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Optimization of Fibre Orientation for Composite Reinforcement of Circular Hollow Section KT-joints

Abstract (reduce to 250 words, no more than 100 words in each section)

Purpose – ~~In recent years, composite~~ Composite materials are ~~have emerged as an~~ effective alternative for rehabilitating critical members of offshore platforms, bridges, and other structures. The structural response of composite reinforcement greatly depends on the orientation of fibres in the composite material. ~~However, limited research has focused on the optimum reinforcement orientation for reinforcing circular hollow section joints. These joints are often subjected to brace axial and bending loads simultaneously.~~ Joints are the most critical part of tubular structures. Various existing studies have identified optimal reinforcement orientations for a single load component, but none have addressed the combined load case, even though most practical loads are multiplanar ~~(involving combined load components)~~.

Design/methodology/approach – This study investigates the optimal orientation of composite reinforcement for reducing stress concentration factors (SCF) of tubular KT-joints ~~subjected to any combination of loads~~. The joint reinforcement was modelled and simulated using ANSYS. A parametric study was carried out to determine the effect of the orientations of reinforcement in the interface region on SCF~~, as the reduction in SCF measures the enhancement in fatigue life. SCF was determined~~ at every 15˚ offset along the weld toe using linear extrapolation of principle stress. The impact of orientation for uniplanar and multiplanar loads was investigated, and a general result about optimum orientation was inferred.

Findings – It was found that the maximum decrease of SCF is achieved by orienting the fibres of composite reinforcement along the maximum SCF~~, which depends on the magnitudes and directions of the components of the static loads~~. Notably, ~~these~~ the optimal direction~~s~~ for any load configuration ~~were~~ was consistently orthogonal to the weld toe of the chord-brace interface. As such, unidirectional composites wrapped around the brace axis, covering both sides of the brace-chord interface, are most effective for SCF reduction. ~~Moreover, it was found that the optimal reinforcement direction can be determined through the superposition of hot-spot stress.~~

Originality – The findings of this study are crucial for ~~better~~ adequate ~~composite~~ reinforcement of tubular joints using composites~~. Instead of concluding the optimum orientation in reference to a specific coordinate system, a general conclusion was an incredible finding~~, offering a broader and universally applicable optimum orientation that transcends specific joint and load configuration.

Keywords Tubular joints, FRP reinforcement, optimal orientation, fatigue life enhancement, stress concentration factor

Paper type Research paper

1. Introduction

Tubular members are widely used for structural applications. The weld line of such structures is the most vulnerable spot for fatigue failure initiation. Structural and environmental degradation necessitates that the strength and stiffness of the joint be enhanced for sustained integrity of the structure. These joints can be between two circular hollow section (CHS) members or between a CHS and a square hollow section member (Feng *et al.*, 2020; 2021a; 2021b; 2021c). Various approaches have been discussed for the rehabilitation of compromised tubular joints (Iqbal *et al.*, 2023a). These approaches are sometimes utilized to enhance and upgrade the structure to meet increased load demands. Among these, the most advantageous is repairing tubular joints using composite reinforcement (Barros *et al.*, 2017). Composite reinforcement does not cause any stress concentrations and residual stresses, unlike repair methods that involve welding. Composite reinforcement can be applied using room-temperature cured epoxies without hindering the ongoing operations (Djahida *et al.*, 2021). The hand layup of composite on any complex geometry eliminates the need for special tooling. The tolerability of composite for various load requirements enables the design of lightweight repair schemes. Moreover, by proper layup design, stress or displacement can be reduced (Perrut *et al.*, 2019). The availability of special epoxies that can be cured underwater widens the applicability of composite repair to underwater structures, where welding is reasonably challenging (George *et al.*, 2021; Naser *et al.*, ~~Hawileh and Abdalla,~~ 2021).

Fibre-reinforced polymers (FRP) are commonly used for structural applications in aerospace, automotive, and many other industries due to their high strength-to-weight ratio, high specific stiffness, and customizable material properties, with unidirectional FRPs found to be the best option for the reinforcement of tubular joints (Xu *et al.*, 2020). However, FRPs are anisotropic, meaning their properties and response depend on the fibre orientation. Hence, the proper orientations of fibres are critical for obtaining optimal reinforcement performance. Various types of glass, carbon, aramid, and basalt FRPs are frequently used to reinforce tubular structures. These materials are robust and cost-effective, and they are lightweight. The importance of accurate modelling was highlighted, and design guidelines were proposed for predicting the behaviour of tubular joints under different loading conditions (Feng *et al.*, 2021d; 2021e; 2021f). Although the requirement for lightweight material is not as critical in civil and oil and gas fields as it is in the aerospace and automotive fields, misorientation can reduce the capability of composite reinforcement to enhance the load-bearing capacity of the tubular member. The optimal orientation of reinforcement is independent of the fibre material, making the findings of this study applicable to any reinforcement material.

Various researchers have explored the composite reinforcement of simple tubular joints. Hosseini *et al.* (2021) investigated the Carbon FRP (CFRP) and Glass FRP (GFRP) reinforcement of T/Y joints under axial load. A 30% enhancement was reported in the joint's static load-bearing capacity (SLC) for CFRP reinforcement compared to GFRP reinforcement. They also conducted an experimental investigation and found up to 28% reduction in stress concentration factor (SCF) due to 6 mm GFRP reinforcement of T-joints subjected to axial load (Hosseini *et al.*, 2020). Lesani *et al.* (2013, 2014) reported a more than 50% increase in the ultimate compressive load-bearing capacity of T-joints. Hosseini *et al.* (2019) considered SCF reduction with FRP reinforcement in T-joints subjected to axial and bending loads. A 30% and 50% decrease were recorded in SCF at the crown and saddle for the axial load, whereas there was a 45% and 50% reduction for IPB and OPB loads when the joint was reinforced with 6 mm CFRP. Tong et al. (2019) also found a decrease in SCF for CFRP reinforcement of K-joints. Xu *et al.* (2020) investigated SCF reduction with CFRP reinforcement of K-joint under balanced axial loads and explored the effect of various geometric and reinforcement parameters.

Hosseini *et al.* (2021) reported a reduction of more than 50% in SCF at the saddle point due to FRP reinforcement of KT-joint under axial load. This impact was consistent with the reduction of 30% for IPB and 55% for OPB-loaded KT-joint reinforced with CFRP (Zavvar *et al.*, 2021). Zavvar and Soares (2023) reported a similar finding of SCF reduction in DKT-joint under axial load. These studies primarily focused on uniplanar loads, for which the peak value of SCF usually occurs at the crown for IPB and the saddle for OPB and axial load cases. It was reported that with FRP reinforcement of CHS joints, their load capacity increased, and the SCF decreased. The magnitude of this difference depends on the properties of the reinforcement material, the number of reinforcement layers, and their orientation.

Fatigue is the primary cause of failure in tubular joints, with the structural hot-spot stress approach widely used for fatigue life estimation. This method utilizes SCF to determine hot-spot stress, which is used in conjunction with the respective S-N curve to estimate the fatigue life. A reduction in SCF measures an enhancement in the fatigue life of a tubular joint. Properly orienting reinforcement can result in a maximum decrease in SCF for a given amount of reinforcement, thus resulting in a maximum increase in the fatigue life of tubular joints, thereby directly influencing structural design decisions and operational safety. Applying reinforcement inadequately causes a substantial increase in dead weight, while no significant reduction in SCF results in negative consequences. While various researchers have investigated the appropriate orientation of reinforcement, as referenced in previous paragraphs, these orientations are described for specific joints and loads. A generalized conclusion applicable to any joint geometry and load configuration is still lacking.

Various optimization strategies are being investigated for advanced structural applications these days (Meng *et al.* 2023a; 2023b; 2024). Such approaches are graded as beneficial for various critical solutions (Yang *et al.*, 2023; Luo *et al.*, 2024; Teng *et al.*, 2024). However, the current study has only a single straightforward objective, which is the magnitude of reduction in SCF; hence, sophisticated algorithms for optimization were not utilized (Meng *et al.*, 2022). In this study, the optimum orientations for reinforcing the tubular joints have been investigated to improve the fatigue strength by reducing SCF and the corresponding hot-spot stress (HSS) used for fatigue life estimation through the S-N curve. A typical KT-joint with a load on the central brace and constrained from chord ends and inclined braces was used for this study. It was observed that the influence of reinforcement orientation remains consistent across different material types. Therefore, reinforcement material was fixed to CFRP UD with 138GPa elastic modulus in the direction of fibre. Joints -reinforced ~~with FRPS~~ at various orientations and loaded with axial, IPB, and OPB loads were simulated, and a general understanding was developed about the optimum orientations. These findings were projected for combined load configurations.

2. Methodology

Circular hollow section KT-joints were simulated through finite element analysis (FEA) using ANSYS. The reinforcement layup was defined using ACP (ANSYS Composite Prep Post). Static structural analysis was performed and SCF response was measured. Detailed methodology is discussed in the following sections.

2.1 ~~Finite element modelling~~Modelling of geometry

A KT-joint geometry was modelled using the ANSYS Design Modeler according to the dimensions outlined by Ahmadi and Zavvar (2020). The joint has braces of equal size, while the two inclined braces are symmetrically attached to a chord, as shown in Figure 1.

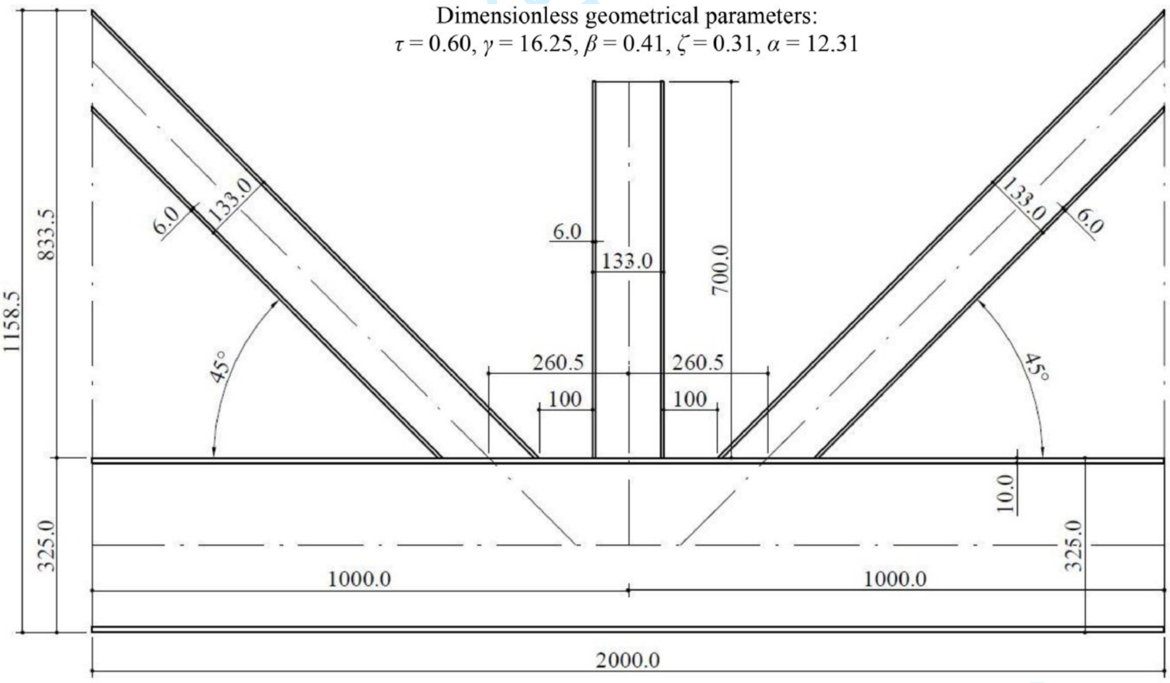

Figure 1. Geometry of the typical joint
Source: Ahmadi and Zavvar (2020)

2.2 Finite element meshing

High-order solid elements were used ~~for meshing~~to mesh the joint geometry~~, as shown in Figure 1~~. Mesh independence was ensured through a sensitivity analysis, as depicted in Figure 2. A KT-joint, as per dimensions given in Figure 1, reinforced with 5mm unidirectional composite reinforcement having an elastic modulus of 5GPa in the fibre direction, was used in this study. Sensitivity analysis was carried out for both axial and bending load configurations. A relatively fine mesh was employed in the interface region. A factor was introduced in the mesh sizing control, and this factor was optimized after achieving a mesh-independent FE model. The final mesh was comprised of 791644 tetrahedral elements, as shown in Figure 3. The composite reinforcement was meshed with a quadrilateral surface mesh consisting of 73432 elements. This FE model was used in all simulations.

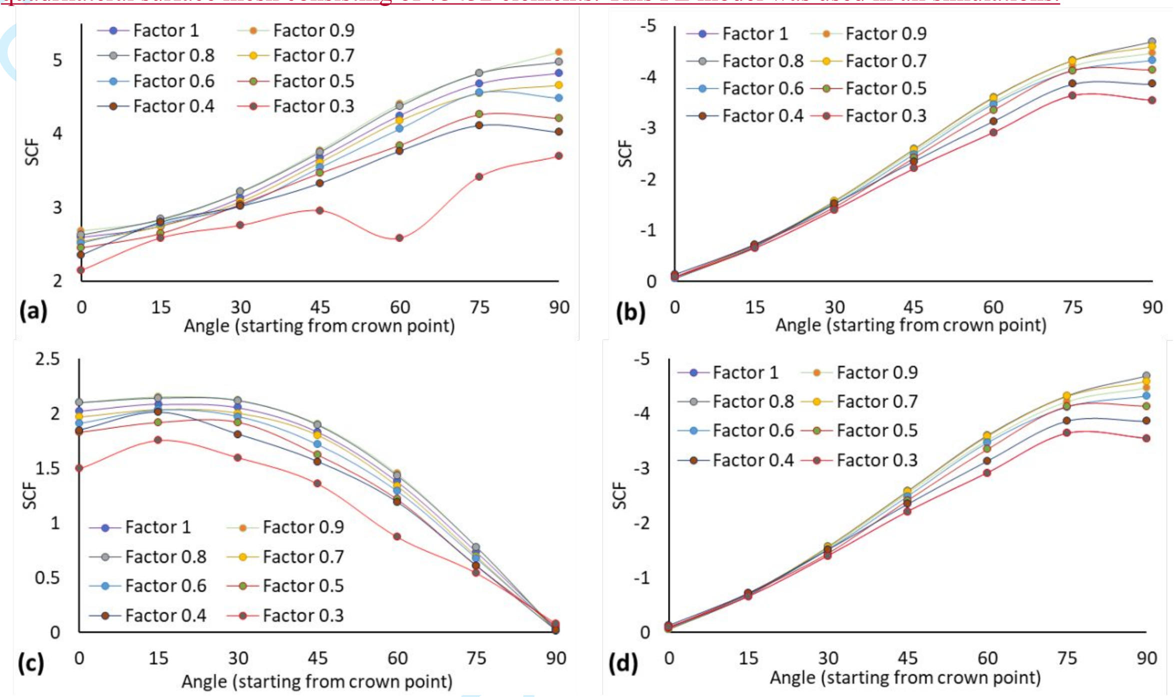

Figure 2. Meshed independence plots (a) Axial compression (b) Axial tension (c) IPB (d) OPB
Source: Own work

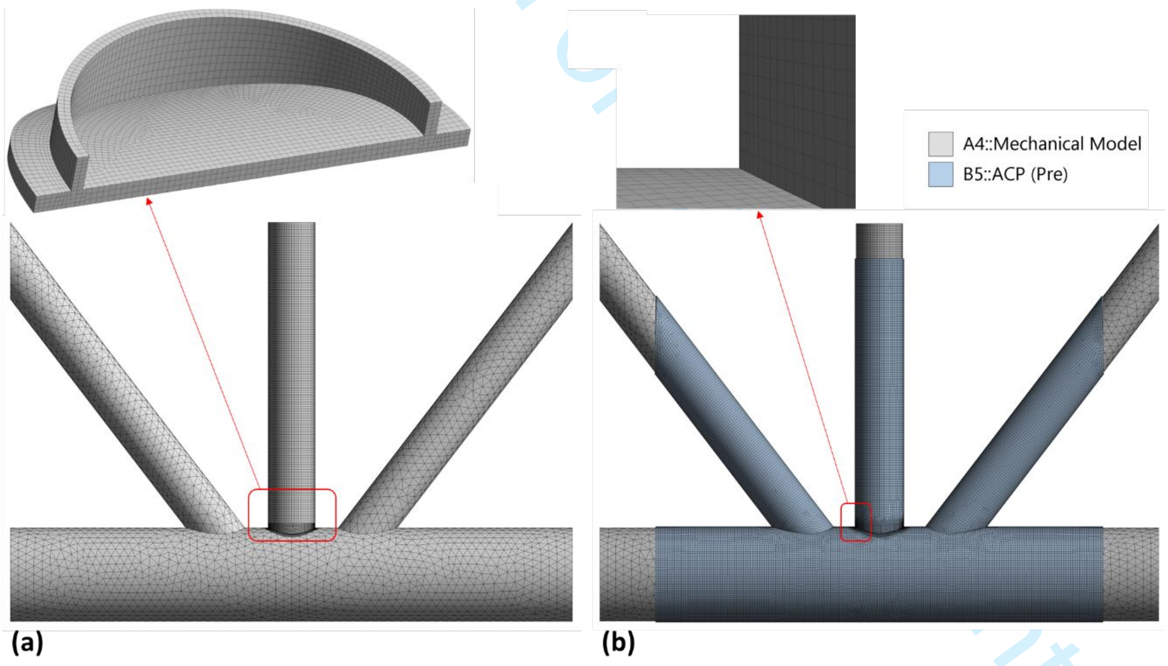

Figure 3. Meshed model: (a) KT-joint (b) joint with FRP reinforcement
Source: Own work

2.3 Validation of FE model

The developed FE model was validated against published results. The difference in SCF was less than 15% between the SCF computed through the numerical model of this study and the literature, thereby validating the model (Ahmadi and Zavvar, 2020), as depicted in Figure 4.

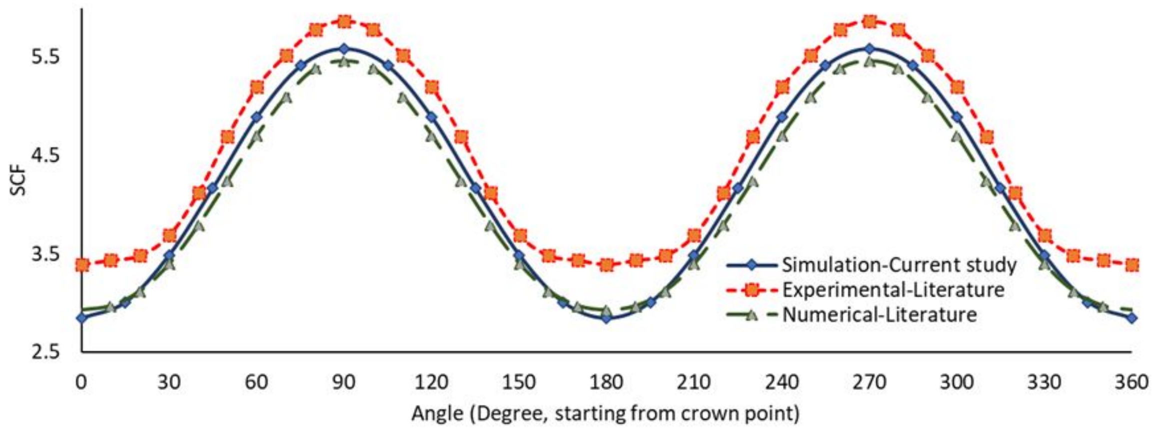

Figure 4. Validation of the finite element model
Source: Own work

2.4 Composite reinforcement

The joint reinforcement was modelled using the ANSYS Composite Pre/Post (ACP) module. FPR reinforcement was defined at the interface. The interface between joint and reinforcement material was assumed to be a perfect bond (Lesani *et al.*, 2015; Hosseini *et al.*, 2020b). The length of composite reinforcement has a negligible effect once a minimum length is ensured (Xu *et al.*, 2020). The joint was divided into zones, and an independent layup was defined for each zone, considering the variation of the magnitude and direction of load within the joint, as illustrated in Figure 5. It was observed that SCF is primarily affected by reinforcement in zone-1. Hence, the fibre orientation of reinforcement in this zone was defined as a variable. For other regions, a minimal reinforcement was defined with a fixed orientation, using expert intuition. Zone-2 was defined for the upper half of the chord, excluding zone-1, while zone-3 was defined for braces. Similarly, zone-4 was defined for the lower half of the chord. The SCF was determined for the joint with FRP reinforcement and compared to the unreinforced joint. The fibre orientation was varied, and the orientation resulting in the maximum drop in SCF was determined. This procedure was repeated for each load case. It was observed that the orientation effect remains independent of joint geometry, load magnitude, and reinforcement material; therefore, these parameters were kept constant. Only the orientations were varied, and the resulting SCFs were plotted to deduce the optimal outcomes.

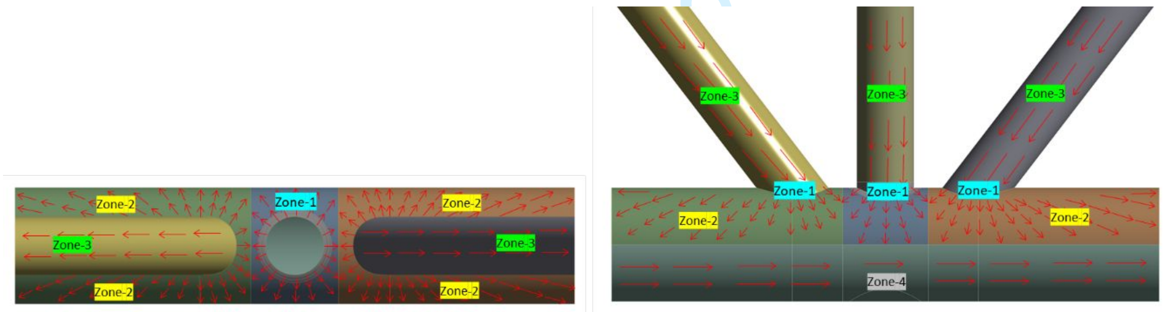

Figure 5. Definition of various zones for composite reinforcement of KT-joint
Source: Own work

2.5 Boundary ~~condiditons~~ conditions and loading

The ends of the inclined braces and chord were constrained, and a static load was applied to the central brace. The magnitude of the applied load was maintained below the elastic/strength limit of the joint material (steel). The boundary conditions of the joint are illustrated in Figure 6. Static analysis was carried out, and the stress response was studied. All load components, i.e., axial compression, axial tension, IPB, and OPB, were simulated separately.

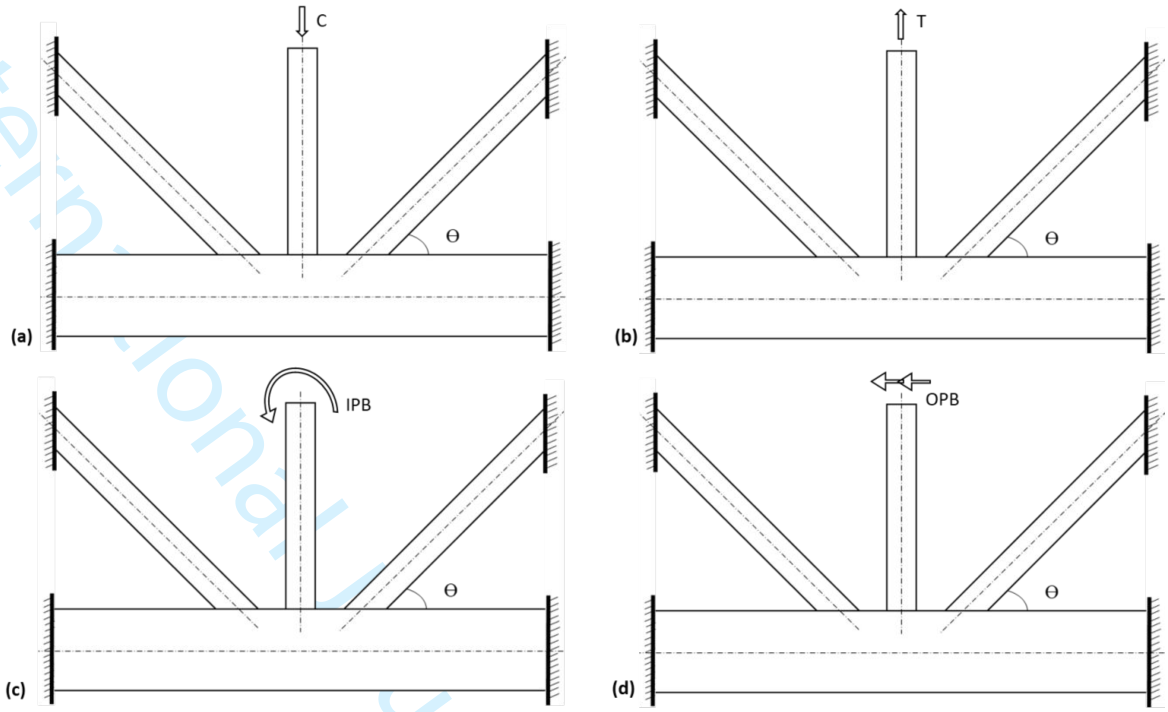

Figure 6. KT-joint under central brace loading: (a) axial compression (b) axial tension (c) in-plane bending (iv) out-of-plane bending
Source: Own work

2.6 ~~Post processing~~Post-processing

The complex geometry at the chord-brace interface and the weld causes a significant rise in stress. The structural stress approach of fatigue analysis accounts for the stress amplification due to geometry variation while excluding the weld notch effect. The HSS is used with the S-N curve to estimate fatigue life, a preferred approach at the design phase (Poutiainen *et al.*, 2004; Niemi *et al.*, 2018). The HSS was determined using linear extrapolation of surface stress, utilizing principal stress at $0.4T$ and $1.4T$ (T is chord thickness), following IIW recommendations (Niemi *et al.*, 2018), as shown in Figure 7, and given as Equations (1)-(4). SCF was determined for each load case at the interface of chord and central brace.

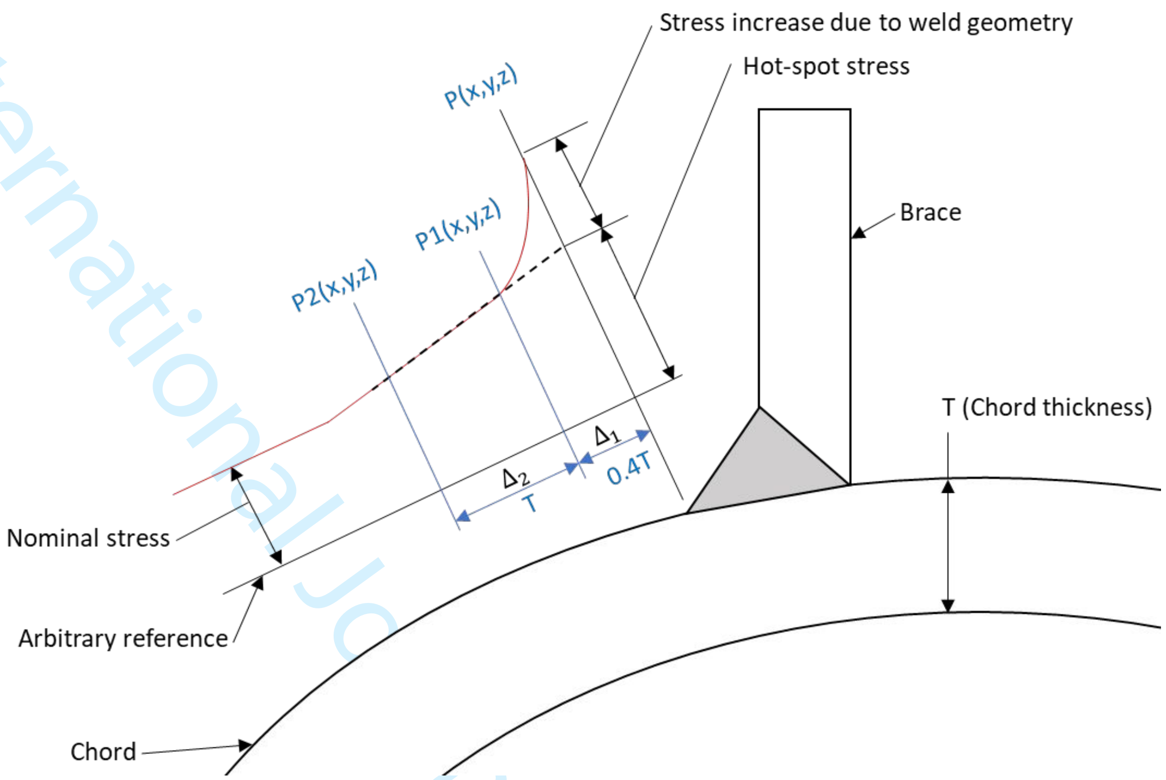

Figure 7. Extrapolation of stress at weld toe
Source: Iqbal *et al.* (2024)

$$SCF = \frac{HSS}{\sigma_{nominal}} \quad (1)$$

$$HSS = \sigma_1 \pm \left(\frac{\sigma_1 - \sigma_2}{\Delta_2}\right)\Delta_1 \quad (2)$$

$$\Delta_1 = \sqrt{(x_1 - x)^2 + (y_1 - y)^2 + (z - z)^2} \quad (3)$$

$$\Delta_2 = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2} \quad (4)$$

Where σ_1, and σ_2 is the maximum principle stress at extrapolation points 1 and 2, respectively, and (x,y,z) represents the geometric position of extrapolation points and weld notch.

3. Results and discussion

A KT-joint reinforced with FRP at various orientations was simulated under multiple central brace loads, namely axial, compression, axial tension, IPB, and OPB. An equal load of 30 MPa was used for these simulations. This study focused on SCF, which is measured in Zone-1, that is the zone consisting of the interface of chord and brace. The effect of reinforcing Zone-2, 3, and 4, which define the remaining surfaces of chord and brace, was not significant; hence, these are not discussed. It was observed that the maximum reduction in SCF was achieved for axial and OPB when reinforcement was oriented at 90˚ (hoop direction of the chord), according to the orthogonal coordinate system shown in Figure 8. When the joint was subjected to IPB load, optimum results were obtained with reinforcement oriented at 0˚ (along the axis of the chord). Figure 9 illustrates the SCF trend for a fixed thickness and reinforcement material. Quarter symmetry was used for a KT-joint subjected to load on the central brace under axial load, whereas half symmetry was used for IPB and OPB loads. The two-quarters of the half-symmetric model in IPB and OPB loads showed stress responses of similar magnitude with opposite signs. Hence, SCF is presented only for the quarter model.

Based on Figure 9, it was inferred that the optimum reinforcement orientation consistently remained normal to the weld toe when the joint was subjected to any uniplanar load. Hence, this optimal direction can be well represented by the "r" direction of the r-ϴ coordinate system, having its origin at the intersection of the centre brace axial with the chord outer surface, as shown in Figure 8. When a joint needs to be reinforced against a single load, reinforcement should be applied in this direction. However, the application of unidirectional FRP in a small portion of the tubular structure is not recommended, and it is better to wrap the reinforcement around the brace-chord interface, ensuring the fibre direction of reinforcement is normal to the weld toe in zone-1, as shown in Figure 10.

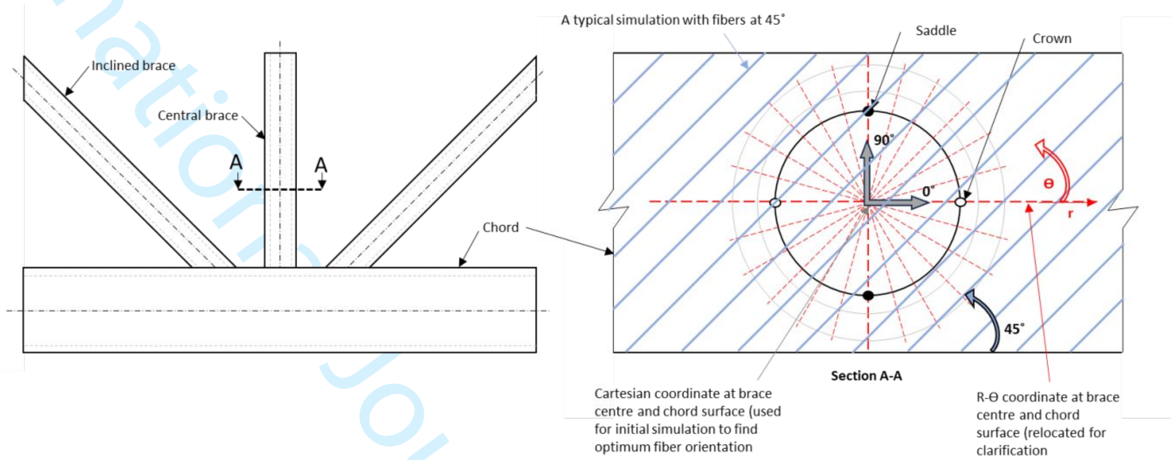

Figure 8. Reinforcement orientation in zone-1 (central brace-chord interface zone)
Source: Own work

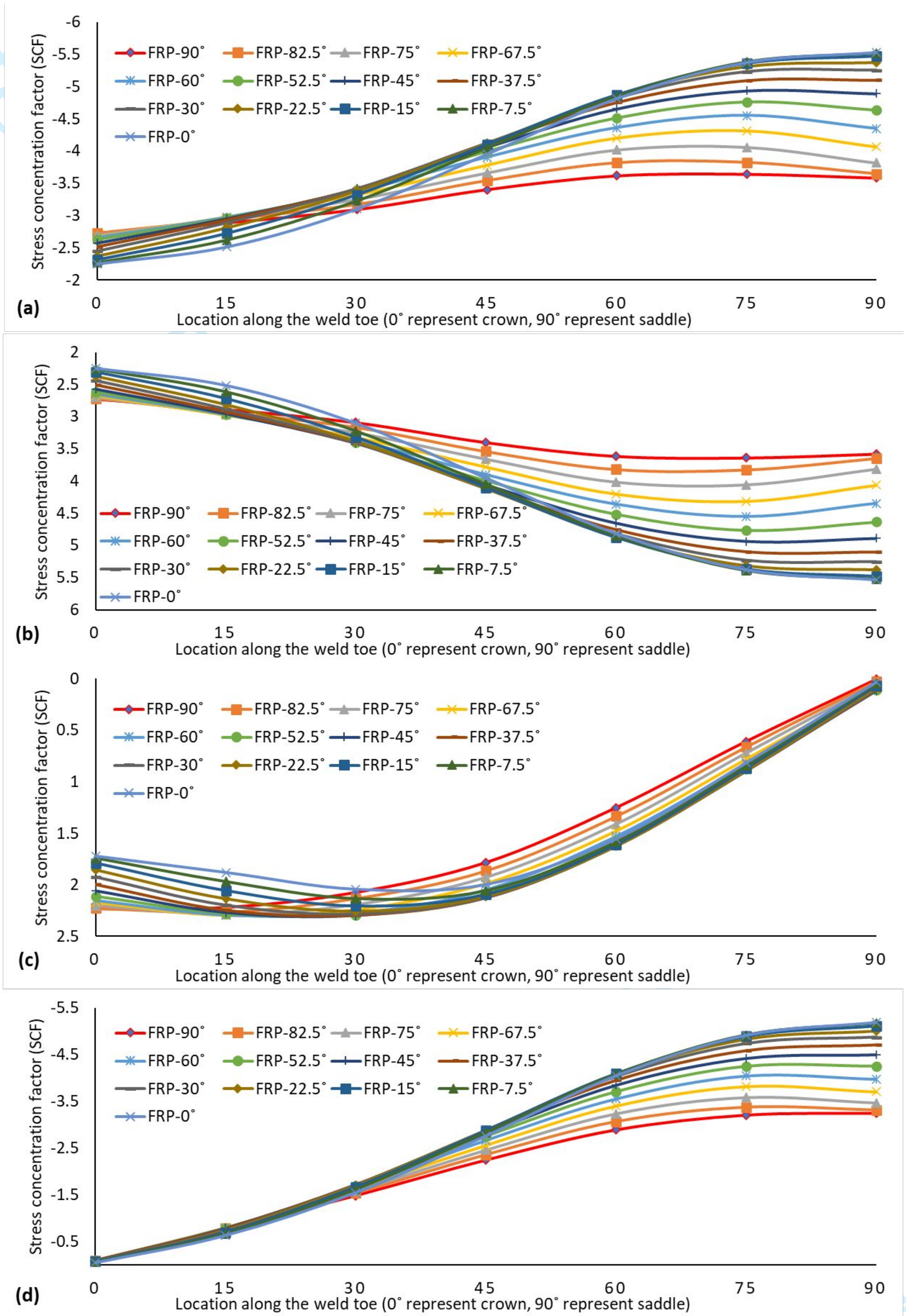

Figure 9. Optimal orientation for reduction of SCF around the weld toe of KT-joint, reinforced with 3mm of unidirectional CFRP with 138GPa modulus in the direction of fibre subjected to load around the central brace under (a) axial compression (b) axial tension (c) IPB (d) OPB

Source: Own work

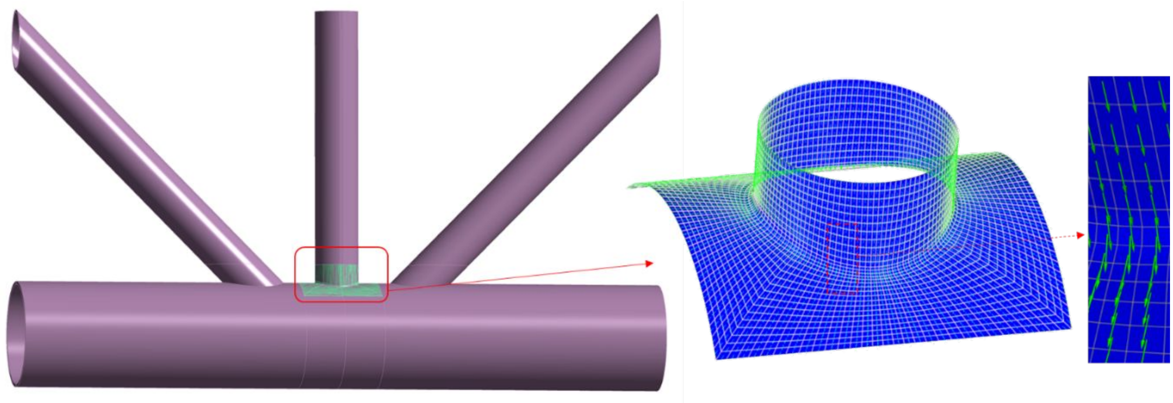

Figure 10 Reinforcement zones-1 and orientation of unidirectional FRP in zone-1
Source: Iqbal *et al.* (2023b)

Joints under a uniplanar load rarely exist practically. Most real joints are subjected to multiplanar loads. The optimum fibre orientation also varies when a joint is under axial and bending loads. Simultaneous loads were applied in 4:1, 1:1, and 1:4 to investigate the optimum orientation of reinforcement. It was observed that the optimum direction of reinforcement depended on the load components' directions and relative magnitudes, as shown in Figure 11–Figure 13.

Figure 11 presents the optimal direction of composite reinforcement for a KT-joint subjected to IPB and OPB load. When both loads have equal magnitudes, the reinforcement oriented at 105˚ offers a maximum reduction in SCF, while the optimal orientation is 135˚, which aligns with a direction orthogonal to the chord axis for a 4:1 and 1:4 IPB-OPB. The optimal direction for OPB and axial load remains orthogonal to the chord axis consistently, as shown in Figure 12. This optimal direction differs at 180˚ for axial compression and axial tension. Similarly, Figure 13 shows the optimal direction of reinforcement for various configurations of simultaneous IPB and axial load.

The location of peak hot-spot stress was determined using the superposition of HSS (Iqbal *et al.*, 2023c; Iqbal *et al.*, 2023d), and it was found that for any combination of simultaneous planar loads on the joint, the optimum direction of reinforcement aligns with the maximum hot-spot stress. The HSS for multiplanar loads can be determined using the weighted sum of the individual SCF and nominal loads on the joint. The optimal orientation of reinforcement is in the direction of peak HSS. However, it is advisable to wrap the reinforcement around the interface, as shown in Figure 10. This ensures some fibres are always oriented in the optimum direction.

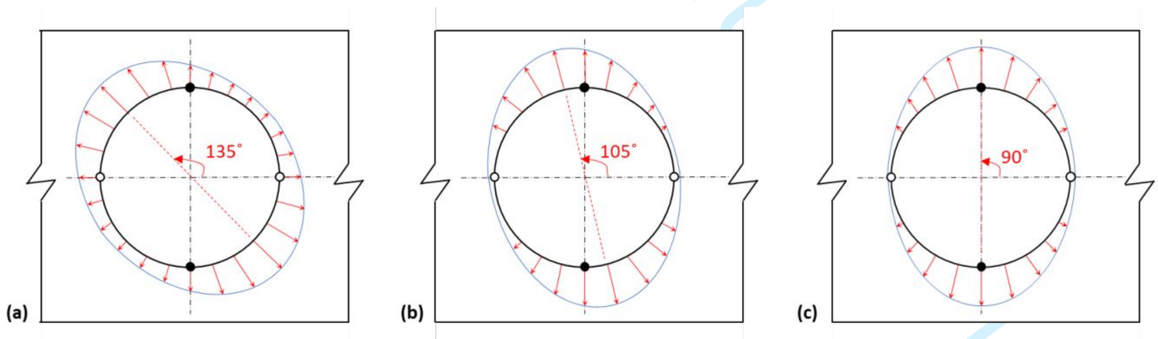

Figure 11. Optimal direction of FRP for the reduction of SCF in the joint under combined IPB-OPB loads: (a) 4:1 (b) 1:1 (c) 1:4
Source: Own work

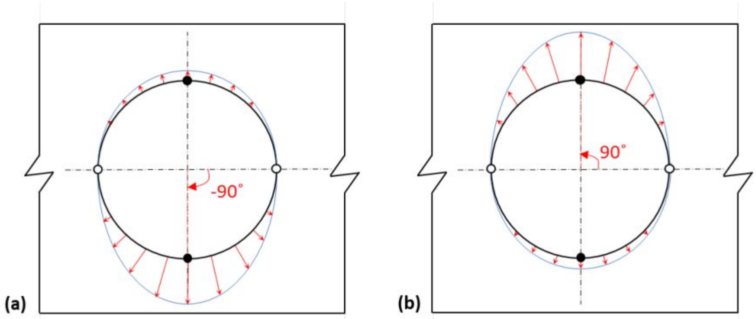

Figure 12. Optimal direction of FRP for the reduction of SCF in the joint under combined OPB-axial: (a) axial tension (b) axial compression
Source: Own work

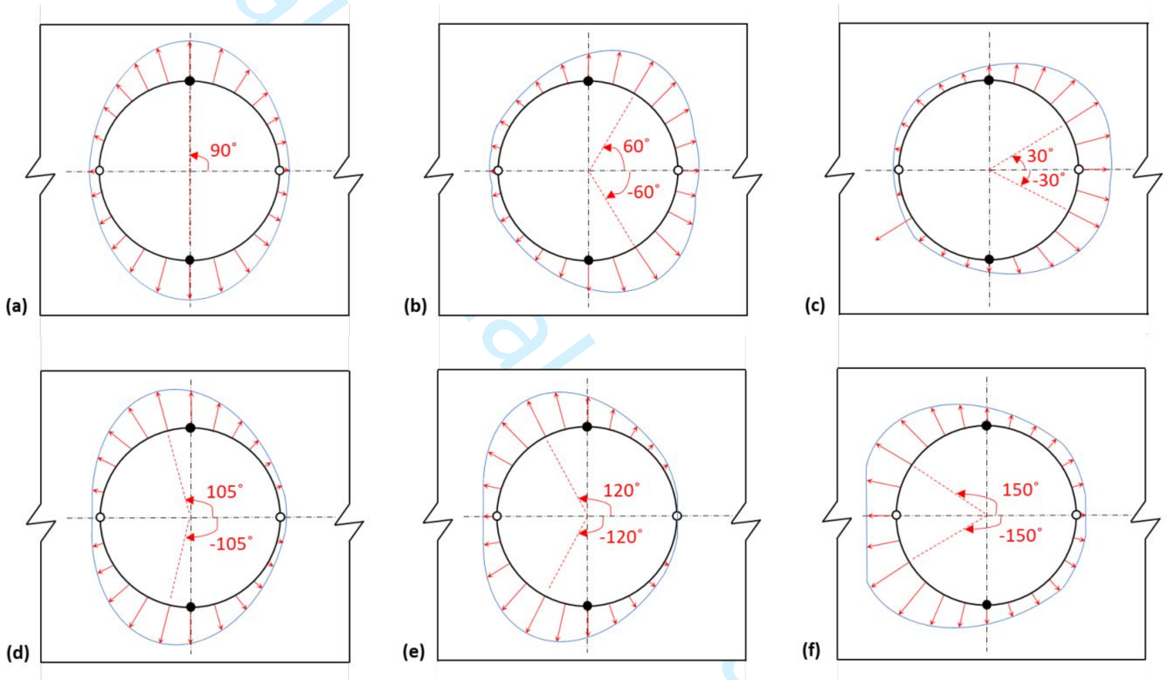

Figure 13. Optimal direction of FRP for a reduction of SCF in a KT joint under the following IPB-axial load ratios: (a) IPB-axial tension 4:1 (b) OPB-axial tension 1:1 (c) OPB-axial tension 1:4 (d) OPB-axial compression 4:1 (d) OPB-axial compression 1:1 (d) OPB-axial compression 1:4
Source: Own work

4. Conclusions

This study investigated the effect of reinforcement orientation on reducing stress concentration factors in tubular KT-joints. ~~It was found that the~~ The optimal orientation of composite reinforcement for joints under axial and out-of-plane bending ~~is~~ was in the hoop direction ~~orthogonal to the~~of chord ~~axis~~ and~~oriented with the~~ parallel to ~~chord~~the chord axis for in-plane bending. ~~The~~ It was observed that the optimal direction of reinforcement for a joint under any combined load (multiplanar load) depended~~s~~ on the magnitudes and directions of the load components. Moreover, ~~while~~ the optimum orientation of ~~unidirectional~~ reinforcement was consistently ~~fibre-reinforced polymer (FRP) is~~ orthogonal to the weld toe for any load configuration. Thus, wrapping the FRP around the brace-chord interface, ~~to~~ ensuring~~e~~ fibres are aligned orthogonally to the weld toe, was found to offer~~s~~ the maximum reduction in stress concentration factors and, thus, a ~~corresponding~~ maximum increase in fatigue life. The optimal direction of reinforcement depends on the location of peak HSS and~~. The optimum direction of reinforcement in multiplanar load~~ could be determined ~~was based on~~ using the superposition of hot-spot stresses (HSS) resulting from uniplanar load components. ~~The optimal direction of reinforcement depends on the location of peak HSS.~~ These findings help to ensure that the composite reinforcement of tubular joints is appropriately oriented, ultimately leading to improved fatigue life and structural integrity. Future research endeavours may include experimental validation of these findings and further investigations into similar reinforcement strategies for other types of joints.

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Conflicts of Interest

The authors declare no conflict of interest.

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Response to Reviewer(s)' Comments:

Reviewer: 1

1. Introduction:

The authors need to respond to the comments below that do not need to be included in the revised manuscript.

Comment a)

What is the significance of optimizing fiber orientation in composite reinforcement for circular hollow section KT-joints? How does the orientation of fibers in composite materials affect the structural integrity of circular hollow section KT-joints?

Response:

The significance of optimizing fiber orientation in composite reinforcement for circular hollow section KT-joints lies in its direct impact on the structural integrity and fatigue life of these joints. By properly orienting the reinforcement, it is possible to achieve a maximum decrease in the Stress Concentration Factor (SCF), which directly correlates with an enhancement in fatigue life. This improvement in fatigue life is crucial for ensuring the longevity and reliability of tubular joints, thereby influencing structural design decisions and operational safety. Conversely, inadequate application of reinforcement can lead to a substantial increase in dead weight without significant reduction in SCF, resulting in detrimental effects on the structural performance and safety of the joints. This discussion has been elaborated upon in the fifth paragraph of the Introduction section.

Comment b)

What are the key factors considered in the optimization process of fiber orientation for enhancing the performance of composite-reinforced KT-joints? Can you explain the methodology used to determine the optimal fiber orientation in composite materials for KT-joint reinforcement?

Response:

The investigation revealed that the orientation effect is consistent regardless of joint geometry, load magnitude, or reinforcement material. Consequently, these parameters were held constant throughout the study. The focus was solely on varying the orientations, with resulting Stress Concentration Factors (SCFs) plotted to discern the optimal outcomes. This discussion has been incorporated into the latter part of section 2.2.

Comment c)

What types of composite materials are typically used for reinforcing circular hollow section KT-joints, and why is fiber orientation critical in these applications? How does the optimization of fiber orientation contribute to the load-bearing capacity and fatigue life of composite-reinforced circular hollow section KT-joints?

Response:

Carbon and glass fiber-reinforced composites are commonly utilized for reinforcing circular hollow section KT-joints, chosen based on factors such as application requirements, cost, and mechanical properties. However, it was observed that the influence of reinforcement orientation remains consistent across different material types. Therefore, reinforcement material was fixed to CFRP UD with 138GPa elastic modulus in the direction of fiber. This point was discussed in Paragraph 6 of the introduction. A paragraph (paragraph 5) was introduced to expound on how fiber orientations impact the load capacity and fatigue life of the joints.

Comment d)

What computational tools or simulation methods are commonly employed in optimizing fiber orientation for composite reinforcement of KT-joints? In what ways do environmental conditions affect the optimization of fiber orientation in composite-reinforced KT-joints?

Response:

In this study, simulation was utilized to analyze a specific output, namely the magnitude of reduction in the Stress Concentration Factor (SCF) with respect to reinforcement orientation, as depicted in Figure 7. Given the emphasis on a single objective and a lone independent variable, advanced optimization algorithms were not required. The effect of environmental factors is beyond the scope of the current manuscript.

Comment e)

How is the optimized fiber orientation for composite reinforcement of KT-joints tested and validated in a real-world context?

Response:

The validation of optimized fiber orientation for composite reinforcement of KT-joints involves fabricating typical tubular joints, reinforcing them, and subjecting them to rigorous testing. While this essential step is planned for future work, it necessitates considerable time and resources and, therefore, falls outside the scope of this manuscript.

Comment f)

How will the geometric and dimensional characteristics of the rectangular hollow flange beams be varied or controlled in the study? What types of loading conditions will be applied to assess the flexural performance? Will there be consideration for different load scenarios, such as uniform loads or point loads?

Response:

The rectangular hollow flange beams are beyond the scope of the current study; hence, they were not discussed in the manuscript.

Comment g)

In the event of failure during testing, how will the failure modes be analyzed, and what insights can be gained from understanding these failure mechanisms? Will there be a comparative analysis between rivet-fastened rectangular hollow flange beams and other types of beams, such as welded or bolted connections?

Response:

The analysis of failure modes during testing and comparative assessments between rivet-fastened rectangular hollow flange beams and other beam connection types, such as welded or bolted connections, are outside the scope of the current manuscript and, therefore, were omitted.

Comment h)

Please conduct an extensive literature review. Some of the most relevant references that need to be cited in the literature review section are:

1. Nonlinear behaviour and design of stainless steel hybrid tubular K-joints with SHS-to-CHS
2. Experiments on stainless steel hybrid K-joints with square braces and circular chord
3. A numerical study and proposed design rules for stress concentration factors of stainless steel hybrid tubular K-joints
4. An experimental study on stress concentration factors of stainless steel hybrid tubular K-joints
5. Finite element modelling and proposed design rules of stainless steel hybrid tubular joints with square braces and circular chord
6. Experimental study on material properties and stress concentration factors of stainless-steel hybrid tubular joints

Response:

The introduction section of the manuscript has been revised, and these references were also included.

2. Methodology:

Comment a)

Present sections can be reorganized in sub-sections rather presenting in a cluster form as follows: Numerical Study- Modelling of Geometry and Material Properties; FE Meshing-With necessary figs; Boundary Conditions and Loading Procedure- With necessary figs; Modeling of Initial Geometric Imperfections and Residual Stresses (5) Validation of the Finite Element Model- With necessary figs and contour plots.

Response:

The methodology section has been reorganized according to the suggested structure.

Comment b)

Explain the modelling procedure used to model the surface interaction locations. There is no modelling detail given on residual stress and corner strength enhancement, which may influence strength prediction. Explain how these two are taken into account in the FE model.

Response:

The interfacial bond between the joint and reinforcement material was assumed to be ideal (bonded contact), in alignment with previous scholarly findings (Lesani et al., 2015; Hosseini et al., 2020b). This discourse has been appended to Section 2.4.

Comment c)

Mesh convergence study (there is no mesh convergence study in this manuscript authors must add this information to the manuscript with a fully detailed explanation including the mesh size and the reason for using that mesh size in their simulation).

Response:

The mesh independence study was included in section 2.2 and Figure 2.

Comment d)

Present all details about the element types and type of simulation chosen for the design.

Response:

Mesh details were presented in section 2.2, while further information about simulation type is given in section 2.5.

Comment e)

Fig.2 provide the comparison between the experimental failure and numerical failure model.

Response:

The specimen underwent loading within the elastic regime, as delineated in Section 2.5. Additionally, extant literature provided experimental data solely for the Stress Concentration Factor (SCF). Information pertaining to failure mode falls beyond the scope of this paper.

3. Results and Discussion:

Refer to "Stress concentration factors in FRP-strengthened steel tubular KT-joints" for better interpretation of the results.

Comment a)

Zones 1, 2 and 3 shown in Fig.5, needs a brief explanation in the saddle and crown points.

Response:

An explanation was added, as recommended.

Comment b)

Fig.7 shows a vast difference in the SCF for IPB and OPB after 300-State the reason.

Response:

It is evident that the effect of reinforcement is more pronounced when the magnitude of SCF is high. The more difference in SCF for an unreinforced and reinforced joint shows that the impact of reinforcement is substantial.

4. Conclusion:

Must be re-written based on the orientation of the saddle points, optimal direction of placing the FRP and more detailed on the performance of IPB, OPB and a combination must be highlighted precisely.

Response:

The conclusion was organized as recommended.

General Comment:

Comment a)

What are the challenges and limitations associated with optimizing fiber orientation for the reinforcement of circular hollow section KT-joints? Discuss the impact of optimized fiber orientation on the cost-effectiveness and manufacturing processes of composite-reinforced KT-joints.

Response:

Optimizing fiber orientation for circular hollow section KT-joints poses challenges in achieving uniform distribution and alignment. While this may require advanced manufacturing techniques, the enhanced structural performance justifies the investment. Although initial costs may be higher, long-term benefits include reduced maintenance and replacement expenses. Integrating optimized fiber orientation may necessitate adjustments in manufacturing processes, but advancements in automation can enhance efficiency and cost-effectiveness.

Comment b) How do advancements in materials science and engineering technology influence the strategies for optimizing fiber orientation in composite reinforcements? Can you explore the potential future developments in the optimization of fiber orientation for enhancing the structural performance of KT-joints?

Response:

The development of design equations and S-N curves tailored for composite reinforced structures remains an unexplored avenue crucial for efficient implementation. Moreover, the emergence of advanced materials with heightened specific strength and specific stiffness holds promise for expanding the application of composites in reinforcement strategies for tubular joints. Innovative methods of reinforcement could further streamline application processes and reduce associated costs and dead weight. These advancements underscore the evolving landscape of materials science and engineering, presenting exciting opportunities for enhancing the structural performance of KT-joints.

Comment c) How does the optimization of fiber orientation align with sustainable and eco-friendly practices in the construction and automotive industries where KT-joints are commonly used? What are the implications of optimized fiber orientation for the repair and maintenance of existing structures using composite-reinforced circular hollow section KT-joints?

Response:

The optimization of fiber orientation in composite reinforcements for KT-joints holds significant implications for sustainability and eco-friendly practices in both the construction and automotive industries. By strategically aligning fibers, we can enhance the structural performance of KT-joints, leading to lighter and more durable structures. This optimization reduces the overall material usage and weight, resulting in lower energy consumption during the construction and operation phases, thereby contributing to environmental sustainability.

Furthermore, the use of composite-reinforced circular hollow section KT-joints in repair and maintenance activities offers several advantages. Optimized fiber orientation allows for more efficient load distribution and stress reduction, prolonging the service life of existing structures. Additionally, the lightweight nature of composite materials facilitates easier handling and installation, reducing the need for heavy machinery and minimizing disruption to the surrounding environment.

Reviewer: 2

Comment 1.

The innovation and contribution of the manuscript should be emphasized in the Introduction section. The reason why the authors take the circular hollow section KT-joints as the research object should be explained.

Response:

KT-joints were selected for PhD research of the corresponding author because these joints are the most frequently used in tubular structures, yet least investigated as compared to T, Y, and K-joints. Moreover, the inferred findings about the optimum orientation of reinforcement are also applicable to other joints.

Comment 2.

In section 2.1, why does the complex geometry at the chord-brace interface and the weld cause a significant rise in stress?

Response:

The stress at the interface increases due to the change in geometry and the presence of weld, as shown in Figure 7 of the revised manuscript. The amplification due to geometry is defined as SCF, while the effect of the weld notch is included in the respective S-N curve.

Comment 3.

The manuscript should provide the boundary conditions set in the finite element model.

Response:

Section 2.5 of the revised manuscript now contains details about boundary conditions and loadings.

Comment 4.

It is mentioned in Section 2.1 that "The structural stress approach in fatigue analysis accounts for stress amplification due to geometric variations while excluding the weld notch effect." The accuracy of fatigue analysis largely depends on the precision of the established structural model. Any inaccuracy in the model may lead to errors in fatigue life prediction. How does the author ensure the accuracy of the model? How is the structural stress approach of fatigue analysis different from other methods?

Response:

The structural stress approach, also known as the structural hot-spot stress approach or structural approach to fatigue life estimation, is based on estimating fatigue life through the S-N curve for a specific stress range. The stress range incorporates amplification due to geometric variations at the interface of mating tubular elements. This stress is referred to as hot-spot stress (HSS). Due to the fact that experimental measurement of hot-spot (or SCF) is costly, time-consuming, and often impossible for a non-existing joint that is being designed for the first time, various numerical models have been proposed in the literature. The accuracy of predicted fatigue life greatly depends on the model and S-N curve used. Various other methods have also been investigated for fatigue analysis of tubular joints, such as strain-based, notch stress, averaged strain energy density, stored plastic strain energy density, and linear elastic fracture mechanics approach. However, the structural stress approach is the most straightforward and widely used in the design of tubular joints.

Comment 5.

How was the hot-spot stress (HSS) determined in this study?

Response:

The HSS was determined using linear extrapolation of surface stress, utilizing maximum principal stress at 0.4T and 1.4T (T is chord thickness), following IIW recommendations. This point was explained in section 2.6 (pos-processing) and Figure 7.

Comment 6.

When simulating the performance of KT-type joints under different loads (such as axial, compression, axial tension, IPB, OPB), why was 30 MPa chosen as a unified load value? How was this value determined?

Response:

It was observed that SCF is dependent on the magnitude of the applied load. The concept of structural hot-spot stress is valid as far as the stresses are below the elastic limit of the material, as explained in section 2.5 (boundary conditions and loading) of the revised manuscript. The magnitude of the applied load was maintained to result in stress below the elastic/strength limit of the joint material. A 30 MPa load was used; however, the resulting SCF would remain the same for any increase or decrease in the applied load.

Comment 7.

Could the authors explain in detail how this prcess is carried out? Specifically, how is HSS determined through weighted summation?

Response:

Equations 1-4 have been added in section 2.6 to explain the HSS determination.

Comment 8.

The manuscript mainly focuses on joint performance under static loads. In practical applications, what impact do dynamic or cyclic loads have on joint performance? How would stiffeners behave in such cases?

Response:

Thank you for your insightful comment. While we appreciate the importance of considering dynamic or cyclic loads and the behaviour of stiffeners in such cases, we must humbly acknowledge that these topics are beyond the scope of our current study. Our manuscript primarily focuses on joint performance under static loads, and while dynamic loading scenarios are undoubtedly relevant in practical applications, their detailed analysis falls outside the scope of this research.

Comment 9.

Section 3 of the manuscript mentions that these findings can help ensure that composite stiffeners for tubular joints are appropriately positioned, thereby improving fatigue life and structural integrity. Are there specific engineering examples or case studies to support this conclusion?

Response:

The focus of this study was primarily on numerical analysis, and as such, empirical validation through case studies was not within the scope of this research. There are certain instances when composite reinforcement was used for the repair and rehabilitation of tubular joints, e.g.,

1. Pantelides, C.P., Nadauld, J., Cercone, L. (2003). Repair of Cracked Aluminum Overhead Sign Structures with Glass Fiber Reinforced Polymer Composites, J. Compos. Constr., 7(2), pp. 118–26, Doi: 10.1061/(asce)1090-0268(2003)7:2(118).
2. Fam, A., Witt, S., Rizkalla, S. (2006). Repair of damaged aluminium truss joints of highway overhead sign structures using FRP, Constr. Build. Mater., 20(10), pp. 948–56, Doi: 10.1016/j.conbuildmat.2005.06.014.
3. Nadauld, J.D., Pantelides, C.P. (2007). Rehabilitation of Cracked Aluminum Connections with GFRP Composites for Fatigue Stresses, J. Compos. Constr., 11(3), pp. 328–35, Doi: 10.1061/(asce)1090-0268(2007)11:3(328).

Comment 10.

In the conclusion section, the authors mainly summarize the results of the current research, but lack discussion on future research directions or follow-up work. For example, further research could explore the effectiveness of similar reinforcement methods for different types of joints (such as T-type, Y-type, etc.) and other types of structures.

Response:

The conclusion has been restructured, as recommended.

Comment 11.

The work is interesting and has potential. However, the limitations of the current literature are possibly misrepresented. The following paper addressed some of the issues in the search process. I would like to see the proposed method to better reflect the state of the art including the paper I pointed out.

[1] Active Kriging-based conjugate first-order reliability method for highly efficient structural reliability analysis using resample strategy. Computer Methods in Applied Mechanics and Engineering, 2024, 423: 116863.

[2] Generative adversarial surrogate modeling framework for aerospace engineering structural system reliability design. Aerospace Science and Technology, 2024, 144: 108781.

[3] A novel hybrid adaptive Kriging and water cycle algorithm for reliability-based design and optimization strategy: Application in offshorewind turbine monopole. Computer Methods in Applied Mechanics and Engineering, 2023, 412, 116083.

[4] A novel Kriging-model-assisted reliability-based multidisciplinary design optimization strategy and its application in the offshore wind turbine tower. Renewable Energy, 2023, 203, 407-420.

[5] Kriging-assisted hybrid reliability design and optimization of offshore wind turbine support structure based on a portfolio allocation strategy. Ocean Engineering, 2024, 295: 116842.

[6] A coupled simulated annealing and particle swarm optimization reliability-based design optimization strategy under hybrid uncertainties. Mathematics, 2023, 11(23), 4790.

[7] Multidisciplinary design optimization of engineering systems under uncertainty: a review. International Journal of Structural Integrity, 2022, 13(4): 565-593.

Response:

The introduction section of the manuscript has been revised, as recommended.