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Characteristics of CFRP strengthened tubular joints subjected to different monotonic loadings

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Abstract. Tubular joints are used in the construction of offshore structures and other land-based structures because of its ease of fabrication. These joints are subjected to different environmental loadings in their lifetime. At the time of fabrication or modification of an existing offshore platform, tubular joints are usually strengthened to withstand the environmental loads. Currently, various strengthening techniques such as ring stiffeners, gusset plates are employed to strengthen new and existing tubular joints. Due to some limitations with the present practices, some new techniques need to be addressed. Many researchers used Fibre Reinforced Polymer (FRP) to strengthen tubular joints. Some of the studies were focused on axial compression of Glass Fibre Reinforced Polymer (GFRP) strengthened tubular joints and found that it was an efficient technique. Earlier, the authors had performed studies on Carbon Fibre Reinforced Polymer (CFRP) strengthened tubular joint subjected to axial compression. The study steered to the conclusion that FRP composites is an alternative strengthening technique for tubular joints. In this work, the study was focused on axial compression of Y-joint and in plane and out of plane bending of T-joints. Experimental investigations were performed on these joints, fabricated from ASTM A106 Gr. B steel. Two sets of joints were fabricated for testing, one is a reference joint and the other is a joint strengthened with CFRP. After performing the set of experiments, test results were then compared with the numerical solution in ANSYS Parametric Design Language (APDL). It was observed that the joints strengthened with CFRP were having improved strength, lesser surface displacement and ovalization when compared to the reference joint.

Keywords: tubular joints; in-plane bending; out-of-plane bending; CFRP; Ansys; experimental and numerical investigation

1. Introduction

Offshore structures such as jacket and jack up structures are fabricated using tubular joints. The tubular joints are subjected to different monotonic loadings such as an axial compression, in-plane bending and out-of-plane bending.

Axial compression, in-plane and out-of-plane bending is due to the self-weight of deck structure and other operational loads from the platform in their service life. In designing of tubular joints, due consideration is given to address these loads. These tubular joints when subjected to different types of loads experiences high stress concentration at the intersection and lead to failure. At times, these joints need to be strengthened or stiffened. Usually techniques such as filling of grout, adding of internal/external stiffeners and gusset plates are employed for strengthening repair. These techniques face major difficulties like corrosion and drag force, so new technique need to be addressed to resolve this.

Idea to use composite material such as glass fibre reinforced polymer (GFRP) and carbon fibre reinforced polymer (CFRP) to strengthen steel sections was popular in the 90s. In the 20th century, Miller *et al*. (2003) and Sen *et al*. (2001) used CFRP for strengthening bridge structures and found that the ultimate load carrying capacity of steel bridge got increased. Karbhari (2003) had shown that the durability of FRP composites for civil structures can provide significant advantages over other conventional materials in civil infrastructure applications. The idea of strengthening steel sections with FRP lead Aguilera and Fam (2013) to use GFRP to strengthen hollow square sections. For transverse load, the bearing capacity of steel sections strengthened with GFRP got increased when compared with the through-wall bolt technique.

Later, studies were done by Lesani *et al*. (2014) on tubular T-joint strengthened with GFRP under axial compression. Investigation was then extended to Y-joints strengthened with GFRP for axial compression. From their research, this technique was found to be an effective technique to strengthen tubular joints. Alam and Fawzia (2015) had found that strengthening the hollow sections with CFRP and GFRP found that CFRP sheets were better than GFRP to control global deformation. Fu *et al*. (2016) strengthened K-joints with CFRP and found that the CFRP sheets helped in delaying its primary failure mode.

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Narmashiri and Mehramiz (2016) strengthened circular cross-sections using CFRP and found that the load-bearing capacity got increased.

Al Zand *et al*. (2015) strengthened simply supported hollow steel tubes with CFRP by a partial wrapping technique (U-shaped wrapping). This technique improved the ultimate strength, and energy absorption capacity. Keykha (2017) strengthened steel square sections with CFRP and showed that the wrapping length, number of layers, and the location at which CFRP wrapped is going to create an increase in the ultimate load. Kadhim *et al*. (2018) strengthened square sections with CFRP in different loading directions and application of load in transverse direction showed a higher loading rate to other CFRP configurations.

Kim *et al*. (2014) had noticed that the crush force efficiency and specific energy got improved when thickness of CFRP lamina got increased while wrapping on to an aluminium square hollow section. Fatigue calculations on perforated hollow sections with CFRP were compared with perforated hollow sections by Ghazijahani *et al*. (2014) and found that fatigue life cannot be fully recovered with CFRP strengthening. Wang *et al*. (2014) had found that due to eccentric loading, the eccentric compressive strength of CFRP strengthened tubular structure filled with concrete section was affected.

The authors in their earlier study had performed numerical and experimental investigation on CFRP strengthened tubular T joints under axial compression and found that it was an effective technique Prashob *et al*. (2017). Only few studies were done on joints strengthened with CFRP; and all of these were on FRP strengthened joint subjected to axial compression.

In this work, the tubular Y-joints strengthened with CFRP subjected to axial compression were addressed. The studies were then performed on a T-joint subjected to in-plane and out-of-plane bending. For each set of experiments two identical joints are fabricated with ASTM A106 Gr. B steel. Initial one acts as a reference joint and the latter is the CFRP strengthened joint. Initial set of experiments were carried on Y-joints under axial compression. The next set of experiments were performed on a tubular T-joint subjected to in-plane bending, and the final set of experiments on a tubular T-joint subjected to out-of-plane bending.

2. Investigation of Y-Joints

The material used for fabrication of Y-joints is of ASTM A106 Gr. B (2015) steel designed using API RP-2A (2007). For the present investigations, two Y-joints were fabricated for axial compression. The joints were reduced in size to fit in a displacement controlled universal testing machine (UTM). According to API, the brace of the Y-joint need to be welded to the chord with an angle of 30° to 90°. The chord diameter was taken as 141.3 mm (ASTM scheduled sizes, 5- inch schedule 40 pipe); the brace diameter was 60.3 mm (ASTM scheduled sizes, 2- inch schedule 40 pipe). The chord length was measured between two extreme ends of the support. Two 6 mm plates were welded to the chord ends and 8 mm plate were welded to the brace end. The details of Y-joint designed using API standards are shown in Table 1 and the Y-joint configuration for the experimental setup is shown in Fig. 1.

Table 1 Y-Joint properties

D (mm)	d (mm)	T (mm)	t (mm)	L (mm)	θ	β	τ	α
141.3	60.3	6.55	3.91	892.3	60	0.42	0.59	12.62

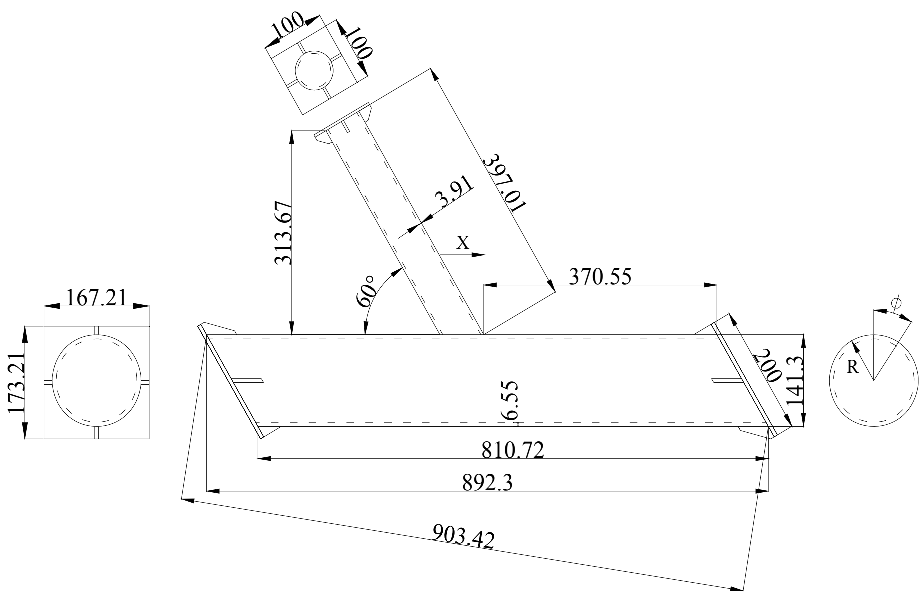


Fig. 1 Y-joint configuration for axial compression

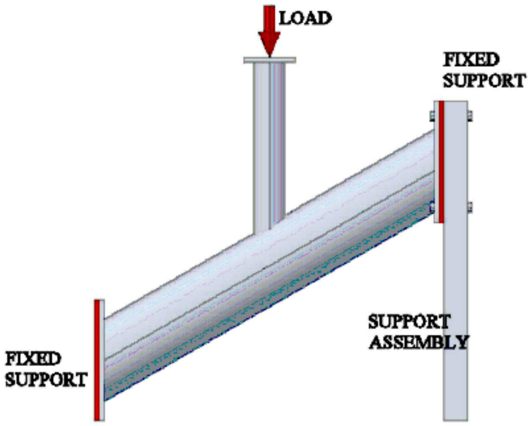


Fig. 2 General arrangement of Y-joint for axial loading

For the experimental setup, Y-joint needs to be kept on the UTM. To attain this, Y-joints were fabricated in such that brace of the joint was perpendicular to the loading plate of the UTM. A separate assembly was fabricated with a C-section to support the tubular joint. Then the tubular joint was bolted to the assembly using high strength bolts. General arrangement of Y-joint on the UTM is shown in Fig. 2.

2.1 Fixing of strain gauges

Strain gauges were used to measure the stresses at each location. For the CFRP strengthened joint strain gauges were kept below the first layer and for the reference joint the strain gauges were kept on the tubular joint at the same locations. A total of nine strain gauges were used in each joint. At each location shown in Fig. 3, three strain gauges were arranged as a strain rosette with 0°, 45° and 90°. Initially, the locations were strain gauges need to be kept was cleaned using a P220 water paper to get a smooth finish, and finally with acetone. After cleaning the surface, the strain gauges were kept in a cellophane tape and positioned accurately at the locations. Figs. 4 to 7 show the procedure for fixing of strain gauges at each location.

The two terminals of the strain gauge were insulated from the bare metal of the tubular joint by an insulation tape. After insulation, the terminals of the strain gauges were connected to the data acquisition system (DAS) by means of soldering. The soldered wires were then properly fixed to the tubular joint with the help of hot gun glue; else there is a chance of detaching the strain gauge from the joint. After fixing the strain gauges and wires necessary markings were done on the wires, for easy identification. By fixing strain gauges as a rosette, measurements are done and stresses can be calculated. The general arrangement of

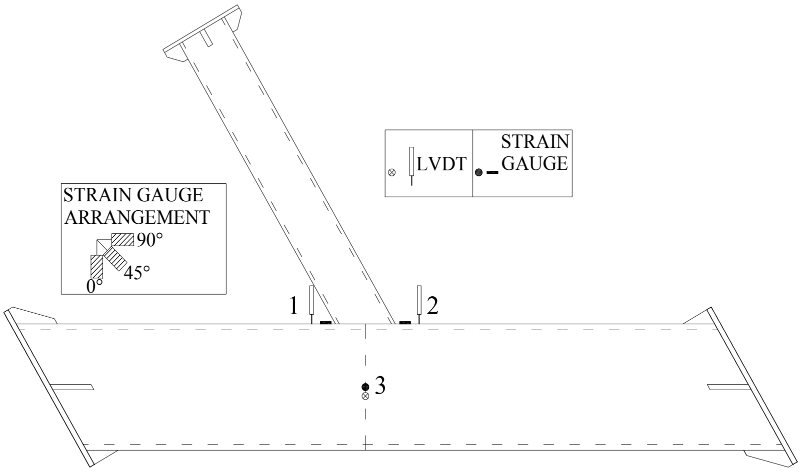


Fig. 3 Arrangement of LVDT and strain gauges for a Y-joint

Fig. 4 Cleaning the location with acetone

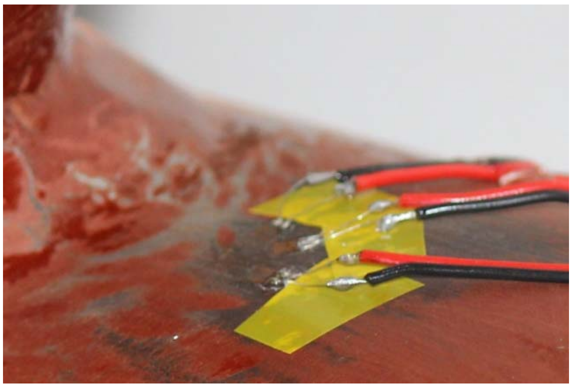


Fig. 5 Strain gauges fixed on the joint

Fig. 6 Soldering the strain gauges to lead wires

Fig. 7 Using hot glue fix the wires on to the joint

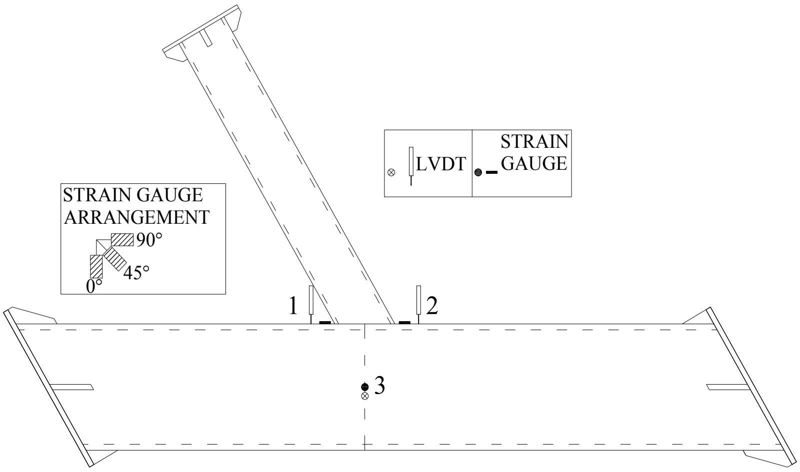


Fig. 8 Schematic diagram of CFRP wrapped on a Y-joint

Table 2 CFRP orientation for Y-Joint

Detail	Orientation Scheme	Total ply thickness
Brace	[0/90/0/90]	2.0
Chord	[0/-45/0/45/0/45/0]	3.5
Brace-Chord Intersection	[0/0/90/-45/0/0/90/45/0/45/0]	5.5

strain gauges (locations were marked by numbers) and LVDT arrangements are shown in Fig. 3.

2.2 CFRP wrapping on Y-joint

A template of length equal to chord circumference and width of wrapping length was cut from the CFRP fibre sheets for wrapping the chord of tubular joint, similarly for the brace a profile was cut to meet the brace-chord intersection. The wrapping length, number of layers and orientation of CFRP sheets were selected based upon the previous study conducted by the authors Prashob *et al.* (2018). Details of CFRP wrapping on Y-joint is shown in Table 2. Thickness of each ply is presumed to be 0.5 mm. Schematic diagram of CFRP wrapped on to a tubular Y-joint and dimensional details of template for the chord and brace are shown in Figs. 8 to 9.

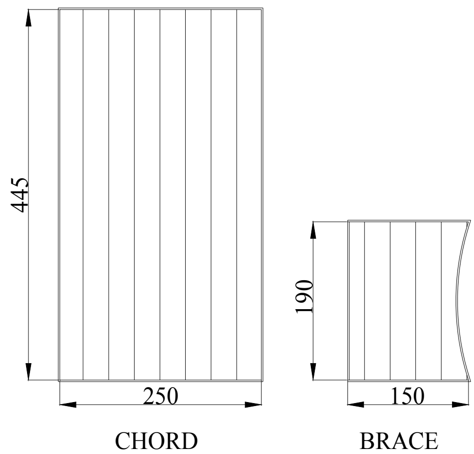


Fig. 9 Details of chord and brace template

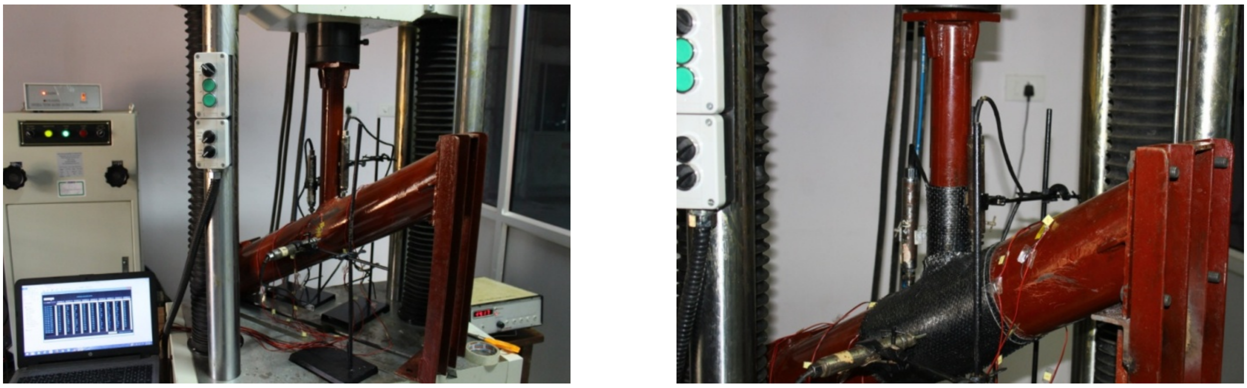
2.3 Experimental investigation on Y-joints

Computer controlled electro-hydraulic servo UTM with a maximum load of 1,000 kN was used to perform the test on the Y-joint. The tubular joint was kept on the bed of the universal testing machine with the support assembly. Chord end plates of the joint were bolted onto the support assembly; this support assembly was then bolted onto the dove tail grove provided on the UTM bed. Speed of the testing was set to 2 mm/min. Firstly; the reference joint was tested under axial compression on brace and then the joint with CFRP wrapping. Specimen arrangements on UTM are shown in Fig. 10. A numerical model of reference and CFRP strengthened Y-joints are also shown in Fig. 11.

3. Investigation of T-joints subjected to IPB and OPB

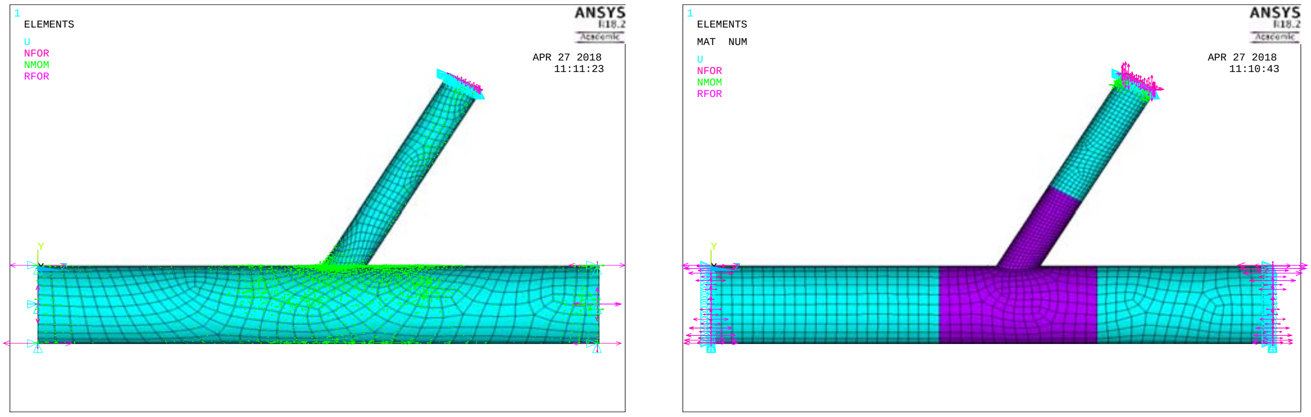
3.1 Design of T-Joints for in-plane and out-of-plane bending

Tubular T-joints subjected to in-plane bending (ipb) moments are called Vierendeel joints, named after Arthur Vierendeel; these joints are common in offshore structures.



(a) Reference Y-joint (b) CFRP strengthened Y-joint

Fig. 10 Arrangement of Y-joint specimen on UTM



(a) Reference Y-joint (b) CFRP strengthened Y-joint

Fig. 11 Numerical model of Y-joint in ANSYS APDL

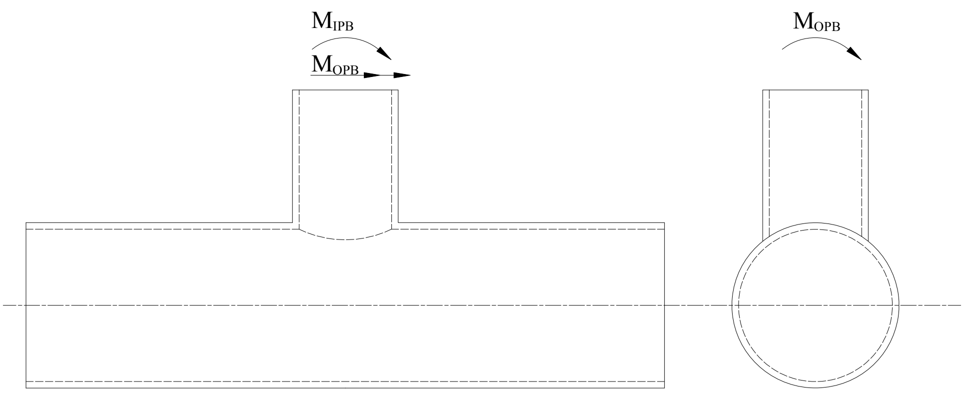


Fig. 12 In-plane bending moment and out-of-plane bending moment

Out- of-plane bending (opb) moments are more frequent in multiplanar structures like offshore structures, not very common in uniplanar structures. Apart from axial compression and tension, tubular member's experiences in-plane and out-of-plane bending. Joints to resist in-plane and out-of-plane bending was given due consideration in the design process. Fig. 12 shows in-plane and out-of-plane bending moment applied on a T-joint.

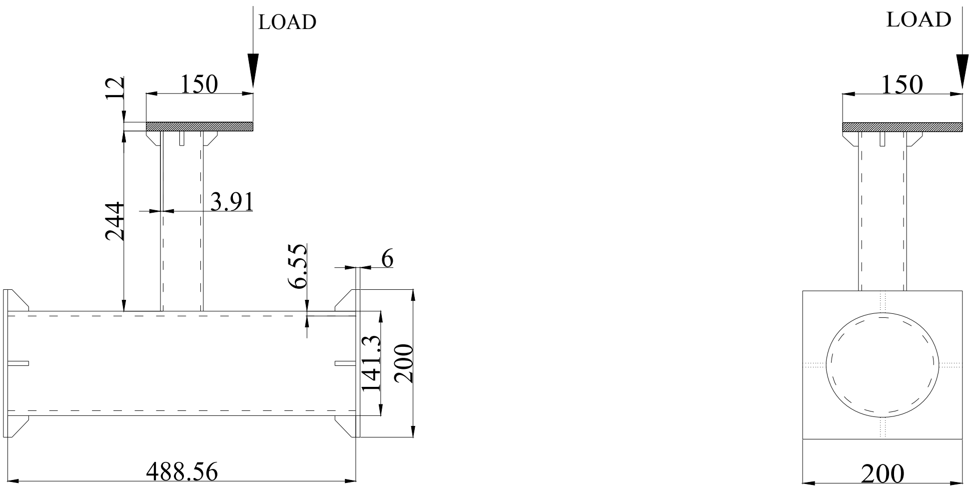
The joints were reduced to scale so that it can be accommodated in a strain controlled universal testing machine. The details of specimen for in-plane bending and out-of-plane bending moment of T-joints are shown in Table 3. T-joints were fabricated so that the loading plate of UTM can apply both in-plane and out-of-plane bending. The T-joint configurations for in-plane and out-of-plane bending are shown in Fig. 13.

T-joints are fabricated from circular tubes, and are tested under in-plane and out-of- plane bending in a universal testing machine. The chord length was measured between two extreme ends of the support and two 6 mm plates were welded to the chord ends and 8 mm plate were welded to the brace end.

For the T-joint subjected to in-plane bending, one LVDT was kept on the crown line and on either side of the brace. For the T-joint subjected to out-of-plane bending, one LVDT was kept on the crown line (i.e., either left or right

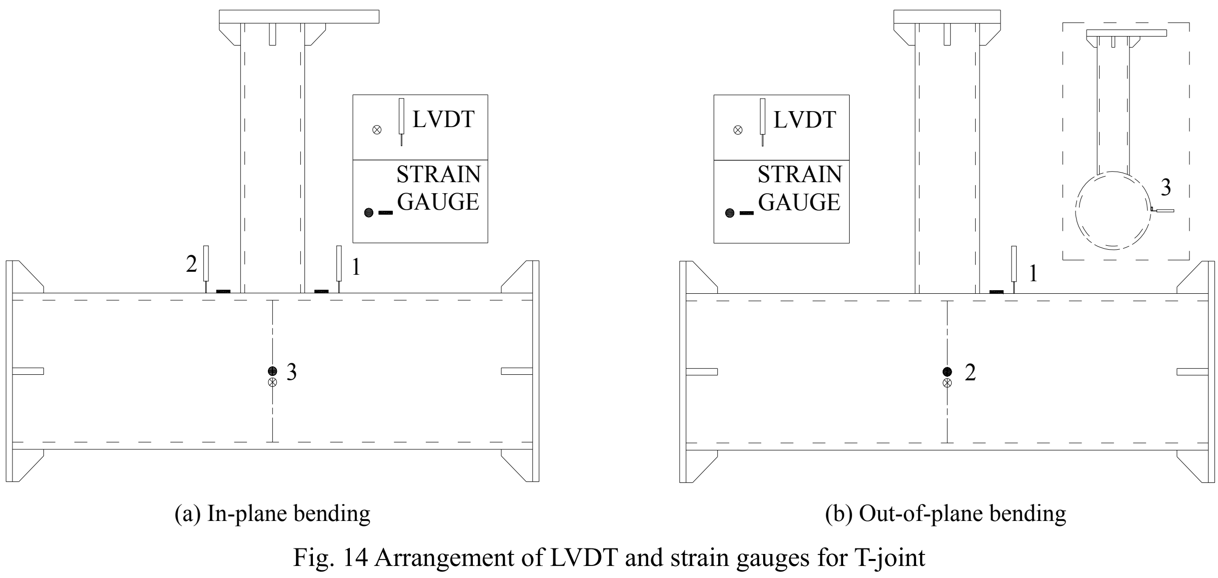
Table 3 T-Joint properties

D (mm)	d (mm)	T (mm)	t (mm)	L (mm)	θ	β	τ	γ	α
141.3 60.3	60.3 3.91	6.55	3.91	488.56	90°	0.42	0.59	10.78	6.91 60.3



(a) In-plane bending (b) Out-of-plane bending

Fig. 13 T-joint configuration



(a) In-plane bending (b) Out-of-plane bending

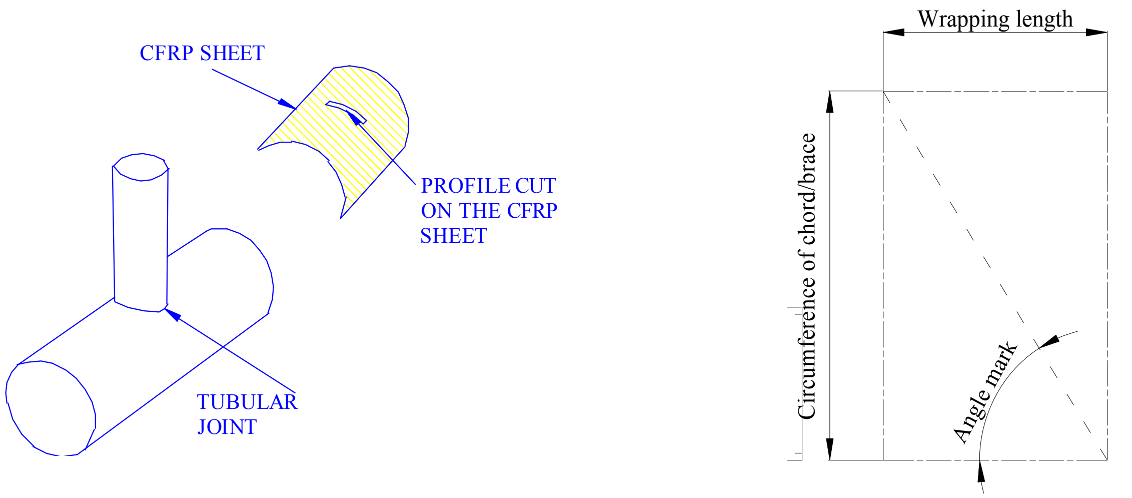
Fig. 14 Arrangement of LVDT and strain gauges for T-joint side of the brace) and two LVDTs were placed on the hoop line of the brace facing each other. Strain gauges were adhered on the same locations where LVDTs were placed. The general arrangement of strain gauges and LVDTs for in-plane and out-of-plane bending are shown in Fig. 14. To identify the strain gauge location, numbers were marked on the IPB and OPB specimen.

For an IPB specimen (1 is where, brace meets the chord at right angles on the crown line on the direction of loading plate, 2 is the place where, brace meets the chord at right angle on the crown line and 3 is the maximum ovalization area, on the hoop line). For an OPB specimen (1 is where brace meets the chord at right angles on the crown line, 2 is on the hoop line on the direction of loading plate and 3 is on the hoop line on the opposite direction of 2)

Hand lay-up procedure was used to wrap CFRP on to the tubular joint. A slit was made in the carbon fibre sheets and each sheet was inserted through the brace of the tubular joints to wrap it on the chord. For wrapping the brace member, a profile was cut from the template by measuring the brace chord intersection. To achieve a ply other than 0°, a template was cut from a card board sheet. The required directions were marked on the template by placing unidirectional carbon fibre sheets and unwanted edges were cut using a scissors. The wrapping procedure and the template for a T-joint subjected to in-plane and out-of-plane bending are shown in Fig. 15. Details for wrapping the T-joint were as per the sequence of Y-joint followed earlier. The wrapping length was chosen to be 4√DT from the plug centre for T-joints.

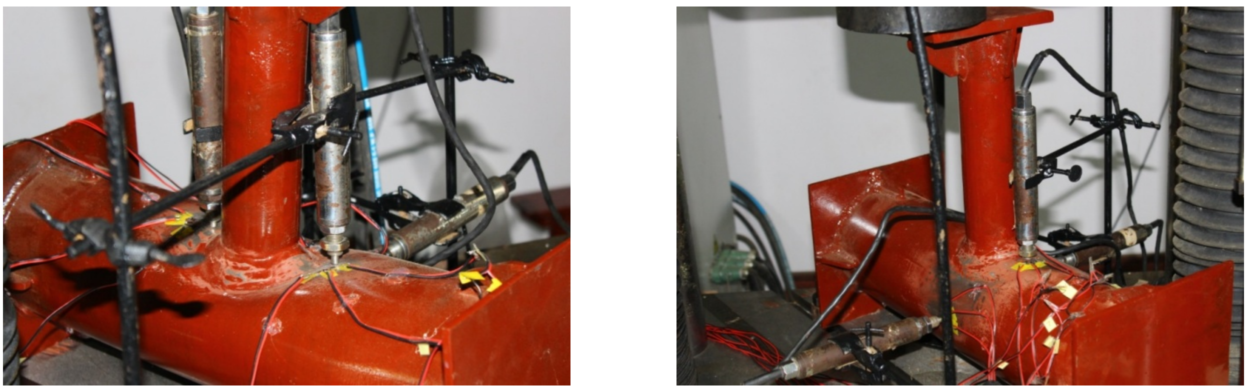
3.2 Experimental investigation on T-joints subjected to IPB and OPB

Computer controlled electro-hydraulic servo UTM was used to perform the test for in-plane and out-of-plane bending. The testing speed for Y-joint was also used for in-plane and out-of-plane bending. A test on reference joint subjected to in-plane bending was performed initially, and then the joint with CFRP wrapping. Later, the reference joint was tested to out-of-plane bending and then the joint with CFRP wrapping. The arrangements of T-joint on UTM subjected to in-plane and out-of-plane bending for reference and CFRP wrapped joints are shown in Figs. 16 to 17.



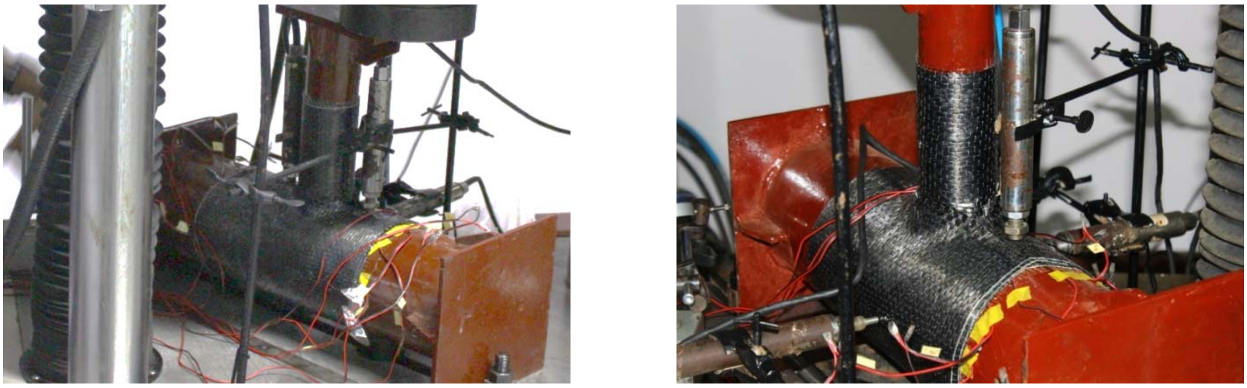
(a) Wrapping procedure of CFRP (b) Template for cutting CFRP sheets

Fig. 15 Illustrating CFRP wrapping procedure on to the tubular joint



(a) In-plane bending (b) Out-of-plane bending

Fig. 16 Arrangement of reference T-joint specimen on UTM



(a) In-plane bending (b) Out-of-plane bending

Fig. 17 Arrangement of CFRP wrapped T-joint specimen on UTM

4. Summary

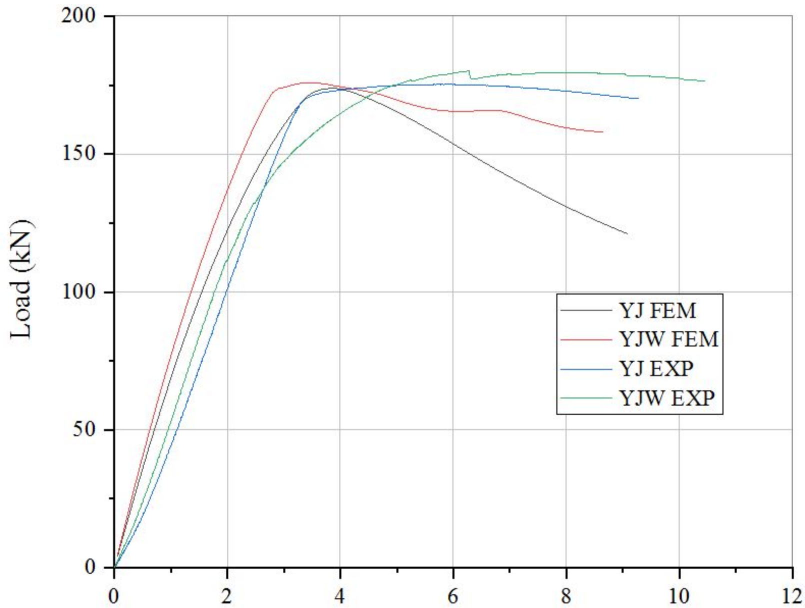
4.1 Results of Y-Joint

The crown point was located at X/√DT = 1.14 and the saddle point was located at Rφ/√DT = 1.18. Preliminary investigation was carried on the tubular joint and a length of 4√DT from the plug centre was wrapped using CFRP. For an axial compression, reference joint failed by punching shear and CFRP wrapped joint experienced only matrix/fibre failure at the brace chord intersection. Load versus displacement of Y-joint for reference and wrapped joints are shown in Fig. 18. From the experimental investigation, it was clear that the ultimate load of wrapped joint was more than the reference joint.

After performing the experiments on strengthened joint, CFRP was removed from the tubular joint using a hand grinder. CFRP wrapped joint experiences less deformation compared to the reference joint, this shows contribution of CFRP in taking the load. Later, a thorough inspection was done for the tubular joints after loading and no defect in welding was observed. Fig. 19 shows the deflected shape of reference and wrapped tubular joint subjected to axial compression in UTM. Numerical investigation results of deflected shape of reference and wrapped tubular joints are also shown in Fig. 20. From the numerical model, it can be observed that the deflection for reference joint is more compared to the CFRP strengthened joint. At the wrapping length the contours had shown that there is also less deflection and stresses in the strengthened joint while in the reference joint variation of displacement and stress contours can be seen.

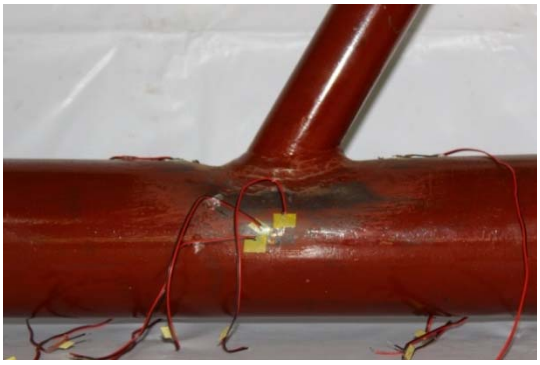
4.2 Results of T-Joint subjected to IPB and OPB

The deflection for CFRP strengthened joint along the crown line was less than the reference joint in case of IPB, this was due to the presence of CFRP layers which



(*YJ – Y-joint*; *YJW – CFRP strengthened Y-Joint*; *FEM – finite element investigation*; *EXP – experimental technique*)

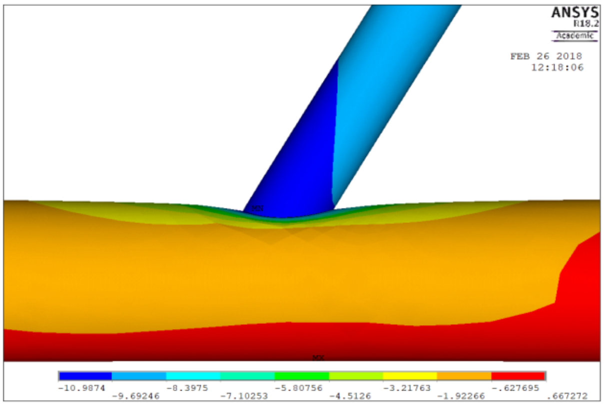
Fig. 18 Load versus deflection for Y-joint



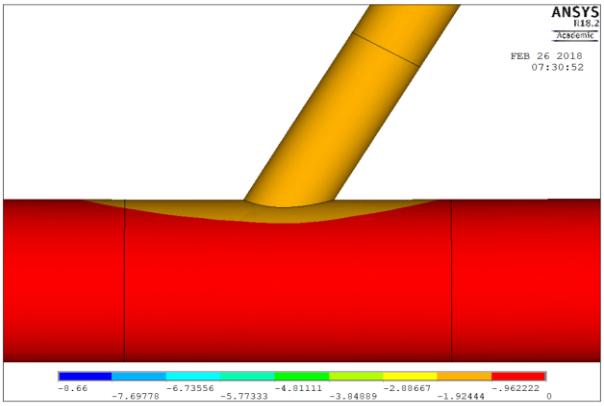
(a) Reference Y-joint

(b) CFRP wrapped Y-joint

Fig. 19 Deflection of Y-joint (Experimental)

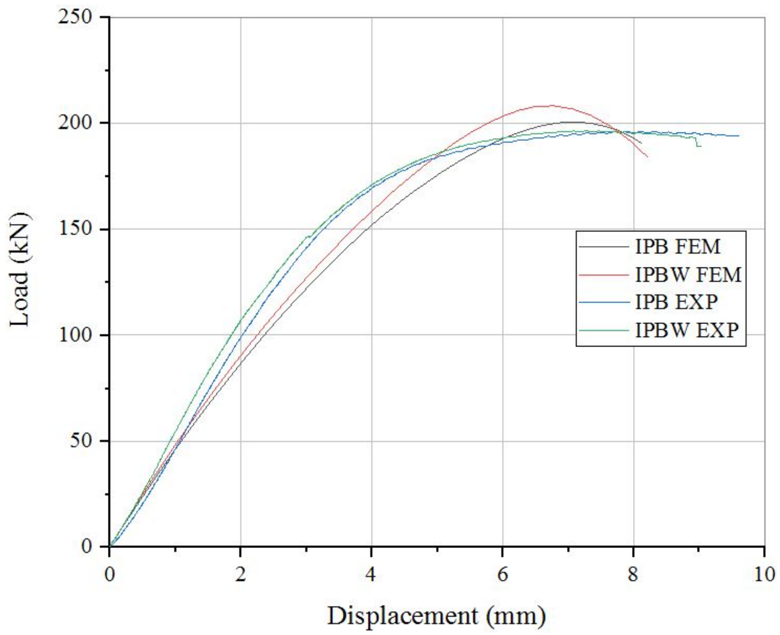


(a) Reference Y-joint



(b) CFRP wrapped Y-joint

Fig. 20 Deflection of Y-joint (Numerical)

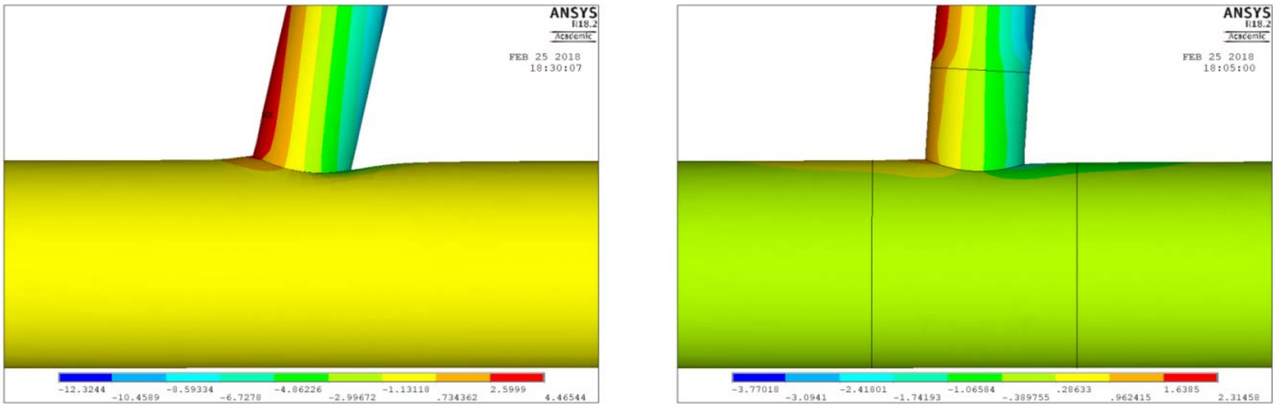


(*IPB – Reference T-joint subjected to in plane bending*; *IPBW – CFRP strengthened T-joint subjected to in plane bending*; *FEM – finite element investigation*; *EXP – experimental technique*)

Fig. 21 Load versus deflection for T-joint (IPB)

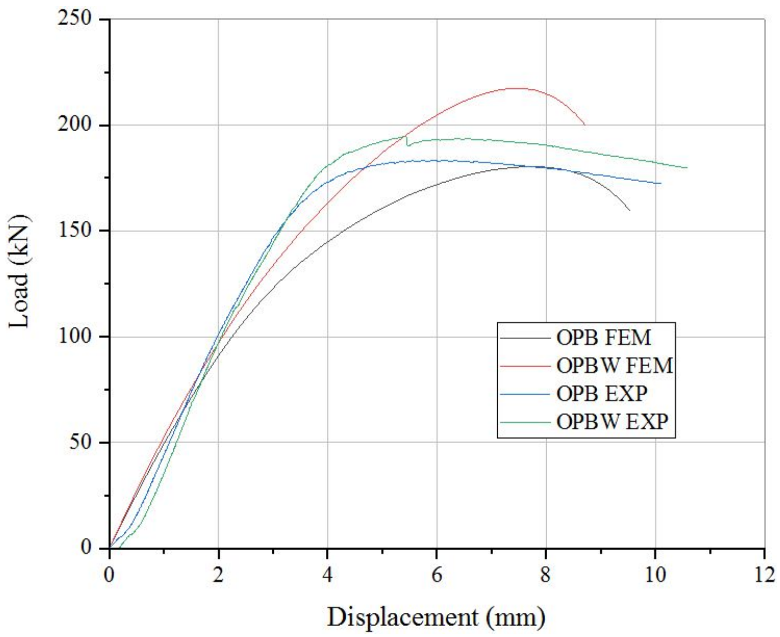
(a) Reference T-joint (b) CFRP wrapped T-joint

Fig. 22 Deflected shape of T-joint subjected to IPB (Experimental)



(a) Reference T-joint (b) CFRP wrapped T-joint

Fig. 23 Deflected shape of T-joint subjected to IPB (Numerical)

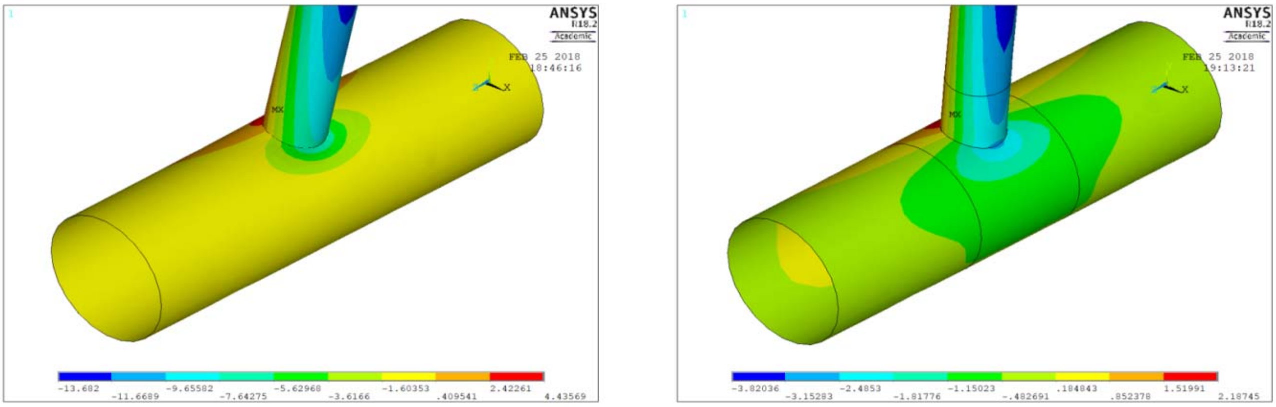


(*OPB – Reference T-joint subjected to out of plane bending*; *OPBW – CFRP strengthened T-joint subjected to out of plane bending*; *FEM – finite element investigation*; *EXP – experimental technique*)

Fig. 24 Load versus deflection for T-joint (OPB)

(a) Reference T-joint (b) CFRP wrapped T-joint

Fig. 25 Deflected shape of T-joint subjected to OPB (Experimental)



(a) Reference T-joint (b) CFRP wrapped T-joint

Fig. 26 Deflected shape of T-joint subjected to OPB (Numerical)

prevented the tubular joint from further deflection. Load versus displacement for T-joint (IPB) for reference and wrapped joints are shown in Fig. 21. To compare the deflection, experimental and numerical model of CFRP strengthened tubular joint subjected to IPB is shown along with the reference joint in Figs. 22 and 23.

It was also inferred that the deflection for CFRP strengthened joint along the hoop line was less than the reference joint in case of OPB, this was due to the presence of CFRP layers which prevented the tubular joint to deflect. Load versus displacement for T-joint (OPB) for reference and wrapped joints are shown in Fig. 24. To compare the deflection numerical model of CFRP strengthened tubular joint subjected to IPB is shown along with the reference joint in Figs. 25 and 26.

5. Conclusions

(i) For a Y-joint, the ultimate load of CFRP strengthened joint was 201 kN and for the reference joint, it was 190.5 kN. The deflection of CFRP strengthened and reference joint at 190.5 kN was having a variation of 6%. Maximum principal stresses at location 2 and 3 were less for CFRP strengthened Y-joint.

(ii) For the T-joint subjected to in-plane bending, the ultimate load of CFRP strengthened joint was not having many variations with the reference joint. But, when the deflection was seen, CFRP strengthened joint prevented from in-plane bending. By wrapping CFRP maximum and minimum principal stresses are reduced. So it can be inferred that the joint strengthened with CFRP can prevent in-plane bending.

(iii) For the T-joint subjected to out of plane bending the ultimate load of CFRP strengthened joint was 5% greater than the reference joint. CFRP strengthened joint and the reference joint subjected to out of plane bending the deflection was almost same.

(iv) A wrapping method has been proposed using CFRP to strengthen the tubular structures of various configurations subjected to monotonic loadings.

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