Journal of Coastal and Marine Engineering
Volume 1 • Number 1 • June 2018

Stress Concentration Factors Of FRP-Wrapped Tubular T-Joints Of Jacket Type Offshore Platforms under Brace Axial Loading

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Abstract: The present research investigates the relative stress concentration factors (SCF) in a T-joint strengthened with fiber reinforced polymers (FRP) subjected to brace axial loading employing finite element analysis. In this research, three types of FRP material consisting of glass-vinyl ester, glass-epoxy and carbon-epoxy were used as strengthening materials. The FRP was applied on a basic numerical FE model, which were validated against the well-known experimental results on weld toe SCFs. The results showed that the use of stiffer FRP materials on the chord induced more reduction in SCF values. Besides, the use of carbon-epoxy material had efficacy about three times that of GFRP materials in decreasing SCF values. Carbon-epoxy with thickness of 1mm, as the strengthening material decreased the SCF values up to 2.5 and 10.1% at the chord crown and saddle points, respectively.

Keywords: Tubular T-joint, FRP, SCF, Fatigue, Finite Element, CHS

1. Introduction

Steel circular hollow sections (CHS) are widely employed in offshore structures owing to their appropriate performance against buckling, bending and torsion as load bearing members. One of the most prevalent and basic joint configurations in jacket type offshore platforms include T-joints which are made by simply welding the cross section of one tube (brace) perpendicular to the undisturbed exterior surface of the other tube (chord).

Due to the cyclic nature of wave loading on such structures, attention must be given to their fatigue resistance. The fatigue life of offshore jacket joints is computed using a parameter called stress concentration factor (SCF), which represents the ratio of the local surface stress in the chord to the nominal direct stress in the brace. SCF can be calculated in unstiffened and stiffened joints. In unstiffened joints, many researchers have made efforts since the 70s and their main objective was to derive parametric equations for the calculation of SCF. Ahmadi and Lotfollahi-Yaghin [1] have conducted recent studies in this field.

There are some metallic based techniques, which are used for strengthening CHS in order to decrease the SCF. Lesani et al., [2] reviewed some of these strengthening techniques. Ring stiffening of the structure section could be mentioned as one of these methods. The effect of geometric parameters on SCFs in ring stiffened T and Y-joints was investigated by Ramachandra et al., [3] and presented relevant formulae. The stress distribution along the ring stiffened T-joints was studied by Nwosu et al., [4]. This research shows the effect of geometry and location and number of stiffeners. More recently, Ahmadi et al., [5,6] proposed fatigue design equations for internal ring stiffened KT-joints under axial loading.

Generally, it can be found that many of the prior researches on stress concentration factor parameter resulted in the design of parametric equations. API [7] and Lloyd's Register (LR) [8] give such equations, which are derived from fitting curves on the existing SCF database. The SCFs in saddle and crown positions in T, Y, X, K and KT-joints were covered by these equations and are now being considered as one of the most reliable references for SCF estimation.

There are also some non-metallic external reinforcement schemes such as FRP strengthening technique. FRP wrapping method due to its convenience for handling and application, potentially high overall durability, corrosion resistance, light weight, superior strength-to-weight ratio, tailorability and high specific performance properties can be easily applied in areas where the use of conventional materials may not be feasible due to durability, weight or lack of design flexibility constraints. Fiber reinforced polymers are composed of two distinguishable parts namely fibers and matrix. By employing different fibers and matrixes as the constituents, one can make various compositions. Lesani et al., [2] achieved remarkable improvement in joint ultimate capacity of steel tubular T-joints strengthened by GFRP (Glass/epoxy) under axial brace compressive loading through the investigation of the failure pattern, ultimate static strength and detailed behavior of the joint. Ultimate load bearing capacity of the GFRP (Glass/vinyl ester)

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strengthened tubular T-joint under static compressive loading showed an increase up to 50% compared to the unstrengthened joint in the experimental study by Lesani et al., [9]. Lesani et al., [10] conducted numerous comprehensive numerical and experimental research on GFRP strengthened T and Y shaped CHS steel tubular connections. Some structural parameters such as the state of joint strength, deformation, ovalization, stresses and failure of T and Y-joints under compressive loading were investigated in this study. According to the results of this research, the FRP wrapping technique could significantly enhance the static strength of tubular joints. According to the results of these studies and the high importance of fatigue performance in offshore structural T-joints, it seems imperative to investigate SCF enhancement employing the FRP wrapping technique. This paper is aimed at presenting the relevant findings of such investigations.

In the present paper, the results of numerical analysis on FRP strengthened steel tubular T-joints were used to present general remarks on the effect of using three different FRP materials on SCF distribution along the weld toe under brace axial load. The finite element models were verified against the experimental results from HSE OTH 354 [8] and the predictions of Lloyd's Register (LR) equations [8] and API equations [7]. The results of this study could be beneficial to the designer in understanding the effects of different FRP material on the joint fatigue life in a strengthened joint.

2. Finite Element Modeling

To study the distribution of SCFs along the weld toe in FRP strengthened tubular T-joints, finite element models were generated and analyzed. All the joints had similar unstiffened geometry, which was chosen from JISSP project results [8], with different FRP materials. They were subjected to axial load applied on the brace member.

In this study, three types of common FRP materials, glass/vinyl ester, glass/epoxy (Scotch ply 1002) and carbon/epoxy (T300-5208) were used in the parametric study to find out how FRP wrapping affects SCF values in a T-joint. It is worth mentioning that the properties, advantages and disadvantages of carbon and glass fibers, vinyl ester and epoxy matrixes have been investigated in the past [11]. Table 1 shows the properties of the FRP materials used in the analyses. In this table, subscripts ‘‘1’’ and ‘‘2’’ represents the fiber longitudinal and transverse directions, respectively.

In order to achieve accurate stresses along the chord-brace intersection, the weld profile should be modeled accurately. In this study, the weld profile along the brace-chord intersection satisfied the specifications addressed in AWS [13]. Figure 1 shows the weld profile section used in the finite element modeling.

In a typical finite element analysis, both shell and solid elements can be employed. Based on the geometry and the relative outputs, the most suitable element type can be chosen. In this study, ABAQUS [9] software package was used for analyses and 3D brick elements were incorporated to model the joint geometry and weld profile after the sensitivity analysis. Element type C3D20, which is a 20-node quadratic brick was used to model the joint.

Table 1: FRP properties [12]

	Glass/ Vinylester	Glass/Epoxy (Scotch ply 1002)	Carbon/Epoxy (T300-5208)
E_1 (Mpa)	28000	38600	132000
E_2 (MPa)	7000	8270	10800
ν_{12}	0.29	0.26	0.24
G_{12} (MPa)	4500	4140	5700
G_{13} (MPa)	4500	4140	5700
G_{23} (MPa)	2540	3100	3400

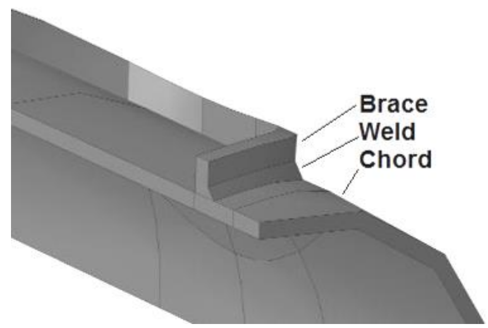


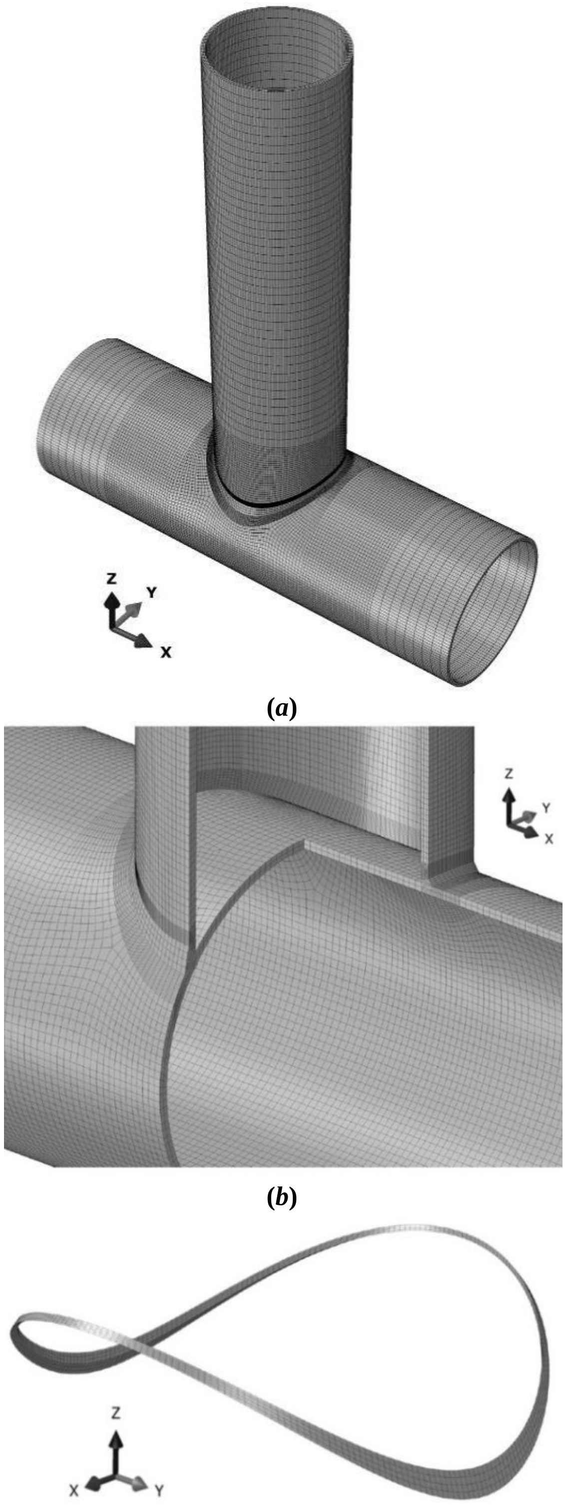
Figure 1.Section of the T-joint including the weld profile

FRP material was modeled using shell elements defined as a skin layer on the joint. ABAQUS [9] element type S4R, which is a 4-node doubly curved thin or thick shell with reduced integration was used to model the FRP skin layers. The inside surface of the FRP elements were tied to the outside surface of the unstiffened T-joint geometry. Therefore, the translational and rotational motion as well as all other active degrees of freedom were equal for these two surfaces. For SCF estimation, linear static analysis was performed. It is presumed that the FRP properties remains intact during the loading and the bond between FRP and the steel remains perfectly intact until the initiation of any fatigue crack on the tube surface.

Different subzone mesh generation methods were used for the weld profile, hot spot stress region, FRP wrapping area and other regions of the joint. The mesh in the hot spot stress region was much finer than the other zones since more computational precision was required in this area. FRP wrapping areas have coarser meshes but still fine enough to ensure computational accuracy. Figure 2 shows the mesh generated for the tubular T-joint.

As previously mentioned, the tubular T-joint modeled in this study was based on JISSP project [8]. Consequently, all the brace and chord geometry details were modeled according to joint “Ref. 1.3” of JISSP project [8].

In this research, boundary conditions were chosen in such a way to represent the actual boundary conditions of the experiment. In the analyses, chord ends were fully restrained (fixed).



(*a*)

(*b*)

(c)

Figure 2. The meshed T joint: a) Isometric view; b) Mesh enlargement; c) Weld geometry

In order to determine the stress concentration factors in a tubular joint, a linear elastic numerical analysis is imperative [14]. In this study, a static analysis in which the loading was controlled in such a way that the maximum strains in the joint remain in the linear elastic part of the stress-strain relationship was conducted. The static axial load was applied at the top of the brace. The Young's modulus and Poisson's ratio of steel were taken as 207 GPa and 0.3, respectively [8]. In order to estimate the SCFs, the method introduced by IIW-XV-E [15] was implemented. In this method, the peak stress at the weld toe is computed by linear extrapolation of the von-Mises stresses at distances of 0.4T and 1.4T from the weld toe; where T is the thickness of the chord member. SCF is calculated by dividing the von Misses stresses at weld toe by the nominal stress in the brace.

In order to validate the finite element model, Lloyd's Register equations [5] and API [6] equations for SCF computation and the test results published in HSE OTH 354 report [5] for JISSP joint "1.3"were employed. Table 2 summarizes the verification results at the saddle and crown points. In this table, e1 and e2 show the percentage of relative difference of Lloyd's Register [5] and API [6] equations with test results, respectively, and e3 denotes the percentage of relative difference between the results of finite element model and the experimental results. According to Table 2, it is clear that the finite element model predicted the SCF at crown and saddle points accurately which was significantly in consonance with the test results; and consequently, the FE model was validated.

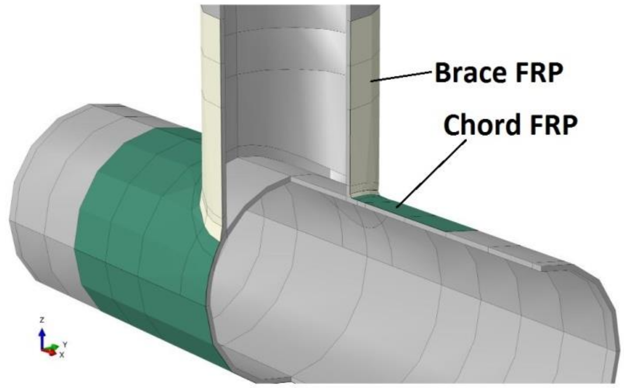
Table 2. Comparison of finite element results with experimental data and predictions of LR [8] and API [7] equations

Position	Test	LR Eq.	API Eq.	FE	e_1 (%)	e_2 (%)	e_3 (%)
Crown	5.4	3.94	3.85	5.3	27.0	28.7	1.9
Saddle	11.4	10.54	12.13	11.1	7.5	6.4	2.6

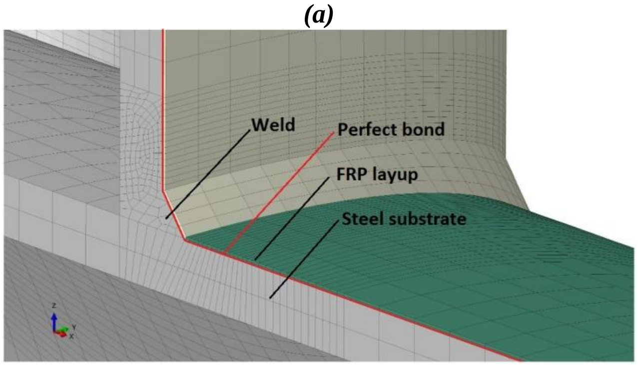
3. Parametric Study

This section presents the results of numerical parametric study conducted to investigate the effect of FRP material type on the stress concentrations at chord-brace intersection zone on the chord member of the T-joint. Figure 3 shows the numerical model of a T-joint wrapped with FRP.

Stress distribution in a T-joint is symmetrically distributed around the brace-chord intersection area. In this study, the results were presented along a 90 degree polar angle for the purpose of brevity. This is a quarter of a chord-brace intersection area which starts from the crown point and ends at the saddle point. Figure 4 shows the schematic plan of T-joint with the mentioned 90° polar angle.



(a)



(b)

Figure 3. Numerical model of a FRP wrapped T-joint: a) Isometric view of the strengthened joint; b) Mesh enlargement around Crown Point

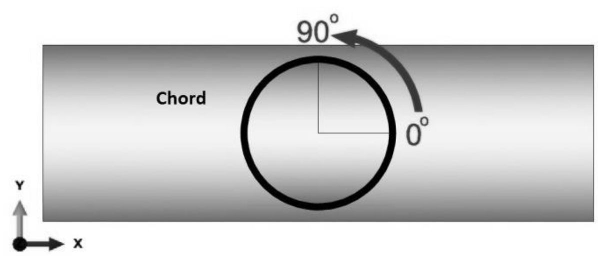


Figure 4. Plan view of the chord-brace intersection area defines the90°polar angle between the crown and saddle points

Change of fiber and/or matrix material properties corresponds to change in FRP mechanical properties. This strongly affects the joint stress distributions and subsequently the SCF values. As mentioned earlier, in this study two types of fibers (glass and carbon) with two different matrices (epoxy and vinyl ester) were used as strengthening material, and their effects on SCF distribution along the chord-brace intersection were investigated. In general, three types of FRP material, namely glass-vinyl ester, glass-epoxy and carbon-epoxy were used as strengthening material with fibers oriented at 0°(chord hoop direction), 1 mm in thickness and a relative length equal to a single diameter of the chord member for chord wrapping and a single diameter of the brace member for brace wrapping. Figure 5 presents the effect of FRP material variation on SCF values for the strengthened T-joint. In this figure, "SCFs" and "SCFu" stand for the SCF values of the FRP strengthened joint and the unstiffened joints, respectively.

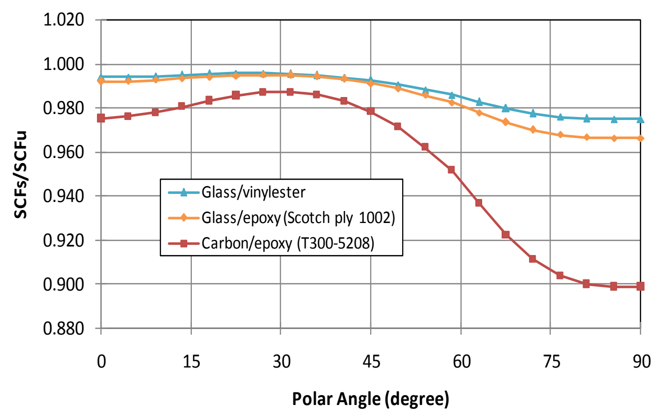


Figure 5. Ratio of SCF distribution in FRP strengthened tubular T-joint with different FRP materials to SCF distribution in unstiffened joint (horizontal axis: polar angle from chord to saddle position)

According to Figure 5, higher mechanical properties of FRP strengthening material results in more decrease in SCFs. This implies that the use of carbon/epoxy gives much lower SCF values. In addition, the maximum efficacy of FRP strengthening material in SCF reduction was observed at the saddle point, while the least effect was at30°polar angle of the chord-brace intersection zone.

Figure 6 illustrates how the SCF ratio (SCF_s/SCF_u) in crown and saddle points of the T-joint varies with different FRP materials.

Figure 6 shows that the use of stiffer materials in decreasing the SCF values is more remarkable at the saddle point

These SCF values presented here are attributed to the FRP, which is composed of 1 mm layer of 0° fiber orientation in the matrix field.

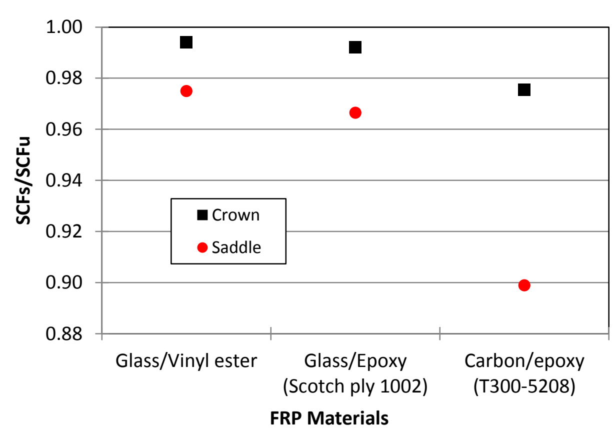


Figure 6. Ratio of SCFs in FRP strengthened tubular T-joint with different FRP materials to SCFs in unstiffened joint in crown and saddle points

4. Summary and Conclusion

In this research, changes in SCF values at 90º polar angle in one quarter of the chord-brace intersection area in an axially loaded tubular T-joint due to change in the FRP material used for wrapping the joint was investigated.

Change in fiber and/or matrix material properties corresponds to change in FRP mechanical properties. In general, three types of FRP materials, glass-vinyl ester, glass-epoxy and carbon-epoxy were employed as strengthening material. Use of FRP material with higher values of mechanical properties showed more efficacy in decreasing the SCF values. According to the results, the use of carbon-epoxy material had efficacy about three times that of GFRP material in decreasing SCF values at the saddle point.

The use of carbon/epoxy FRP with thickness of 1mm, as the strengthening material decreased the SCF values up to 2.5 and 10.1% at the crown and saddle points, respectively. In industrial applications, FRP layer thickness could be higher. Accordingly, more increase in SCFs might be observed.

Due to the superior fatigue performance of CFRP materials in comparison to other materials such as GFRPs; and due to GFRP stress corrosion problems, and the better performance of CFRPs in reducing SCF values especially in the saddle region vis-à-vis the findings of this study, it would be beneficial to use CFRP as wrapping strengthening material in order to extend the fatigue life of tubular joints.

5. References

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