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Review of existing techniques and fibre reinforced polymers used for strengthening tubular joints

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Abstract. Fibre reinforced polymers (FRP) are widely used to strengthen steel structures and retrofitting of existing structures due to its excellent properties. This paper reviews the use of carbon fibre reinforced polymer (CFRP) and glass fibre reinforced polymer (GFRP) in strengthening steel and concrete structures. The paper discusses the use of FRP in strengthening of steel bridges, uses of FRP in repairing of corroded structures and the behaviour of different adhesives. The paper then deals with the FRP strengthened hollow sections and the different failure experienced. The paper then reviewed the current state of art used in strengthening tubular structures and focusing on FRP in strengthening of joints.

Keywords: steel structure; FRP, tubular joints; strengthening; repairing; retrofit

1. Introduction

Tubular structures are used in the construction of offshore structures, bridges and other superstructures due to its ease of fabrication and light weight. The tubular joints used in offshore structures are subjected to reverse cyclic loading by waves which arise in high stress concentration. Strengthening and retrofitting is needed for these joints to increase their lifespan and fatigue life. Conventional methods of strengthening tubular joints are, by adding external gusset plates or by using ring stiffeners. By welding gusset plates and stiffener to the tubular joint, the joint experiences high stress concentration at the intersection and is more prone to failure Ahmadi *et al.* (2012, 2013b), Zhu *et al.* (2014, 2016).

An alternative technique for strengthening the tubular joints with Glass Fibre Reinforced Polymer (GFRP) revealed that the ovalization, chord surface displacement and stresses got reduced Lesani *et al.* (2013, 2014, 2015). Deshpande (2006) had shown that Carbon Fibre Reinforced Polymer (CFRP) and Glass Fibre Reinforced Polymer (GFRP) can be generally used to strengthen steel structures. Haedir and Zhao (2011) in the design and evaluation of externally bonded CFRP sheets for strengthening circular steel tubular short columns had shown that usage of CFRP for the strengthening of steel tube increased the yield capacity.

Ghafoori and Motavalli (2015) had developed an innovative retrofit system to prestress CFRP

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plates and when attached to existing metallic beams, the results had shown that strengthening of steel beam by CFRP increased its yield and ultimate load. Tavakkolizadeh and Saadatmanesh (2003) had used CFRP sheets in the strengthening of steel-concrete composite girders; it was found that the CFRP sheets increased the ultimate load. Duell *et al.* (2008) had developed a new method to stop external corrosion and structurally reinforce steel pipes by external wrapping of damaged sections using FRP. By wrapping with carbon composites, external corrosion of pipeline can be prevented, and can also help in the structural reinforcement of pipes.

Some parameters were discussed in detail by Gholami *et al.* (2013) while CFRP was used in strengthening bonding of CFRP to steel specimen, surface preparation to form a chemical bond between steel and adhesive, numerical model were developed for steel and CFRP bonding, thermal effects on CFRP bonded steel structure, moisture, ultraviolet radiation and presence of salt water.

Teng *et al*. (2012) had done a review on strengthening of steel structures with fibre-reinforced polymer composites. The different issues faced in strengthening of steel structures were adhesive failure, debonding of FRP plates at the end of beams, strengthening against local buckling and FRP confinement in hollow and concrete filled steel tubes.

Bakis *et al.* (2002) had done a survey on composites for construction applications in civil engineering. FRP composites used for construction of different structural shapes, internal and external bonded reinforcements focusing historical review, current state of the art and challenges to be faced in future were discussed. Zhao and Zhang (2007) reviewed the areas which were given less importance in previous review articles, such as: the bond between steel and FRP, the strengthening of steel hollow section members, and fatigue crack propagation in the FRP-Steel system.

2. Role of FRP in strengthening steel structures

Initiation of corrosion in steel and concrete structure leads to retrofitting. Post strengthening is also required for structures if it exceeds the design loads. This section has different subsections which describes the role of FRP in strengthening steel/concrete structure.

2.1 General

Meier (1995) had shown that high performance FRP composites, used for the last two decades in the aircraft and space industries, may be employed to strengthen existing structures for civil engineering purposes. In early 90s, carbon fibre with epoxy resin was used as an alternative to steel plates for strengthening when durability was needed. The compressive strength, tensile strength, modulus of elasticity and fatigue behaviour of carbon, aramid, and E-glass fibres are compared. Among these, light weight carbon fibres have high tensile strength and outstanding fatigue performance, so CFRP laminates was an excellent choice for retrofitting and rehabilitation of civil structures.

Al-saidy *et al*. (2004) had investigated the cause of deterioration of steel bridge structures subjected to corrosion due to extensive use of de-icing salts in winter weather. They used CFRP laminates and resins with different properties on the tension flange of steel beam for strengthening. Corroded steel beams of I-section strengthened using CFRP plates bonded to the tension side flange had shown that the strength and stiffness got increased for the CFRP strengthened beam. Colombi and Poggi (2006) presented the results of an experimental and numerical programme to characterize the static behaviour of steel beams reinforced by pultruded CFRP strips. The studies were done on steel beams of I-section with different CFRP reinforcements and resins which were bonded to the tension flange and tested under three point bending. Improvement in load carrying capacity and increase in the plastic stiffness was observed for CFRP strengthened beam.

Al-saidy *et al*. (2007) had presented the results of an experimental study on the behaviour of strengthened steel concrete composite girders using Carbon Fibre Reinforced Polymers (CFRP) plates. Different types of CFRP plates with varying modulus are used to strengthen steel-concrete composite girders by attaching some to the bottom flange and to the beam web. Results had shown that increase in stiffness was observed in post-elastic range, when wrapped with light weight CFRP plates. Linghoff *et al*. (2006) had done research on the behaviour of beams strengthened with different configurations of CFRP laminates. Beams strengthened with CFRP were tested under four point bending and the results show that the moment capacity of I-section with CFRP bonded on its tension flange got increased.

2.2 Strengthening of steel bridges using CFRP

In the 20th century, many studies were focusing on the strengthening of steel bridges using CFRP. While traditional retrofitting methods for steel bridge girders could be time consuming and uneconomical, an alternative repair method was suggested by Salama and Abd-El-Meguid (2007) using CFRP laminate strips. Strengthening of steel bridge girders using CFRP had showed a significant increase in flexural capacity of steel beams. Configurations of CFRP laminate, laminate thickness, modulus of elasticity, are very important for maximum gain in enhancing the strength of beam. Miller *et al.* (2001) used CFRP plates for strengthening of steel bridge girders and found that its ultimate capacity got increased. Schnerch *et al.* (2007) had shown that CFRP was a better alternative strengthening technique than bolting or welding, for bridge girders.

Sen *et al*. (2001) had done experimental investigation to determine the feasibility of using CFRP laminates to repair steel bridges. Studies indicated that, when the thickness of CFRP was altered for strengthening a bridge deck, its ultimate load gets varied, i.e., to achieve strength and stiffness thickened composites are needed. Afefy *et al*. (2016) presented experimental and numerical studies on the flexural behaviour of steel-concrete I-girders strengthened by CFRP sheets. They concluded that flexural strength and ductility are enhanced when the number of CFRP sheet gets increased.

2.3 High modulus carbon fibre

Application of high modulus carbon fibre in the strengthening of steel structures has proven to be an efficient technique. Kobayashi *et al.* (2015) summarizes the strengthening and repairing method for concrete and steel members of bridges using FRP in Japan. Studies had shown that for corroded steel members, high modulus CFRP sheets are effective in reducing the strain of steel members subjected to bending and tensile forces. Rizkalla *et al.* (2008) had proved that high modulus CFRP is an efficient method for retrofitting of steel structures. They also proposed a flexural design guideline from their findings.

Schnerch *et al.* (2003) had shown that 25% increase in stiffness was observed in the elastic range for the steel structure after strengthening with CFRP. Fawzia *et al.* (2007) had found that retrofitting of steel tubes by high modulus CFRP was superior to normal modulus CFRP and a decrease of strain was seen in CFRP, from bottom to top layer. Fam *et al*. (2009) had shown that as the CFRP modulus stiffness gets higher, flexural strength gets reduced for steel beams.

2.4 Repairing of corroded structures using CFRP

CFRP and steel are two dissimilar materials in which galvanic corrosion occurs, to prevent this, Afefy et al. (2016) suggested a layer of GFRP can be wrapped onto the steel surface which acts as an insulation for the CFRP layers. Kobayashi *et al.* (2015) had shown that for corroded steel members, high modulus CFRP sheets are effective in reducing the strain of steel members subjected to bending and tension. Sen (2003) had done external wrapping of FRP to repair damaged structures by corrosion, and found that the performance of the columns after wrapping has been excellent. Corroded columns wrapped with CFRP are shown in Fig. 1.

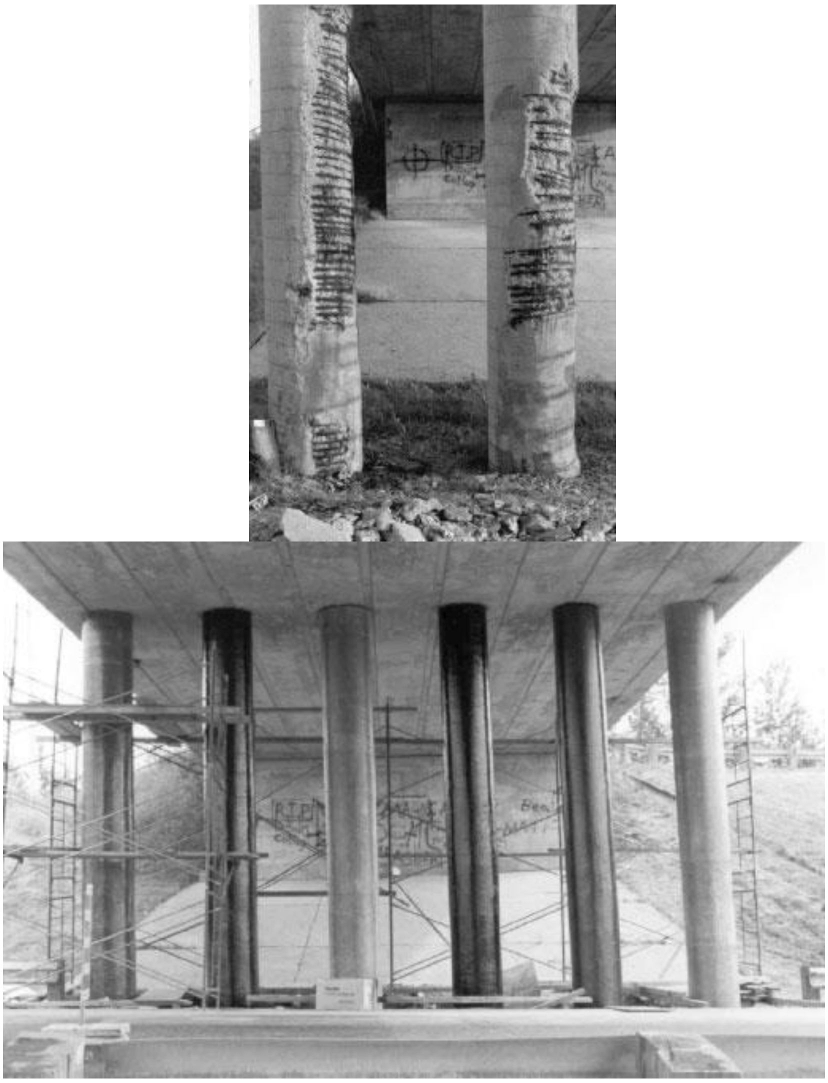

Fig. 1 View of corroded and wrapped columns (Sen 2003)

Colombi and Poggi (2006) had used CFRP reinforcements for bolted steel joints, and it shows a good increment in the failure load. Deng *et al*. (2016) conducted theoretical and experimental study on notched steel beams strengthened with CFRP plate. By strengthening with CFRP, the strength of notched beam can be increased twice. Deng and Lee (2007) had shown that, when the length of CFRP plate becomes longer there is an increase in the strength of retrofitted beams; this is due to the reduction in bending moment at the plate ends. For an improvement in the strength of retrofitted beams, use of longer and tapered plates are suggested.

2.5 Adhesive properties and delamination

Bocciarelli (2009) had shown that rupture of CFRP and interface delaminations are the different possible failures which prevent the reinforced beam from achieving its full flexural capacity. Fernando *et al*. (2009) observed the different failure modes such as adhesion, cohesion, combined adhesion and cohesion, inter-laminar failure of a CFRP strengthened rectangular hollow section. The studies concluded that the properties of adhesive have a significant effect on CFRP i.e., greater load carrying capacity for the adhesives having larger values of ultimate tensile strain leads.

Bocciarelli *et al*. (2009) joined two steel plates with CFRP and epoxy to find the double shear. Failure happened in the steel adhesive interface, which was identified as the major failure mode. Numerical modelling of the adhesive and composite layer was also discussed. Deng *et al*. (2004) had shown that significant stress concentration occurs in the adhesive at the ends of CFRP plate. The results concluded that when the thickness of adhesive gets increased, there is a decrease in the maximum shear and normal stress in steel beams.

Yu *et al*. (2012) had investigated the behaviour of CFRP-to-steel bonded interfaces for single-lap bonded joints Studies revealed that when the thickness of adhesive or the CFRP plate's rigidity gets increased the failure mode changes from cohesion to CFRP failure.

2.6 Fatigue

Bocciarelli *et al.* (2009) investigated the fatigue behaviour of steel structures retrofitted by FRP. Welded steel cover plates and CFRP plates bonded on steel members have almost comparable fatigue resistance. Deng and Lee (2007) had developed an S-N curve for the retrofitted metallic beams strengthened with CFRP. This curve can be used for the different lengths of strengthened metallic beams with the same adhesive. However, this S-N curve cannot be used for other practical application. Jones and Civjan (2003) had performed uniaxial tension on notched specimen. By applying CFRP on two sides of the specimen it was found that fatigue life of steel can be increased.

Tavakkolizadeh and Saadatmanesh (2003) presented the results of retrofitted steel beams with CFRP patches for fatigue loading. From the studies, it had shown that CFRP extended the fatigue life of steel by three times and also reduced the crack growth. Colombi and Fava (2016) investigated the fatigue crack growth of steel beams strengthened using CFRP. Strengthening of steel beams by CFRP using double reinforcement configuration reduces the Stress intensity factor (SIF) compared to a single layer.

2.7 Buckling and crippling

Silvestre *et al.* (2008) reported the results of an experimental and numerical study of CFRP strengthened channel columns. Carbon fibre sheets with transverse fibres are the best option to improve buckling behaviour of the column, while the local plate buckling can be enhanced with carbon fibre sheets by placing fibres diagonally. Zhao and Al-Mahaidi (2009) used different strengthening methods for stiffening light steel beams by applying CFRP plates on the outer side, inner side and both sides of the web. It was found that CFRP strengthening increases the web buckling capacity of the beams. Zhao *et al.* (2006) reported the web crippling capacity of rectangular hollow sections strengthened with CFRP. It was found that by strengthening with CFRP the web crippling capacity gets significantly increased.

3. Strengthening of hollow sections using fibre reinforced polymer

Hollow cross sections are widely used in welded steel frames for the construction of civil structures. Mamaghani (2004) had explained the different retrofitting techniques used for tubular columns and its importance. Fernando *et al*. (2009) had shown that by wrapping CFRP onto the hollow steel tube with the best epoxy can enhance its peak load. In their studies Haedir and Zhao (2011) showed that CFRP sheets delayed the buckling of steel tube while the bare steel tube buckled at its ultimate load.

Fawzia *et al.* (2007) had derived a formula to yield the load carried by CFRP. Area of the CFRP layer multiplied by the ultimate stress in the corresponding layer will be the load carried by CFRP. Teng and Hu (2007) concluded that as the FRP jacket thickness gets increased a threshold value is reached where a further increase in the FRP thickness will provide only less resistance to inward buckling. They also showed that FRP jacketing is also an effective strengthening method to prevent elephant’s foot collapse for shells. Duell *et al*. (2008) described the discontinuities observed in the stress versus thickness plots as the material changes from steel to putty and then to CFRP in a hollow cylindrical section subjected to axial compressive load. Narmashiri and Mehramiz (2016) observed that when the hollow section was wrapped with two layers of CFRP there was a 20% increase in load bearing capacity. Seica and Packer (2007) focussed the offshore industry and methods involved in underwater repair methods. The studies concluded that composite materials wrapped onto a tubular structure and cured in water were not able to attain the flexural capacity of those cured in the air.

4. Tubular joints strengthening: Current state

4.1 General

Failure of tubular joints was discussed by Wang and Chen (2007), they addressed the energy dissipation of axially loaded tubular joints was by means of plastic deformation of chord wall, and for in-plane bending it was by plastic deflection of the brace. Axially compressive loaded T joints failed by chord wall compression and for in-plane bending failure modes are punching shear and chord plastification. Haghpanahi and Pirali (2006) had done studies on tubular joint under axial loading. The critical point identified for axial compression is the saddle point, while for in-plane bending the critical point is located midway between the saddle and the crown point. Talei-Faz *et al.* (2004) had shown that the capacity of tubular joints made of high strength steel was not severely affected due to cracks.

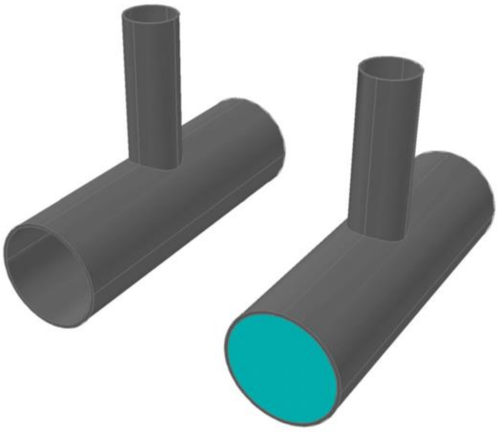

Fig. 2 Conventional T-joint and a T-joint with grout filled in chord

4.2 Filling with grout

Shen and Choo (2012) had used grout to fill the chord region of a tubular joint. The results of grout filled joint where compared with the original joint and was found that the fatigue life of grout filled joint got increased. Fig. 2 shows a conventional tubular joint and the other joint filled with grout in the chord region.

Harwood and Shuttleworth (1988) in their offshore technology report had mentioned the practical difficulties to fill grout in offshore tubular joints. Presently grouts are used for normal fabrication imperfections, geometrical damage and restoration of damaged sections. In the joint industry project MSL Engineering Limited (1994) for the development of grouted tubular joint technology for o shore strengthening and repair guidelines for grout filling, post grouting procedure and grout mix proportions of tubular joints are presented.

Morahan and Lalani (2002) had proved that grout filling in the chord is a mechanically efficient method and cost-effective technique to strengthen or repair tubular joints. Dallyn *et al.* (2015) had done a critical review of the grouted connections used in offshore structures. They discussed about the materials used for grout, design parameters that influence the capacity of joints, confinement provided by pile and sleeve, surface finish of the joint, bending action and connection length, dynamic loading such as wind, premature during grout curing, shrinkage of grout, radial pre-stress and temperature.

4.3 Chord reinforcement and collar plate

Yang *et al.* (2012) had shown that strengthening of tubular joints by increasing the thickness of chord at brace chord intersection will improve the static strength of joints. The studies found that reinforced thickness should not be twice as that of the chord thickness, as it will be ineffective. Yang *et al.* (2014) had done a study on tubular joints with chord reinforcement by focussing on its reinforcement length and thickness. After, the parametric study reinforcement length and thickness were recommended.

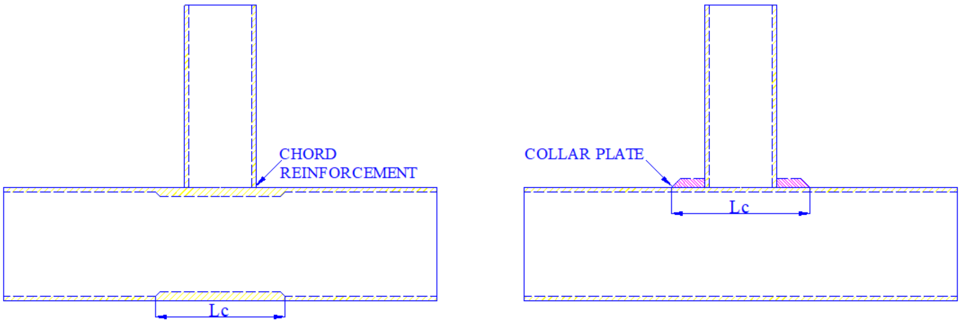

Fig. 3 Tubular joint showing chord reinforcement and collar plate

Shao *et al*. (2011) focussed on the collar plate reinforced tubular joints. The study had shown that the collar plate reinforced tubular joints can absorb more energy than the unreinforced joints. The failure location of the reinforced tubular joint identified was from brace chord intersection region to the weld toe of collar plate.

Nassiraei *et al.* (2016) in a full length article had numerically investigated the ultimate strength, stiffness, and failure mechanisms of T and Y-joints reinforced with doubler plate under axially compression. The findings show an increase in the ultimate strength of up to 295% for collar plate reinforced tubular T and Y joints than the unreinforced joint. For predicting the strength of collar plate reinforced joint under axial compression a design equation was proposed. Later, Nassiraei *et al.* (2016) had continued their studies on tubular joints under axial tension. Studies revealed that an increase in the ultimate strength of 200 % and 180 % is observed for collar plate reinforced tubular T and Y joints than the unreinforced joint under axial tension. The schematic arrangement of chord reinforcement and collar plate is shown in Fig. 3.

4.4 Ring stiffeners

Ahmadi *et al*. (2012, 2013b) had developed an equation for internal ring stiffened joints subjected to fatigue. Lee (2004), Lee and Llewelyn-Parry (2005) shown that internal ring stiffeners do not contribute much to the ductility of tubular joints. Keeping the internal ring stiffeners at the saddle position provides better strength enhancement than keeping at the crown locations. Ahmadi and Lotfollahi-Yaghin (2011) found that internal ring-stiffeners placed in tubular joints lead to the disposition of the peak stress concentration factor along the weld toe.

Nwosu *et al.* (1995) shown that stiffeners reduce the hot spot stresses to a lesser value thereby increasing the fatigue life of the joint. Stiffeners also help in the uniform stress distribution at the brace chord intersection, especially on the chord. From the studies, it was found that the placing of stiffeners should be kept away from the weld line. Thandavamoorthy (2000) had performed axial compression on internally ring stiffened tubular joints. The result shows chord bending was the predominant mode of failure. For eliminating the bending and ovalization of chord placing of three internal ring stiffeners is suggested.

Lee and Llewelyn-Parry (1999) showed that while placing T-shaped stiffeners inside the tubular joint, flange thickness is contributing to the stiffeners strength rather than its width. Zhu *et al*. (2014) had done numerical investigation of external ring stiffeners placed in a tubular joint.

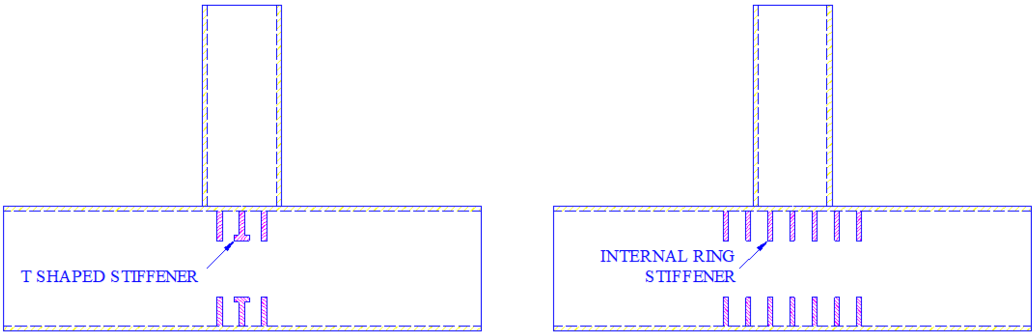

Fig. 4 Joints with T-shaped Stiffener and Internal Ring Stiffener

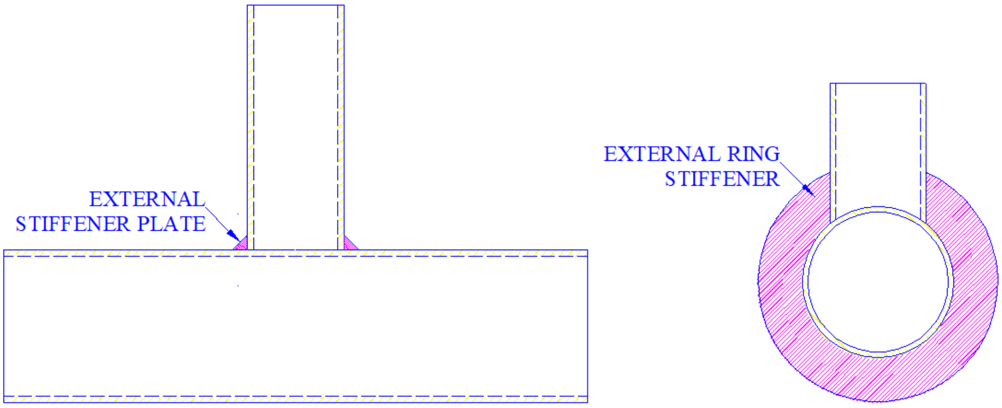

Fig. 5 External stiffener plate and external ring stiffener

Size of stiffener is proportional to the strength of the joint; it was also found that length plays an important role in strengthening than the height of the stiffener. After a couple of years Zhu *et al.* (2016) extended their studies by experimentally investigating on external ring stiffeners placed in a tubular joint. Studies revealed that external ring stiffeners greatly enhance the tubular joints compressive strength, and no ovalization was observed for axial compressive loading. Fig. 4 shows the location of the T-shaped stiffener and an internal ring stiffener placed in a tubular joint. Fig. 5 shows the external ring stiffener and stiffener plate welded on a tubular joint configuration.

5. Strengthening of tubular joints by FRP

Many researchers did not address the strengthening of tubular joints by FRP, but had taken the idea from strengthening hollow sections by FRP. Aguilera (2012) thought of implementing the idea of wrapping GFRP on tubular joints fabricated from hollow square sections (HSS). By wrapping HSS with GFRP, they found that when transverse load was applied to the hollow section, the joints

Fig. 6 Comparison of chord deflections of unwrapped and GFRP wrapped joint (Lesani *et al.* 2014)

bearing capacity got increased. Aguilera and Fam (2013), Aguilera (2012), Aguilera and Fam (2013) compared GFRP wrapped hollow section with the through-wall bolt techniques and found that GFRP wrapping was more effective. Lesani *et al*. (2013, 2014) had done numerical and experimental work on GFRP wrapped tubular T-joint. They explained about the specimen preparation, wrapping of GFRP and length of GFRP to be reinforced. Studies were done by comparing a reference joint and a joint wrapped with GFRP; it was noticed that the ultimate load carrying capacity of wrapped joint increased to 64%, whereas deflection gets reduced by 50 %. Fig. 6 shows the comparison of chord deflections for an unreinforced and wrapped joint. Lesani *et al*. (2015) extended their studies on a Y-joint by wrapping with GFRP and observations were similar to the T-joint.

Fu *et al.* (2016) had done experimental and numerical investigation on load bearing capacity of K-joints strengthened with CFRP. Studies show that the layers of CFRP wrapped for strengthening has a significant effect on its joint strength. The formula for an ultimate load of K-joints wrapped with CFRP was proposed after a detailed parametric study. A remark-able result was that CFRP sheets wrapped onto a tubular joint can only delay its primary failure mode. The authors had done experimental studies on CFRP wrapped tubular T- joint, and an unwrapped joint was compared with the CFRP wrapped joint. Results had shown that by wrapping CFRP on tubular joint, 56% reduction in chord surface deflection and 67% reduction in ovalization was seen Prashob *et al*. (2017).

6. Conclusions

In the 20th century, there was a tremendous change when FRP was used to strengthen steel bridges, this issue was addressed by many researchers who had proven this to be an appreciable technique in the field. Guidelines were proposed to wrap CFRP on existing and new structures for its load bearing capacity. Application of high modulus fibre in the strengthening of steel structures has proven to be better than the normal modulus fibre. By selecting proper adhesive and orientation of CFRP, delamination can be avoided to a certain extent.

Wrapping of CFRP increased the fatigue life of the steel structure, but many tests need to be conducted for obtaining an S-N curve for the CFRP wrapped steel. Though buckling and crippling have reduced by using CFRP, many studies need to be carried out in this area. Strengthening of hollow sections with CFRP helped to reduce the buckling of column. Hollow sections strengthened with CFRP increased the load carrying capacity.

There was an increase in fatigue life of the joint when filling grout which was a cost effective technique, but it has some practical difficulties for an existing joint. Static strength of tubular joints gets improved when the thickness of chord gets increased or by using a collar plate. Internal ring stiffeners contribute to the fatigue life of the joint and reduce stresses and ovalization, while external ring stiffeners enhance the strength of joint. Limited studies were done on external ring stiffeners in a tubular joint so the author cannot conclude many remarks from the available literature. When using the above-said techniques corrosion was a major factor, and placing of stiffeners in the existing structure is a challenging job.

With a few available literatures on FRP wrapped tubular joints certain conclusion can be drawn: increase in load bearing capacity, reduction in ovalization and chord surface deflection. Studies need to be done with different orientations of FRP, the number of layers and on a different configuration of joints. In the offshore scenario corrosion is a major concern so employing the idea from Afefy *et al.* (2016) can be considered when wrapping CFRP.

References

Afefy, H.M., Sennah, K. and Akhlagh-Nejat, H. (2016), “Experimental and analytical investigations on the flexural behavior of CFRP-strengthened composite girders”, *J. Constr. Steel Res.*, **120**, 94-105.

Aguilera, J. (2012), Strengthening T-joints of rectangular hollow steel sections against web buckling under brace axial compression using through-wall bolts, Master of Applied Science, Queens University Kingston, Ontario, Canada.

Aguilera, J. and Fam, A. (2013), “Bonded FRP plates for strengthening rectangular hollow steel section T-joints against web buckling induced by transverse compression”, *J. Compos. Constr.*, **17**(4), 421-432.

Aguilera, J. and Fam, A. (2013), “Retrofitting tubular steel T-joints subjected to axial compression in chord and brace members using bonded FRP plates or through-wall steel bolts”, *Eng. Struct.*, **48**, 602-610.

Ahmadi, H. and Lotfollahi-Yaghin, M.A. (2011), “Experimental and numerical investiga-tion of geometric SCFs in internally ring-stiffened tubular KT-joints of offshore structures”, *J. Persian Gulf Marine Sci.*, **43**, 7-8.

Ahmadi, H., Lotfollahi-Yaghin, M.A. and Shao, Y. (2013), “Chord-side SCF distribution of central brace in internally ring-stiffened tubular KT-joints: A geometrically parametric study”, *Thin Wall. Struct.*, **70**, 93-105

Ahmadi, H., Lotfollahi-Yaghin, M.A., Shao, Y. and Aminfar, M.H. (2012), “Parametric study and formulation of outer-brace geometric stress concentration factors in internally ring-stiffened tubular KT-joints of offshore structures”, *Appl. Ocean Res.*, **38**, 74-91.

Al-saidy, A.H., W.Klaiber, F. and Wipf, T.J. (2004), “Repair of steel composite beams with carbon fiber reinforced polymer plates”, *J. Compos. Constr.*, **9**, 341-351.

Al-saidy, A.H., W.Klaiber, F. and Wipf, T.J. (2007), “Strengthening of steel-concrete composite girders using carbon fiber reinforced polymer plates”, *Constr. Build. Mater.*, **21**(2), 295-302.

Bakis, B.E., Bank, L.C., Brown, V.L., Cosenza, E., Davalos, J.F., Lesko, J.J., Machida, A., Rizkalla, S.H. and Triantafillou, T.C. (2012), “Fiber-reinforced polymer composites for construction-state-of-the-art review”, *Constr. Build. Mater.*, **6**(2), 73-87.

Bocciarelli, M. (2009), “Response of statically determined steel beams reinforced by CFRP plates in the elastic-plastic regime”, *Eng. Struct.*, **31**(4), 956-967.

Bocciarelli, M., Colombi, P., Fava, G. and Poggi, C. (2007), “Fatigue performance of tensile steel members strengthened with CFRP plates”, *Compos. Struct.*, **87**(4), 334-343.

Colombi, P. and Fava, G. (2016), “Fatigue crack growth in steel beams strengthened by CFRP strips”, *Theor. Appl. Fract. Mech.*, **85**, 173-182.

Colombi, P. and Poggi, C. (2006), "An experimental, analytical and numerical study of the static behavior of steel beams reinforced by pultruded CFRP strips", *Compos. Part B: Eng*., **37**(1), 64-73.

Colombi, P. and Poggi, C. (2006), "Strengthening of tensile steel members and bolted joints using adhesively bonded CFRP plates", *Constr. Build. Mater*., **20**(1-2), 22-33.

Dallyn, P., El-Hamalawi, A. and Palmeri, A. and Knight, R. (2015), "Experimental testing of grouted connections for offshore substructures: A critical review", *Structures*, **3**, 90-108.

Deng, J. and Lee, M.M.K. (2007), "Behaviour under static loading of metallic beams reinforced with a bonded CFRP plate", *Eng. Struct*., **78**(2), 232-242.

Deng, J., Jia, Y. and Zheng, H. (2016), "Theoretical and experimental study on notched steel beams strengthened with CFRP plate", *Compos. Struct*., **136**, 450-459.

Deng, J., Lee, M.M.K. and Moy, S.S.J. (2007), "Stress analysis of steel beams reinforced with a bonded CFRP plate", *Compos. Struct*., **65**(2), 205-215.

Deshpande, A.B. (2006), Characterization of CFRP and GFRP Composite Materials At High Strain Rate Tensile Loading, Master of Science, Wichita State University, Kansas, USA.

Duell, J.M., Wilson, J.M. and Kessler, M.R. (2008), "Analysis of a carbon composite overwrap pipeline repair system", *Int. J. Press.Vess. Piping*, **85**(11), 782-788.

Fam, A., MacDougall, C. and Shaat, A. (2009), "Upgrading steel-concrete composite girders and repair of damaged steel beams using bonded CFRP laminates", *Thin Wall. Struct*., **47**(10), 1122-1135.

Fawzia, S., Al-Mahaidi, R., Zhao, X.L. and Rizkalla, S. (2007), "Strengthening of circular hollow steel tubular sections using high modulus CFRP sheets", *Constr. Build. Mater*., **21**(4), 839-845.

Fernando, B., Yu, T., Teng, J.G. and Zhao, X.L. (2009), "CFRP strengthening of rectangular steel tubes subjected to end bearing loads: Effect of adhesive properties and finite element modelling", *Thin Wall. Struct*., **47**(10), 1020-1028.

Fu, Y., Tong, L., He, L. and Zhao, X.L. (2016), "Experimental and numerical investigation on behavior of CFRP-strengthened circular hollow section gap K-joints", *Thin Wall. Struct.*, **102**, 80-97.

Ghafoori, E. and Motavalli, M. (2006), "Innovative CFRP-prestressing system for strengthening metallic structures", *J. Compos. Constr*., **19**(6), 1-14.

Gholami, M., Sam, A.R.M., Yatim, J.M. and Tahir, M.M. (2013), "A review on steel/CFRP strengthening systems focusing environmental performance", *Constr. Build. Mater*., **47**, 301-310.

Haedir, J. and Zhao, X.L. (2011), "Design of short CFRP-reinforced steel tubular columns", *J. Constr. Steel Res*., **67**(3), 497-509.

Haghpanahi, M. and Pirali, H. (2006), "Hot spot stress determination for a tubular T-joint under combined axial and bending loading", *Thin Wall. Struct*., **17**(3-4), 21-28.

Harwood, R.G. and Shuttleworth, E.P. (2009), Grouted and mechanical strengthening and repair of tubular steel offshore structures, OTH 88 283, London, UK.

Jones, S.C. and Civjan, S.A. (2007), "Application of fiber reinforced polymer overlays to extend steel fatigue life", *J. Compos. Constr*., **7**(4), 331-338

Jun Deng, Marcus M K Lee, (2007), "Fatigue performance of metallic beam strengthened with a bonded CFRP plate", *Compos. Struct*., **78**, 222-231.

Kobayashi, A., Hidekuma, Y. and Tateishi, A. (2015), "Strengthening of steel and concrete structures using CFRP in Japan", *Proceedings of the IABSE-JSCE Joint Conference on Advances in Bridge Engineering-III*, Dhaka, August

Lee, M.M.K. (2004), "Offshore Tubular T-Joints Reinforced with Internal Plain Annular Ring Stiffeners", *J. Struct. Eng. - ASCE*, **130**(6), 942-951.

Lee, M.M.K. and Llewelyn-Parry, A. (1999), "Strength of ring-stiffened tubular T-joints in offshore structures: a numerical parametric study", *J. Constr. Steel Res*., **51**(3), 239-264.

Lee, M.M.K. and Llewelyn-Parry, A. (2005), "Strength prediction for ring-stiffened DT-joints in offshore jacket structures", *Eng. Struct*., **27**(3), 421-430.

Lesani, M., Bahaari, M.R. and Shokrieh, M.M. (2013), "Numerical investigation of FRP-strengthened tubular T-joints under axial compressive loads", *Compos. Struct*., **100**, 71-78.

Lesani, M., Bahaari, M.R. and Shokrieh, M.M. (2014), "Experimental investigation of FRP-strengthened tubular T-joints under axial compressive loads", *Constr. Build. Mater.*, **53**, 243-252.

Lesani, M., Bahaari, M.R. and Shokrieh, M.M. (2015), "FRP wrapping for the rehabilitation of Circular Hollow Section (CHS) tubular steel connections", *Thin Wall. Struct.*, **90**, 216-234.

Linghoff, D., Al-Emrani, M. and Kliger, R. (2006), "Performance of steel beams strengthened with CFRP laminate - Part 1: Laboratory tests", *Compos. Part B: Eng.*, **37**, 64-73.

Mamaghani, I.H.P. (2004), "Seismic design and retrofit of thin-walled steel tubular columns", *Proceedings of the 13th World Conference on Earthquake Engineering*, Canada, August.

Meier, U. (1995), "Strengthening of structures using carbon fibre/epoxy composites", *Constr. Build. Mater.*, **9**(6), 341-351.

Miller, T.C., Chajes, M.J., Mertz, D.R. and Hastings, J.N. (2001), "Strengthening of a steel bridge girder using CFRP plates", *J. Bridge Eng.*, **6**(6), 514-522.

Morahan, D.J. and Lalani, M. (2002), "Fatigue and ultimate limit state of grouted tubular joints", *Proceedings of the 21st International Conference on Offshore Mechanics and Arctic Engineering*, Norway, June.

MSL Engineering Limited, (1994), Development of grouted tubular joint technology for o shore strengthening and repair, DOC REF C14100R006, Berkshire, England.

Narmashiri, K. and Mehramiz, G. (2007), "Strengthening of steel hollow pipe sections subjected to transverse loads using CFRP", *Struct. Eng. Mech.*, **60**(1), 163-173.

Nassiraei, H., Lotfollahi-Yaghin, M.A. and Ahmadi, H. (2016), "Static strength of collar plate reinforced tubular T/Y-joints under brace compressive loading", *J. Constr. Steel Res.*, **119**, 39-49.

Nassiraei, H., Lotfollahi-Yaghin, M.A. and Ahmadi, H. (2016), "Web buckling of light-steel beams strengthened with CFRP subjected to end-bearing forces", *Thin Wall. Struct.*, **103**, 141-156.

Nwosu, D.I., Swamidas, A.S.J. and Munaswamy, K. (1995), "Numerical stress analysis of internal ring-stiffened tubular", *J. Offshore Mech. Arct.*, **122**, 223-242.

Prashob, P.S., Shashikala, A.P. and Somasundaran, T.P. (2017), "Behaviour of carbon ber reinforced polymer strengthened tubular joints", *Steel Compos. Struct.*, **24**(4), 383-390.

Rizkalla, S., Dawood, M. and Schnerch, D. (2008), "Development of a carbon fiber reinforced polymer system for strengthening steel structures", *Compos. Part A: Appl. Sci. Manuf.*, **39**, 388-397.

Salama, T. and Abd-El-Meguid, A. (2007), Strengthening Steel Bridge Girders Using CFRP, Report Number 06217, The University of Alabama, Alabama, USA.

Schnerch, D., Dawood, M., Rizkalla, S. and Sumner, E. (2007), "Proposed design guidelines for strengthening of steel bridges with FRP materials", *Constr. Build. Mater.*, **21**(5), 1001-1010.

Schnerch, D., Stanford, K., Lanier, B. and Rizkalla, S. (2003), "Use of high modulus carbon fiber reinforced polymers (CFRP) for strengthening steel structures", *Proceedings of the second international workshop on structural composites for infrastructure applications*, North Carolina

Seica, M.V. and Packer, J.A. (2007), "FRP materials for the rehabilitation of tubular steel structures, for underwater applications", *Compos. Struct.*, **80**(3), 440-450.

Sen, R. (2003), "Advances in the application of FRP for repairing corrosion damage", *Prog. Struct. Eng. Mater.*, **5**, 99-113.

Sen, R., Liby, L. and Mullins, G. (2001), "Strengthening steel bridge sections using CFRP lam-inates", *Compos. Part B: Eng.*, **32**(4), 309-322.

Shao, Y.B., Lie, S.T., Chiew, S.P. and Cai, Y.Q. (2011), "Hysteretic performance of circular hollow section tubular joints with collar-plate reinforcement", *J. Constr. Steel Res.*, **67**(12), 1936-1947.

Shen, W. and Choo, Y.S. (2012), "Stress intensity factor for a tubular T-joint with grouted chord", *Eng. Struct.*, **35**, 37-47.

Silvestre, N., Young, B. and Camotim, D. (2008), "Non-linear behaviour and load-carrying capacity of CFRP-strengthened lipped channel steel columns", *Eng. Struct.*, **30**(10), 2613-2630.

Talei-Faz, B., Brennan, F.P. and Dover, W.D. (2004), "Residual static strength of high strength steel cracked tubular joints", *Mar. Struct.*, **17**(3-4), 291-309.

Tavakkolizadeh, M. and Saadatmanesh, H. (2003), "Fatigue strength of steel girders strengthened with carbon fiber reinforced polymer patch", *J. Struct. Eng. - ASCE*, **129**(2), 186-196.

Tavakkolizadeh, M. and Saadatmanesh, H. (2003), "Strengthening of steel-concrete composite girders using carbon fiber reinforced polymers sheets", *J. Struct. Eng. - ASCE*, **129**(1), 30-40.

Teng, J.G. and Hu, Y.M. (2007), "Behaviour of FRP-jacketed circular steel tubes and cylindrical shells under axial compression", *Constr. Build. Mater.*, **21**(4), 827-838.

Teng, J.G., Yu, T. and Fernando, D. (2012), "Strengthening of steel structures with fiber-reinforced polymer composites", *Constr. Build. Mater.*, **78**, 131-143.

Thandavamoorthy, T.S. (2000), "Investigation on internally ring-stiffened joints of offshore platforms", *J. Offshore Mech. Arct.*, **122**(4), 223-242.

Wang, W. and Chen, Y.Y. (2007), "Hysteretic behaviour of tubular joints under cyclic loading", *J. Constr. Steel Res.*, **63**(10), 1384-1395.

Yang, D.P., Shao, Y.B., Long, F.L., Niu, G.Q., Zhang, L. and Zhi, J.B. (2014), "Static strength of RHS T-joints with reinforced chord under in-plane bending load", *Appl. Mech. Mater.*, **488-489**, 65-70.

Yang, J., Shao, Y. and Chen, C. (2012), "Static strength of chord reinforced tubular Y-joints under axial loading", *Mar. Struct.*, **29**(1), 226-245.

Yu, T., Fernando, D., Teng, J.G. and Zhao, X.L. (2012), "Experimental study on CFRP-to-steel bonded interfaces", *Compos. Part B: Eng.*, **43**, 2279-2289.

Zhao, X.L. and Al-Mahaidi, R. (2009), "Web buckling of light steel beams strengthened with CFRP subjected to end-bearing forces", *Thin Wall. Struct.*, **47**(10), 1029-1036.

Zhao, X.L. and Zhang, L. (2007), "State-of-the-art review on FRP strengthened steel structures", *Eng. Struct.*, **29**(8), 1808-1823.

Zhao, X.L., Fernando, D. and Al-Mahaidi, R. (2006), "CFRP strengthened RHS subjected to transverse end bearing force", *Eng. Struct.*, **28**(11), 1555-1565.

Zhu, L., Han, S., Song, Q., Ma, L., Wei, Y. and Li, S. (2016), "Experimental study of the axial compressive strength of CHS T-joints reinforced with external stiffening rings", *Thin Wall. Struct.*, **98**, 245-251.

Zhu, L., Zhao, Y., Li, S., Huang, Y. and Ban, L. (2014), "Hysteretic performance of circular hollow section tubular joints with collar-plate reinforcement", *Thin Wall. Struct*, **85**, 481-488.

Zhu, L., Zhao, Y., Li, S., Huang, Y. and Ban, L. (2014), "Numerical analysis of the axial strength of CHS T-joints reinforced with external stiffeners", *Thin Wall. Struct.*, **85**, 481-488.

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