitation of metal structures.

To obtain composite behavior between steel and FRP composites it is essential to have a good bond. Existing literature indicates that debonding and delamination are the main failure modes of the experiments done hitherto with FRP and steel. Since the forces are transferred from the steel to the FRP through the adhesive, to take advantage of the full capacity of the composite the adhesive has to be able to transmit the forces efficiently and it is preferred that the fibers rupture before a failure of the adhesive occurs. Some investigators have suggested that, when adhesives are not fully capable of transferring these forces, additional fasteners may be employed [4].

The bond must have good durability at both elevated temperature and freezing conditions, which is the case for bridges located in North America. The adhesive that has demonstrated good durability under such environmental conditions is the epoxy resin and, as mentioned, bonding is enhanced when the surfaces are treated with silane [12].

Another variable that seems to affect the stress concentration on the adhesive is the adhesive thickness. Wright et al. [13] tested a joint between steel plates and FRP and found that, by increasing the thickness of the adhesive layer, the relative stress concentration level was reduced by 21%. Further reduction of the stresses could be accomplished by adding a fillet at the end of the bond line, wherein it was found that the corresponding stress concentration was reduced by 32%.

Studied Experimental data

The objectives of this experimental project by Seica and Packer [14] were to assess the feasibility of strengthening tubular steel members subjected to bending and to develop an adequate repair method for underwater and in-air applications. In the present paper, some of their results were utilized in order to verify the numerical model.

In this test, specimens classified into one reference specimen without FRP, two FRP wrapped specimens prepared in air and four FRP wrapped specimens cured under water. Each retrofitted specimen, wrapped with three FRP laminates by the angle of 0°, 0° and 90° respectively. The specimens were tested under four-point bending with quasi-static method (monotonic loading). The details, place of loading and stacking sequence of FRP layers can be seen in Fig. 1.

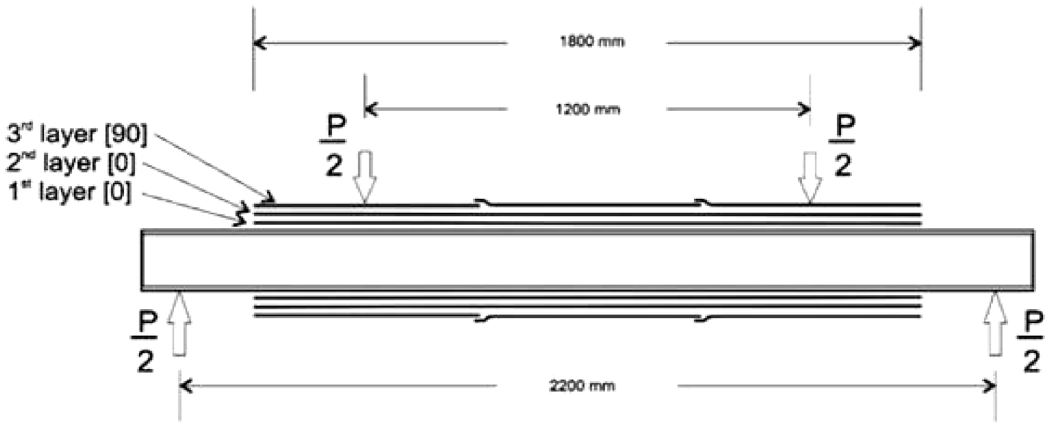


Fig. 1)General detail of tested specimens [23].

Finite Element Modeling

Geometrical characteristics and boundary conditions of analyzed models

ABAQUS finite element software was utilized for the modeling [15]. All of the lengths and geometrical properties were modeled exactly according to test specimens. In order to reduce calculation efforts, symmetry properties were used in the models. So one fourth of experimental specimen was modeled due to this purpose. According to Fig. 2, symmetry was assumed about XY and YZ planes. Hence, in the XY plane Uz= θx= θy=0 and in YZ plane Ux= θy= θz=0. In addition, supports of the model coincided with that of the tests and they were included with a loading plate and a support plate. The sides of the plates which were not in contact with the tube and are parallel to XZ plane were completely fixed except for the loading plate which its Y-direction displacement was assumed to be free and the monotonic displacement was applied to this degree of freedom.

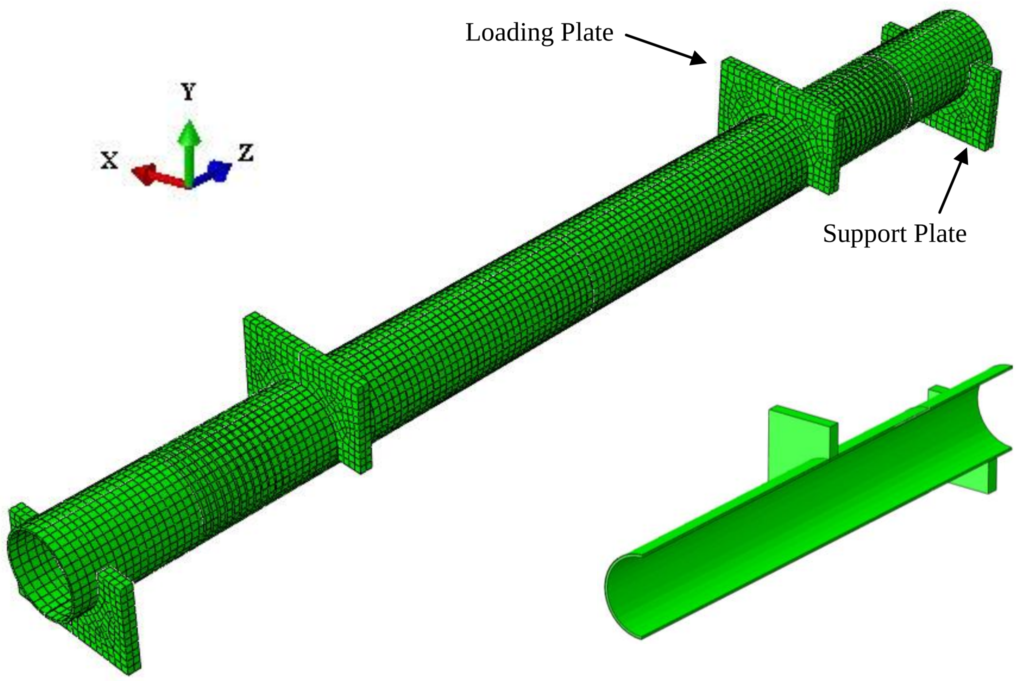


Fig. 2)Simplified Model with Symmetry Effect Consideration.

Selecting the element type

As shown in Fig. 3, in the present study, ABAQUS element type C3D8R was used to model the steel tube, loading plate and support plate. It is an 8-node brick element with reduced integration stiffness, and is used for nonlinear analysis including contact, large deformation, plasticity, and failure. Furthermore, FRP laminates were modeled with shell element S4R. It is a 4-node shell element with reduced integration stiffness. The overall mesh size was 5 mm. The finite element model of the tube is plotted in Fig. 3.

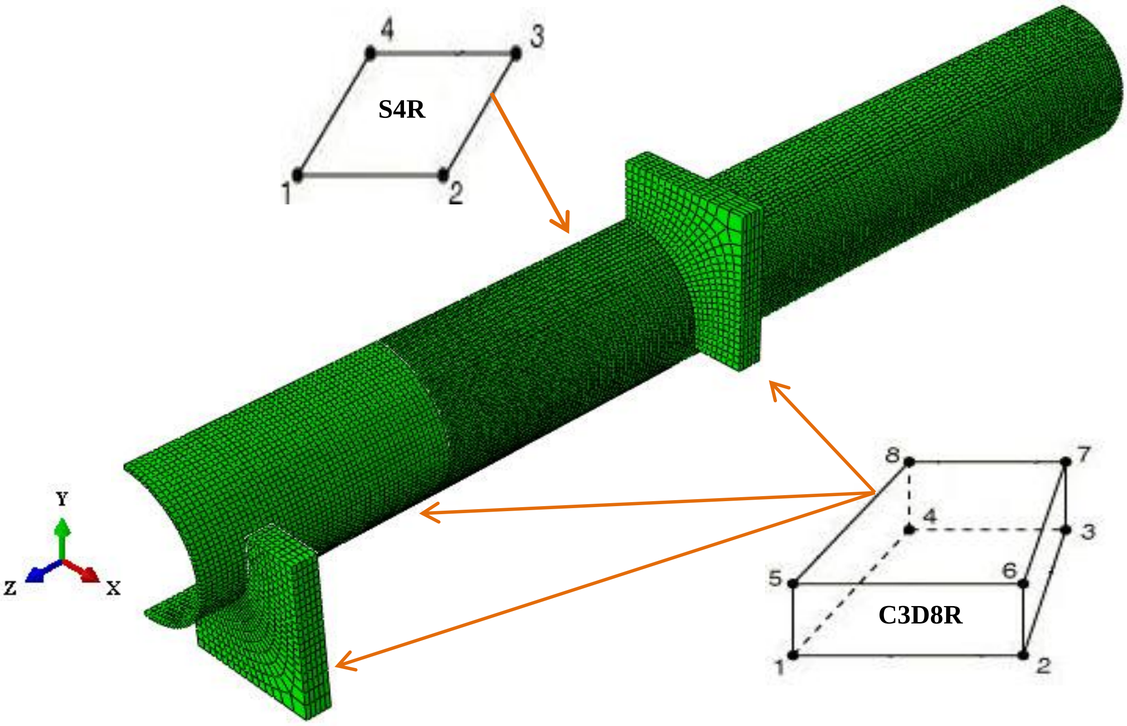


Fig. 3)Finite element model.

Material modeling

The bilinear elastic-plastic model was used for the steel tube according to test data. The mechanical behavior for both tension and compression is assumed to be identical.

To model FRP laminates, it was assumed that FRP materials are elastic and laminar with their elasticity parameters E_1, E_2, ν_{12}, G_{12}, G_{13}, and G_{23}.

Contact interactions

Contact interactions are another important aspect for the finite element modeling of composite steel–FRP and steel-steel models. Improper definition of contact interactions may introduce nonphysical influences into the simulation especially where there are more than two components being considered such as the concrete column, reinforcing steel, steel beam, inner panel, horizontal stiffener, face bearing plates and cover plates.

For the FRP and steel part interface in support regions and also in the model without FRP between the steel tube and steel supports, a surface-based contact was used. The surfaces of supports were taken as the master surface and the tube surface as the slave surface. A hard contact relationship was used to minimize the penetration of the slave nodes and prevent the transfer of tensile stress across the interface with a frictionless contact property.

For the interface of FRP and steel tube, a surface based tie constraint was used to constrain each of the nodes on the surfaces to have the same translational and rotational motions.

Load application

Because of the fact that the type of loading in the laboratory was quasi-static, nonlinear static loading with Newton-Raphson convergence method was applied with loading plate. The monotonic loading pattern in the model is shown in Fig. 4. The applied vertical displacement was similar to the experiment [14]. In fact, we applied displacement and read force from the model.

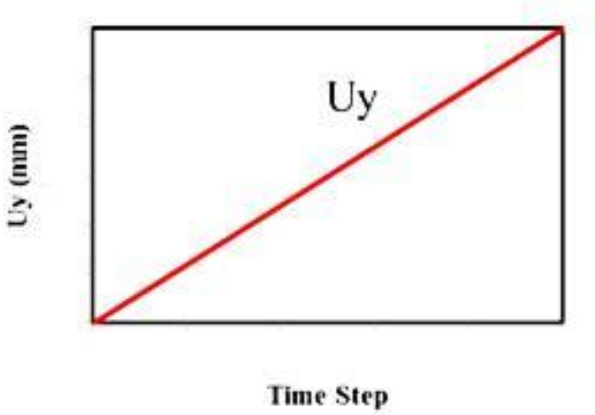
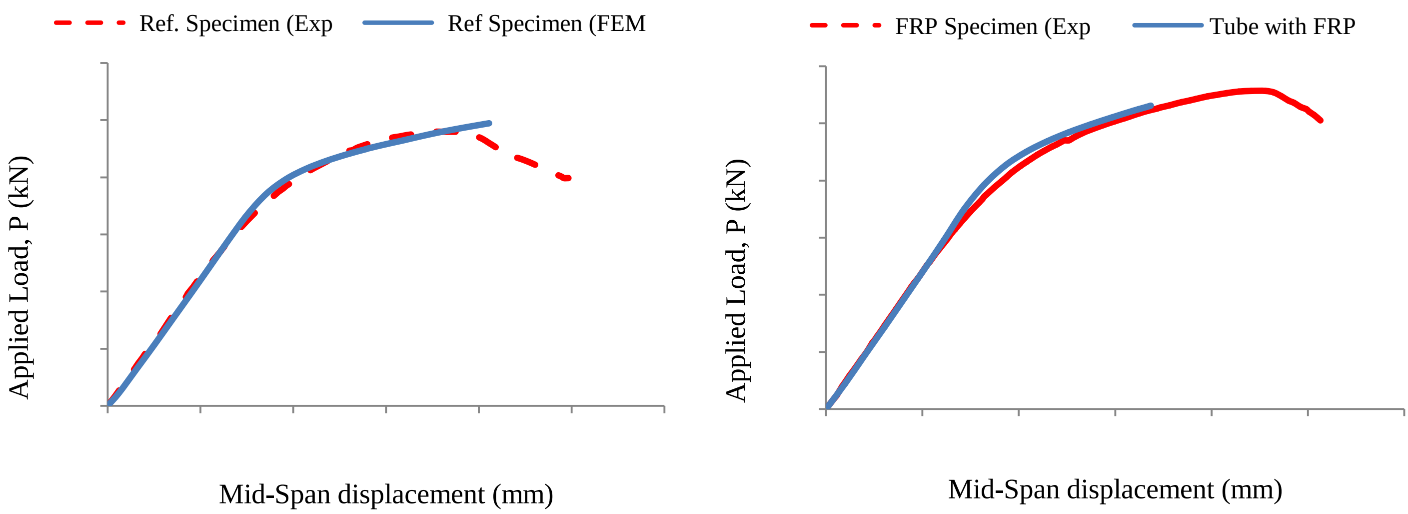


Fig. 4)Loading pattern.

Verification of the FE model

In comparison with experimental study, finite element analysis is more efficient and convenient for determining the stress distribution along the tube and FRP laminates. However, the accuracy of the FEA predictions should be verified by experimental test results. In order to validate the finite element model, two test specimen results was used consisting a bare steel tube (reference specimen) and steel tube wrapped with three layers of FRP laminates cured in air were selected. Verification results which are separately presented for the two selected specimens are plotted in Fig. 5.



(a) Steel tube without FRP laminates (b) Steel tube with FRP laminates

Fig. 5)Comparison of finite element model and experimental result.

Modes of failure and stress distribution

In the reference model (without FRP laminates) under bending, one failure mode was observed in the load and support positions as it can be seen in Fig. 6. The Mises stress distribution in Fig. 6 shows that in the regions, under the loading and support plates, stress concentration is more than other regions for the steel tube without FRP laminates under four point loading which coincides well with the test result reported by [14]. Furthermore, it can be observed that in the region with constant moment, the stress is changing uniformly along Y axis.

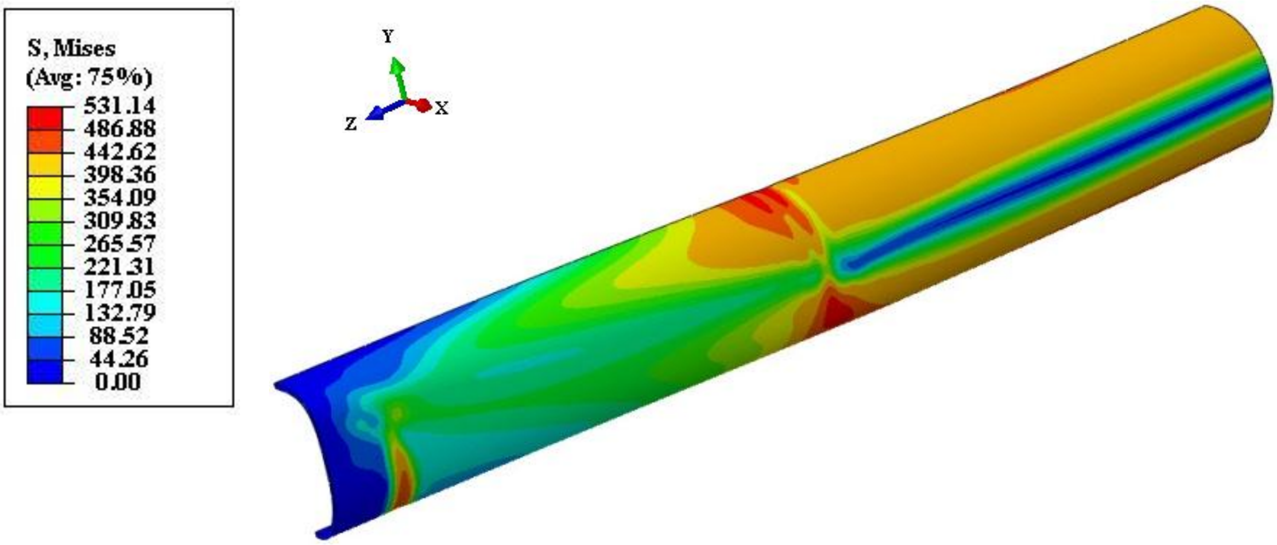
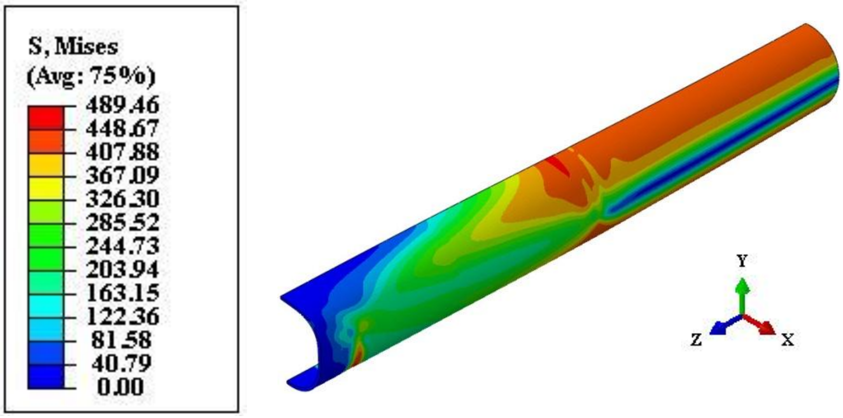
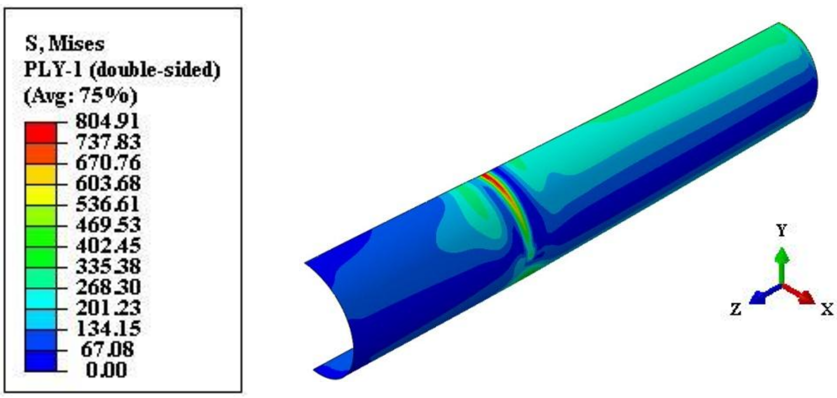


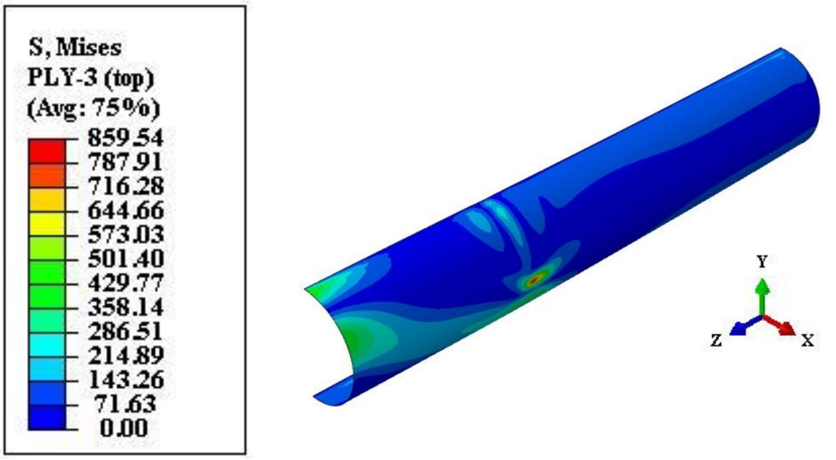
Fig. 6)Mises stress contour for the steel tube without FRP laminate.



(a) Mises stress contour in the steel tube



(b) Mises stress contour in the FRP plies with 0° direction



(c) Mises stress contour in the FRP plies with 90° direction

Fig. 7)Mises stress contour for the steel tube with FRP laminate.

In fig. 7 contour of Mises stress is plotted for steel tube and FRP plies. It can be observed that wrapping FRP laminates around the steel tubes makes stress distribution more uniform and prevents high stress concentration under loading and support plates. Furthermore, there are high stress values which tend to tear 0° FRP plies exactly under the loading plates. In addition, Mises Stress values reach higher because of ovalization increasing in the 90° FRP ply where the loading plate is just finished. Hence, the stress distribution in the loading region is more critical due to ovalization tendency in the region.

Parametric study on the tensile axial force

In order to investigate the effect of tensile force applied to the steel tube, four models were developed. The applied tensile load was 0, $0.2F_y$, $0.4F_y$ and $0.6F_y$. According to the Fig. 11, by applying tensile force to the tube section, the tube strength decreased under bending loading and this decrease was more for $0.4F_y$, and $0.6F_y$ tensile load. The strength deterioration was 1.7%, 4.3%, and 17.6% for $0.2F_y$, $0.4F_y$ and $0.6F_y$ tensile axial load, respectively.

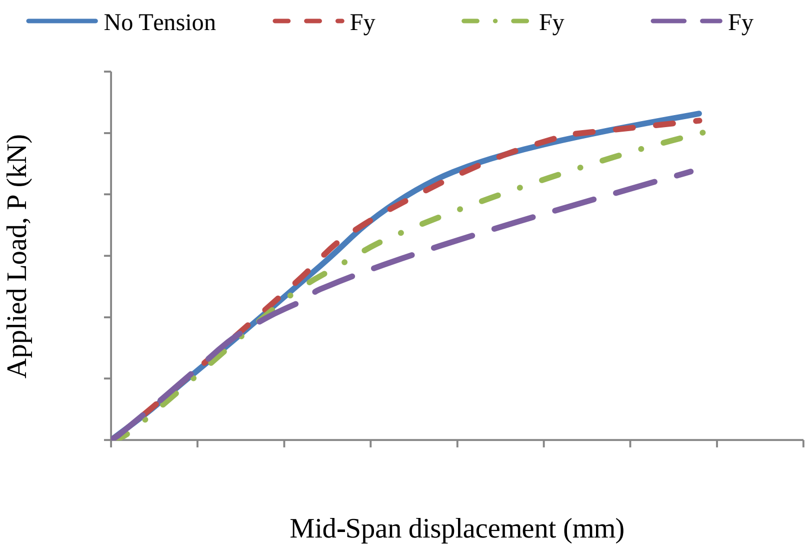


Fig. 11)Effect of tensile axial load.

Parametric study on the compressive axial force

In order to investigate the effect of compressive force applied to the steel tube, three models were developed. The compressive load was 0, $0.1F_y$ and $0.3F_y$ applied to the tube section.

Responses of the models are shown in Fig. 12. As Fig. 12 illustrates, by increasing the compressive force, strength and stiffness decrease significantly. Strength deterioration for the tube was 14% and 28% for $0.1F_y$, and $0.3F_y$ compressive load, respectively. Furthermore, Stiffness decrease was 10.2% and 26.9% for $0.1F_y$ and $0.3F_y$ compression load.

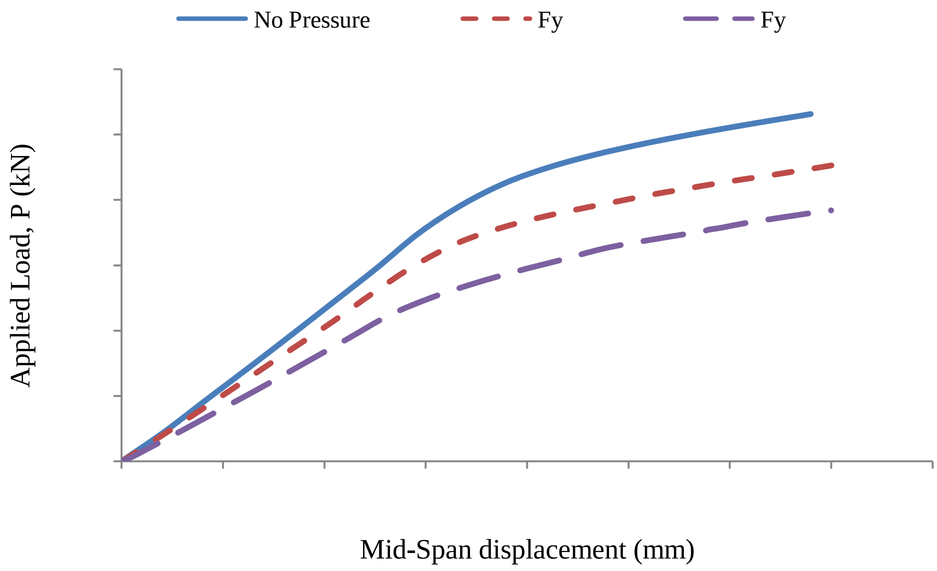


Fig. 11)Effect of compression axial load.

Conclusion

In this paper, a parametric study was carried out by applying tension and compression on the steel tube model wrapped with FRP layers. Thereafter, the effect of using FRP laminates around the steel tube on the parameters of stiffness and strength was examined. Also, the verification results were carried out from the experimental work. Furthermore, stress distribution in the steel tube and FRP laminates were investigated.

In the models (with/without FRP laminates) under bending, one failure mode was observed similar to the experimental results by [14]. Under loading plates and support plates the tube was under high stress values and plastification. It was good agreement for the Force-Displacement curves of numerical models and experimental specimens, as shown in Figure 5.

Moreover, by applying tensile load during the bending, strength deterioration was 1.7%, 4.3%, and 17.6% for 0.2Fy, 0.4Fy, and 0.6Fy tensile axial load, respectively. But no stiffness decrease was observed in responses of the models with tensile strength.

Furthermore, applying compressive load to the tube, during the four point bending load strength and stiffness decreased. Strength deterioration for the tube was 14% and 28% for 0.1Fy, and 0.3Fy compression load, respectively. Furthermore, Stiffness decrease was 10.2% and 26.9% for 0.1Fy and 0.3Fy compression load.

References

[1] Teng JG, Chen JF, Smith ST, Lam L. FRP strengthened RC structures. John Wiley & Sons Ltd; 2002.

[2] Teng JG, Chen JF, Smith ST, Lam L. Behavior and strength of FRP-strengthened RC structures: a state-of-the-art review. Proc Inst Civil Eng–Struct Build 2003; 156(SB1):51–62.

[3] Hollaway LC, Cadei J. Progress in the technique of upgrading metallic structures with advanced polymer composites. Prog Struct Eng Mater 2002; 4:131–48.

[4] Sen R, Liby L. Repair of steel composite bridge sections using CFRP laminates, U.S. Department of Transportation Contract B-7932. Tampa, FL: University of South Florida; 1994.

[5] Mertz DR, Gillespie JW. Rehabilitation of steel bridge girders through the application of composite materials, NCHRP Report No. 93-ID11, Washington, DC: Transportation Research Board; 1996. p. 1–20.
[6] Miller TC, Chajes MJ, Mertz DR, Hastings JN. Strengthening of a steel bridge girder using CFRP plates. ASCE J Bridge Eng. 2001;6(6):514–22.
[7] Tavakkolizadeh M, Saadatmanesh H. Strengthening of steel-concrete composite girders using carbon fiber reinforced polymer sheets. ASCE J Struct Eng 2003; 129(1):30–40.
[8] Tavakkolizadeh M, Saadatmanesh H. Repair of damaged steel-concrete composite girders using carbon fiber-reinforced polymer sheets. ASCE J Compos Constr 2003; 7(4):311–22.
[9] Al-Saidy AH, Klaiber FW, Wipf TJ. Repair of steel composite beams with carbon fiber-reinforced polymer plates. ASCE J Compos Constr 2004; 8(2):163–72.
[10] Schnerch D, Rizkalla S. Strengthening of scaled steel-concrete composite girders and steel monopole towers with CFRP, North Carolina State University Report, Raleigh, NC, 2004.
[11] Garden HN. Use of advanced composites in civil engineering infrastructure. Struct Build 2004;157(6):357–68.
[12] Mertz DR, Gillespie JW. Rehabilitation of steel bridge girders through the application of composite materials, NCHRP Report No. 93-ID11, Washington, DC: Transportation Research Board; 1996. p. 1–20.
[13] Wright PNH, Wu Y, Gibson AG. Fiber reinforced composite-steel connections for transverse ship bulkheads. Plastic Rubber Compos 2000; 29(10):549–57.
[14] Seica MV, Packer JA. FRP materials for the rehabilitation of tubular steel structures, for underwater applications. Compos Struct, 2007;80(3): 440-450.
[15] Hibbit, Karlsson and Sorensen, (2010), "ABAQUS standard user's manual," Version 6.10. USA.