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Fatigue strengthening of tubular X joint using un-bonded CFRP laminates

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ABSTRACT: One of the most important structures composed of circular hollow sections is a steel jacket platform, used to extract oil and gas in offshore drilling, which therefore has to struggle with a harsh and complicated environment. This environment exposes the steel jacket platform to high-cyclic loading, leading to fatal damage in its joint which is known as fatigue damage. Investigating this phenomenon and also preventing or at least decreasing the damage of this failure mode has attracted a lot of research in the past decades. Based on Eurocode and CIDECT, the stress range is an important parameter for determining the fatigue strength of fully stress relieved connections. On the other hand, in recent years a new kind of strengthening technique using un-bonded CFRP laminates has been developed that can reduce the mean stress and it doesn’t suffer from adhesive failure of the adhesive layer. In this paper, this kind of strengthening is proposed for fatigue strengthening of fully stress relieved tubular X-joints. Using FE modeling the effect of such a strengthening scheme is also investigated.

1 INTRODUCTION

Based on catastrophes over the last 100 years and many laboratory investigations, it has been proven that metals can fracture, even under a relatively low stress if the number of loading cycles is large enough, Stephens et al. (2000). The reason of such failure is that a crack is formed due to cyclic loading at levels even lower than the material yield stress. It grows until the remaining cross-section of the load-carrying member cannot transmit the applied loads and then the member fractures. This kind of failure is known as fatigue failure.

One of the most important infrastructures which suffers from fatigue failure is the steel jacket platform used in offshore drilling. A steel jacket platform is generally constructed out of tubular hollow sections and connections and it is subjected to different kinds of loads such as wave loads which are dominant in fatigue loading, Graff (1981). Although a circular hollow section has a lot of advantages such as an equal moment of inertia in any direction, high torsional rigidity and a low drag coefficient, it is very fatigue-susceptible at its connections, due to geometric discontinuities, lead to stress concentrations at some points, named hot spots, around circumference of the joint. These high stresses lead to initiation and growth of cracks (i.e. fatigue damage).

There are a number of uniplanar and multi planar joints that are being used in offshore structures. X-joints are one of the uniplanar joints which are investigated in this paper. In this joint, that member which is cut and welded to the other one (i.e. chord) is called a brace, Fig. (1). Acting against cyclic loading by waves, an X joint may experience tension-tension, tension-compression or compression-compression cycles, Fig. (1). Regarding this fact, it is generally presumed that only braces which have some parts of their load range in tension will be susceptible to fatigue failure, CIDECT (2000). This fact is restated by Eurocode (1993) using another point of view. According to the Eurocode for stress-relieved welded details, the stress range for the calculation of the fatigue life of a detail may be calculated by adding the tensile portion of the stress range and 60% of the magnitude of the compressive portion of the stress range. So, using a pre-stressing technique, one can partially or completely shift the applied stress range of an X joint to the compression mode and hence the fatigue life of the connection would be increased.

Nowadays carbon fiber reinforced polymer material draw researcher's attention due to their high strength-to-weight ratio, high corrosion resistance and excellent fatigue performance for retrofitting steel and concrete structures. The traditional method for retrofitting of steel structures using CFRP material is that it is bonded to the surface of a steel element using glue. CFRP material is sometimes pre-stressed for using a larger portion of the material capacity. This method could be called a pre-stressed bonded reinforcement (PBR) system. Although having a lot of advantages, PBR systems suffer from some drawbacks such as low long performance in moist environment when imposing fatigue loading, difficult removal of anti-corrosion toxic paint of steel surfaces, hard or infeasible installation on unsmooth surfaces and galvanic corrosion between CFRP material and the steel surface. On the other hand, pre-stressed un-bonded reinforcement (PUR) systems which were developed by Ghafoori et al. (2015), could overcome the PBR system's drawbacks by omitting the adhesive layer and introducing special clamps connecting the pre-stressed CFRP plate to the steel substrate.

In this paper, a stress-relieved X joint is strengthened using the PUR system at different pre-stressing levels and the effect of this system is investigated form a fracture mechanics' point of view.

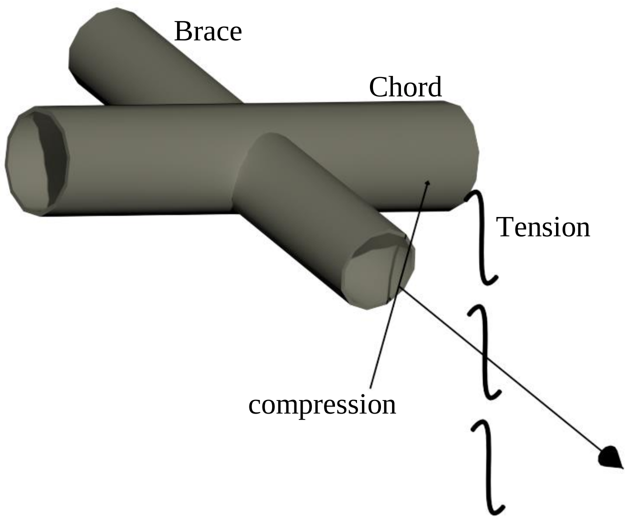


Figure 1. A typical tubular X joint and three probable loading cycles.

2 PROPOSED PRE-STRESSING TECHNIQUE

Based on Eurocode (1993) for stress-relieved connections, the stress range could be considered as:

$$\Delta\sigma_1 = \sigma_{\max} + 0.6|\sigma_{\min}| \tag{1}$$

Where, σ_{max} and σ_{min} are the maximum and minimum stress experienced by the fatigue-susceptible metallic detail. Here, σ_{max} is assumed to be larger than zero and σ_{min} is a negative value. Applying a constant pre-stressing stress, as a portion of a of the real applied stress range $\Delta\sigma_{real}$, the new stress range could be calculated as follows:

$$\Delta\sigma_2 = \sigma_{\max} - a\Delta\sigma_{real} + 0.6(|\sigma_{\min}| + a\Delta\sigma_{real}) \tag{2}$$

The desired situation is:

$$\Delta\sigma_2 < \Delta\sigma_1 \tag{3}$$

Substituting Eq. (1) and Eq. (2) in Eq. (3) yields:

$$0.6 < 1 \tag{4}$$

And this is always true. As a matter of fact, by using a constant pre-stressing force, the new stress range, regarding to Eq. (1) is decreased by $0.4a\Delta\sigma_{real}$.

For strengthening a typical X joint a simple and practical pre-stressing steel platform is considered, Fig. (2-b). as it can be seen, the bottom part of this platform is a rectangular hollow section (RHS) with proper dimensions with respect to the brace diameter. Based on the brace diameter, the bottom of the RHS is cut such that it can be later mounted on the brace. At the top of this RHS, a plate is welded to be a bed for the CFRP plate. Six holes are also created on this plate. The application of these holes is explained later. For strengthening a tubular X joint, 4 pre-stressing platforms are needed and as it can be seen from Fig. (2-b), they are symmetrically welded at both sides of the joint. It should be mentioned that, at the location of connection between the pre-stressing platform and the brace, there are two source of stress concentrations. The first one is due to the presence of brace axial force. This load leads to SCF of around 2 which is considerably lower than those of X- joint. The other one is due to the presence of pre-stressing force of CFRP plates. For this source of stress concentration it should be mentioned that, based on the published literature, that part of stress which is fluctuating through time is a factor for provoking fatigue damage and in the current case the pre-stressing force is always constant during the remaining life of CHS X-joint. So it can be concluded that, there is no concern about the fatigue life of pre-stressing system. After installation of these platforms, using a hydraulic jack, the CFRP plate is pulled and it reaches a desired level of pre-stressing. For fastening the CFRP plate to the platform, an upper plate as shown if Fig(2-b) is used. This upper plate is fixed to the bottom one, using pre-tensioned bolts through aforementioned holes and it introduces a compressive force for anchoring the CFRP plate.

3 FINITE ELEMENT MODELING

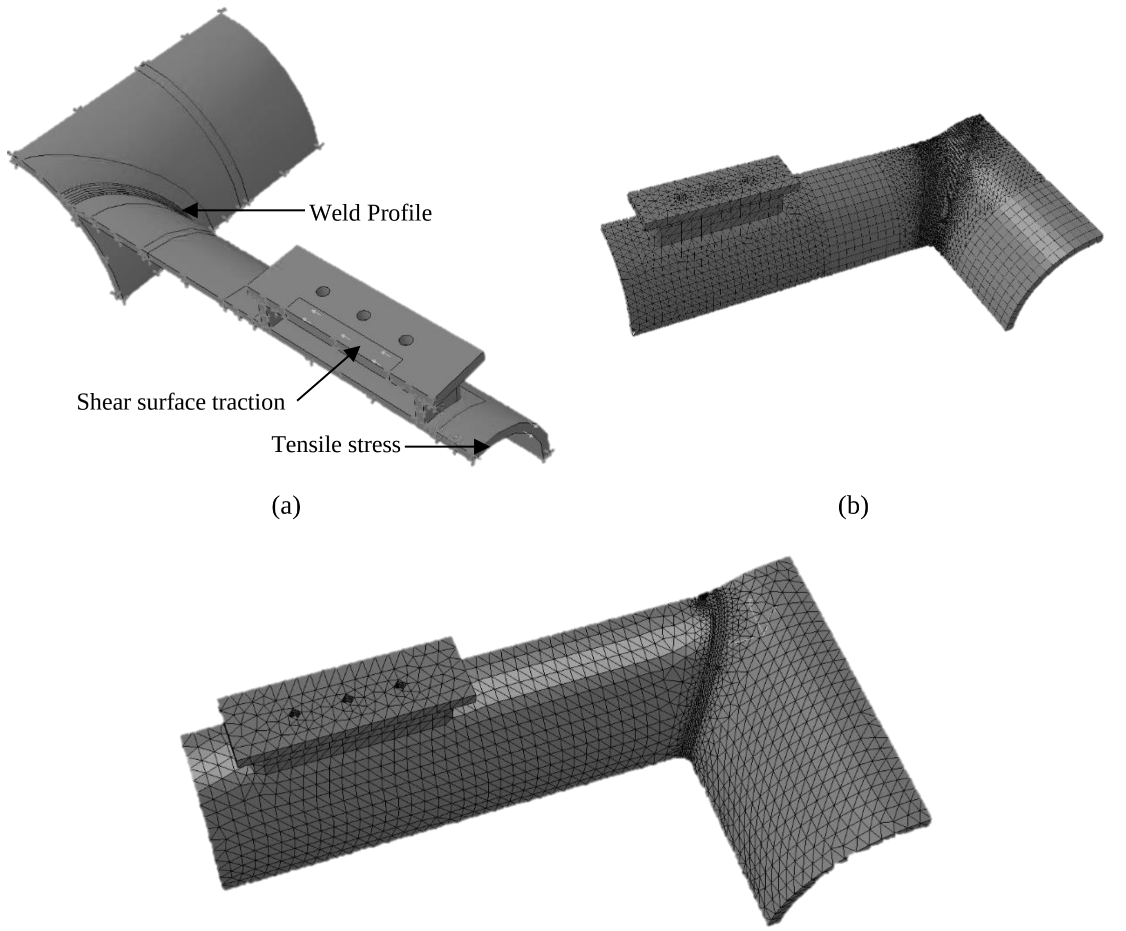
In order to investigate the effect of the proposed PUR system, a tubular X joint is modeled using the ABAQUS commercial FE software (2006). Table (1) shows the joint's dimensions.

Figure 2. Strengthening a tubular X joint with proposed PUR system.

Table 1. Dimensions of the Tubular X joint

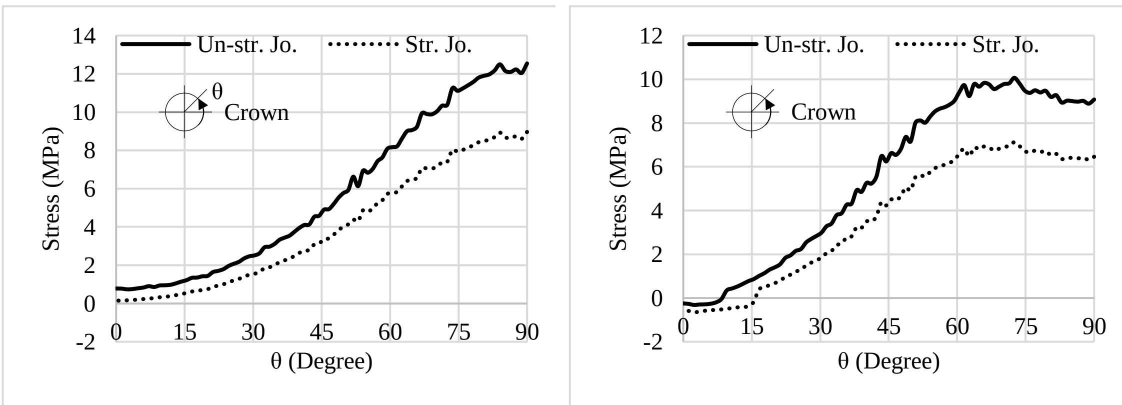
	Outer Diameter (mm)	Thickness (mm)	Length (mm)
Chord	219.1	10	500
Brace	177.8	8	992

The Young's modulus and Poisson' ratio of steel are $2.05*10^{11}$ N/m^2 and 0.3 respectively. Due to the existence of three planes of symmetry, only one eight of the X joint, as shown in Fig. (3-a), is modeled. In addition to the required boundary conditions for the symmetries, it is considered that the chord is free at its extremity and a uniform pressure representing the axial force is applied at the end of the brace. Steel is assumed to be linear elastic. For the sake of simplicity, only the effect of the CFRP plate on the pre-stressing platform (i.e. shear surface traction) is modeled, Fig. (3-a). The pre-stressing platform is merged to the brace member to reflect the butt weld with full penetration and for the sake of simplicity the butt weld profile is omitted from the FE model. On the other hand, due to the important effect of the weld profile at the intersection of chord and brace, it is modeled based on the weld geometry proposed by Borges (2008). As far as this joint is stress-relieved, there is no concern about the residual stress distribution. In this study two meshes are used. The first one is used for calculating the stress concentrations at weld toe of both chord and brace. The elements of this mesh at the weld profile are the quadratic tetrahedral element C3D10 with a size of 2 mm, Fig. (3-b). The second mesh is generated for obtaining the stress intensity factor at an initial stationary crack using XFEM, Belytschko et al. (1999). The standard semi-elliptical crack chosen from published literature, Borges (2008), with $a_i=0.5$ mm and $2c_i=2$ mm is placed at the brace saddle weld toe due to high stress concentration with respect to other hot spots. All elements are 4-node linear tetrahedron C3D4 which are refined at the crack zone with a size of 0.1 mm, Fig. (3-c). Although in this work, the stationary crack is investigated, the crack propagation can also be studied using the proposed FE model.



(c)

Figure 3. Tubular X joint, (a) loadings and weld profile, (b) mesh for obtaining stress concentration at the weld toe, (c) mesh for obtaining stress intensity factor at the weld toe of brace.



(a) (b)

Figure 4. Maximum principal stress distribution at the weld toe of (a) Brace, (b) Chord.

4 RESULTS

To investigate the stress distribution at the weld toe of the X-joint, a uniform tensile stress of 1 MPa is applied at the end of the brace. These stress distributions for an un-strengthened and strengthened joint at both brace's and crown's weld toe are shown in Fig. (4). The reported stress values in Fig. (4) are the maximum principal stresses at each location. As it can be seen, the maximum stress is generated near to brace crown with the size of 12.54 MPa (i.e. the stress concentration factor of 12.54). On the other hand, by applying a pre-stressing shear force at the pre-stressing platform with a magnitude of 30% of the tensile force, the aforementioned value is decreases to 8.96 MPa (i.e. 28% reduction). This reduction can be obviously seen for other locations of both brace's and chord's weld toe.
In order to show the effect of the proposed system on the tubular X-joint, three tensile stresses applied on the brace are introduced as 25.4, 31.75 and 38.10 MPa. Assuming a longitudinal modulus of elasticity of 167.2 GPa and a minimum strain rupture of 1.5% and considering a width of 15 mm and thickness of 1.2 mm for the CFRP plate, a pre-stressing stress of 752 Mpa (i.e. equal to 30% of minimum strain rupture) is considered for the PUR system. Note that these stress and dimension values belong to the reduced FE model described in the previous section. The stress intensity factor, K_I, at the deepest point of the stationary crack is calculated for each case as shown in Fig. (5). As it can be seen, using the proposed system, K_I is reduced by 47%, 37% and 31% for case1, 2 and 3 respectively.

5 CONCLUSION

For fatigue design of fully stress-relieved connections, when the absolute stress ratio is lesser than 1.67, pre-stressing the connection leads to an increase of the fatigue life span. In this study a new pre-stressing un-bonded reinforcement system for a typical tubular X joint is proposed. Based on the FE modeling's results, by using the proposed system the maximum principal stress at the weld toe of brace and chord are decreased. The amount of reduction depends on the pre-stressing level. Using XFEM, the K_I value is also obtained and it shows that the proposed system can increase the toughness of the tubular joint leading to a longer fatigue life span, too.

The authors of this paper is developing the application of this kind of strengthening for non- stress relieved connections, too. The basic idea of the new method is a blend of the current work and the active control concept. In this way, the pre-stressing level of CFRP plates is wisely changed and the stress range of the connection as the main parameter of fatigue life of fatigue-susceptible details is reduced. So the fatigue strength of connection will increase. This idea is now under study numerically and experimentally as a joint PhD thesis between Ferdowsi University of Mashhad, Iran and Ghent University, Belgium.

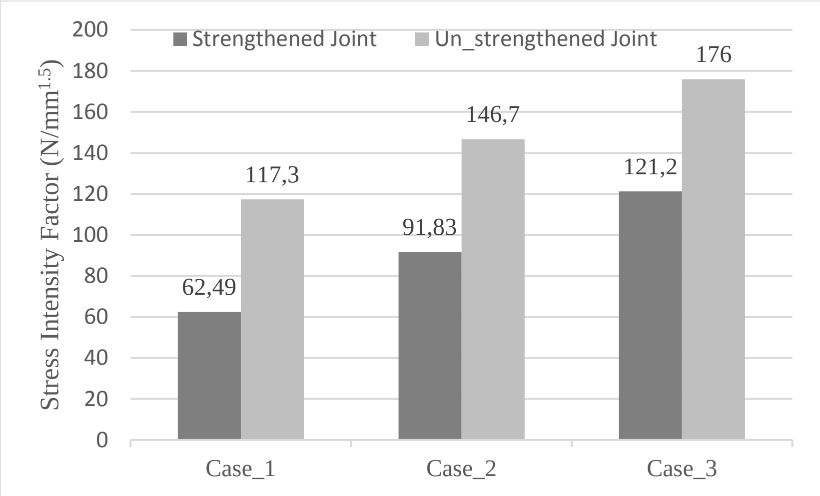


Figure 5. Stress intensity factor for un-strengthened and strengthened tubular X joint.

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