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Fracture Resistance of Steel-Composite Wrapped Joints for Tubular Structures Under Combined Axial and Bending Loads

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Abstract. The design and effectiveness of fatigue load-dominated multi-membered tubular structures, such as offshore jackets, largely hinges on the fatigue performance of welded regions due to stress concentrations, necessitating the use of thick steel members. To address these challenges and reduce overall steel consumption, an innovative bonded joining technology known as wrapped composite joints demonstrating superior fatigue performance has been identified as a potential solution. Offshore conditions introduce combinations of different loading directions, resulting in complex stress states at the root of the composite wrap. This necessitates understanding the influence of such multi-axial loads on the static fracture resistance of the steel-composite wrapped joints. In this regard, interaction criterion exponents play a key role in understanding the correlation between different loading conditions. Ongoing research on wrapped composite joints focuses on these exponents, highlighting that delamination near the steel-composite interface stems as the main failure mechanism. In this context, this paper will develop a finite element (FE) model of X-shaped wrapped joint imposing fracture to the composite material and will study the superposition principle that exists between combined axial and bending loads. Combinations of load cases will be simulated to derive the interaction criterion exponents defining the failure envelope of such steel-composite wrapped joint. Modification to the current design recommendation is proposed with alternative an criterion with a good fit that aids in the design.

Keywords: Bonded Joints · Offshore structures · Wrapped composite joints · Composite fracture resistance · Interaction exponents

1 Introduction

Today, Europe remains one of the largest markets for offshore wind, accounting for over half of global installations. To meet the target of 300 GW by 2050 outlined in the Paris Climate Change Agreement, offshore wind capacity must increase by a factor of 25 [1]. The coastal or countries with offshore areas present massive potential for wind energy,

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but as nearshore sites become occupied for several reasons, moving towards deeper sea unfolds as the most imperative solution representing a vast untapped potential - particularly across European seas such as the North Sea, Baltic Sea, Black Sea, and the Atlantic-Mediterranean corridor. In this respect, the increase in water depth and harsh sea environments necessitates massive supporting structures for ever-increasing wind turbine sizes, creating both technical challenges and opportunities for innovation.

The most commonly used supporting structures for such huge turbines have been the traditional monopile foundations owing to their simple structure and ease of installation. According to WindEurope reports from 2020, monopiles accounted for 80.5% of installations, while jacket structures represented 19%. Exploring deeper seas for efficient harnessing of wind energy directly correlates to adapting more jacket foundations for high-power wind turbines [2] as they outperform monopiles in terms of economic benefits and structural performance [3]. A study by [4] indicates that the capital cost for supporting structures comprise approximately 22% of the total project cost. One of the main reasons for this stems from the necessity for enhanced structural safety, often achieved at the expense of significant material overdesign. This is especially critical in fatigue-driven multi-membered tubular designs, particularly those with corner welds vulnerable to stress concentrations.

To address the limitations of jacket support structures, research at Delft University of Technology demonstrated innovative wrapped composite joints connecting steel tubes by bonding that eliminates welding. The Circular Hollow Sections (CHS) containing the brace (or) diagonal and chord members are bonded together by E-Glass Fibre Reinforced Polymer Composites (GFRP) combined with vinyl ester-based thermoset resin shaped in an optimal way to minimize the stress concentrations as shown in Fig. 1.

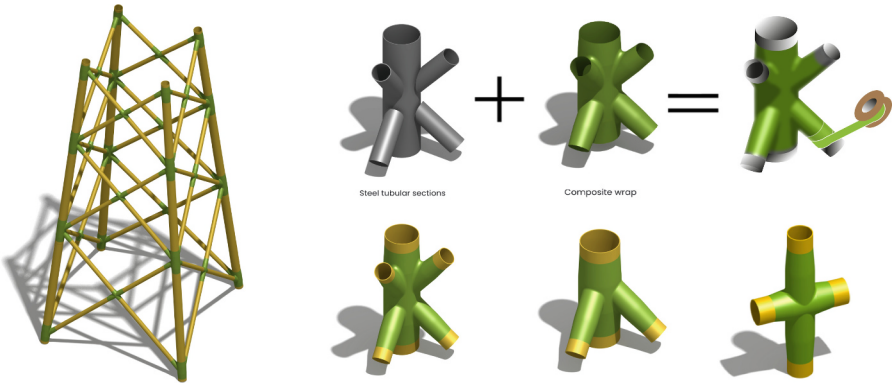


Fig. 1. Offshore jacket foundation structure with wrapped composite joints

In these joints, load transfer occurs through a dedicated composite wrap rather than relying on the small area of welds in the case of traditional welded joints. Extensive testing over recent years has demonstrated the excellent bonding strength between the steel and the composite interface. Fatigue endurance of such wrapped composite X-shaped full-scale joint exceeded more than 10 times the design life of a circumferential

weld connecting the joint to the structure and 4 times the design life of an unwelded tube in a reference jacket [5]. According to [6], the following failure modes exist for wrapped composite joints, as pictorially represented below (Fig. 2):

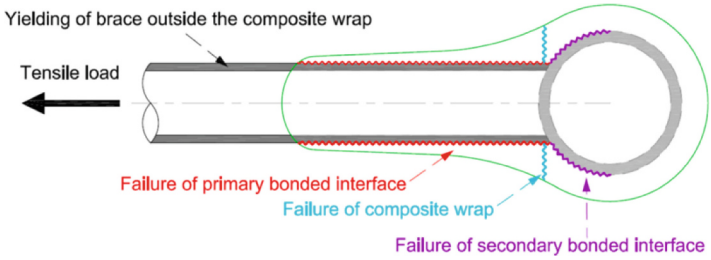


Fig. 2. Possible failure modes in wrapped composite joints loaded in tension [6]

Previous studies have primarily focused on the interface behaviour between the steel and the composite materials. However, it is also equally important to study the failure of the composite material in offshore jacket structures experiencing wind and wave loads that impose multi-axial loading on these joints. The main objective of this paper is to conduct a numerical investigation of a 90° X-shaped wrapped composite joint under combined axial and bending loads. This detailed analysis aims to establish the failure envelope for a medium-scale X90 joint. The interaction criterion obtained from these failure envelopes can further help to develop the maximum limits of the joints under different loading conditions, with a primary focus on studying the failure of the composite wrap as the governing failure mode.

2 Numerical Investigation

The mechanical behaviour of the X90 joint configuration, shown in Fig. 3, was modeled using Abaqus/Explicit. To facilitate an experimental campaign for determining interaction exponents, the scale of the joint was designed to be 3.6 times smaller than the actual scale, keeping in mind the equipment's geometrical capacities. These joints are referred to as medium-scale X90 joint configuration. The design of this joint's composite wrap configuration was specifically optimized to ensure fracture to the composite in all loading combinations simulated in this research, as shown in Table 1. This was achieved by reducing the wrap thickness, promoting material failure over interface failure, in contrast to the configurations reported in [7].

2.1 Geometry, Element Type and Meshing

The medium-scale X90 joint design imposing material failure and the corresponding experimental specimen to be tested are shown in Fig. 3. The flanges in the experimental specimen are used to help mount the specimen onto the test bench. These flanges are welded to the brace sections by full penetration butt welds that are smoothened both

Table 1. Applied load conditions on medium-scale X90 joints

Load case	Applied displacement and/or rotations
Axial	U1 = 5.5 mm
OPB*	UR2 = 0.065 rad
IPB**	UR3 = 0.075 rad
Axial + OPB	U1 = 5 mm; UR2 and/or UR3 = 0.03 rad
Axial + IPB	U1 = 4.5 mm; UR2 and/or UR3 = 0.047 rad
Axial + OPB + IPB	U1 = 3.5 mm; UR2 and/or UR3 = 0.0532 rad U1 = 2.5 mm; UR2 and/or UR3 = 0.059 rad U1 = 1.5 mm; UR2 and/or UR3 = 0.062 rad

*OPB refers to Out-of-Plane Bending
**IPB refers to In-Plane Bending

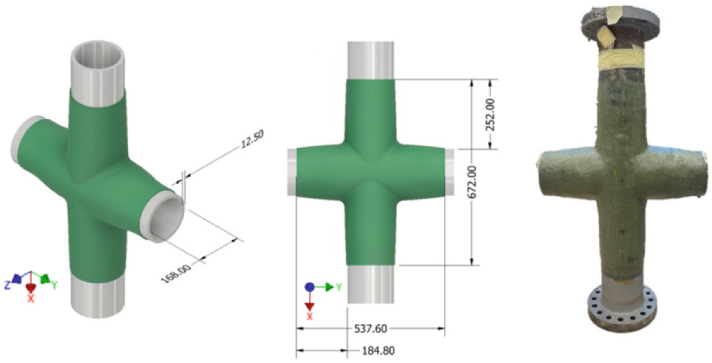


Fig. 3. Dimensions and reference experimental specimen of X90 joint

on the inside and outside. The Abaqus model constructed replicates the experimental specimen, as shown in Fig. 4.

The mesh model was created using linear tetrahedron elements with four nodes (C3D4) for the composite with a global mesh size of 10 mm on the outer surface and near the tapered region, the meshes were refined from 10 mm to 4 mm. The composite surface in contact with the steel had a mesh size of 4 mm. A mesh sensitivity analysis confirmed convergence in strain predictions and computational efficiency. The steel flanges also had similar elements but with a global mesh size of 12 mm. The braces and the chords were created using hexahedral eight-node solid elements with reduced integration (C3D8R) with a global mesh size of 4 mm.

2.2 Material Properties

The CHS profiles of the specimens made with mild steel of grade S355 was assigned an initial modulus of elasticity, E = 210 GPa, Poisson's ratio, $\nu = 0.3$. In addition, a material density of 7.85 g/cm^3 was assigned. The input for the nominal stress-strain relationship

was obtained from the study by [8] to define the plasticity curve within Abaqus. The material properties of the composite wrap were considered transversely isotropic due to the composition of bidirectional woven fabric and chopped strand mat. The elastic constants, based on standard material tests for E-Glass fibre mixed with thermoset resin can be found in Table 2 as outlined in [9]. In addition, Hill's plasticity model was used to capture the behaviour of the composite in different directions of stress states. A damage model was also implemented to capture the post-peak behaviour.

Table 2. Material properties of the composite wrap laminate

Material	Elastic constants (GPa)	Poisson's ratio
Composite wrap - GFRP	E1 = E2 = 11.8, E3 = 5.7, G12 = 2.6, G13 = G23 = 1.8	$\nu_{12} = 0.22$, $\nu_{13} = \nu_{23} = 0.35$

2.3 Contact Modeling, Boundary Conditions and Loading

The interactions between the surfaces of different components necessitated using general contact that enabled the concurrent definition of multiple contact pairs and behaviours. A finite-sliding formulation with a penalty method to enforce contact constraints for a tangential behaviour that adhered to the coulomb friction was used with a friction coefficient of 0.3 between the steel surfaces and 0.55 between the composite and steel interface measured experimentally using a multi-functional tribometer (Rtec MFT-5000) documented in [10]. For normal behaviour, the interactions were defined to exhibit a 'hard' pressure-overclosure relationship. Furthermore, to account for bonding between the steel and the composite, cohesive and interface damage were assigned where the interface thickness is small, as in the wrapped composite joints. In this approach, the traction-separation law, introduced by CZM, is assigned to the contact surface pairs. As a result of the enhanced fracture toughness of the resin, improved steel surface roughness, and existence of fibre bridging, the cohesive law to simulate the fracture process of the composite-steel bonded interface of the wrapped composite joints follows a four-linear traction-separation law similar to [11].

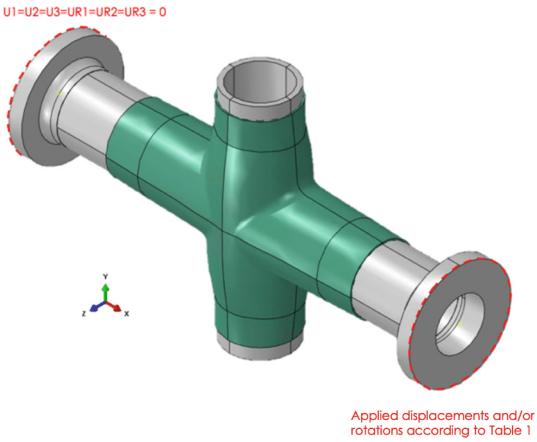


Fig. 4. FE assembly of X90 joint with corresponding boundary and loading conditions

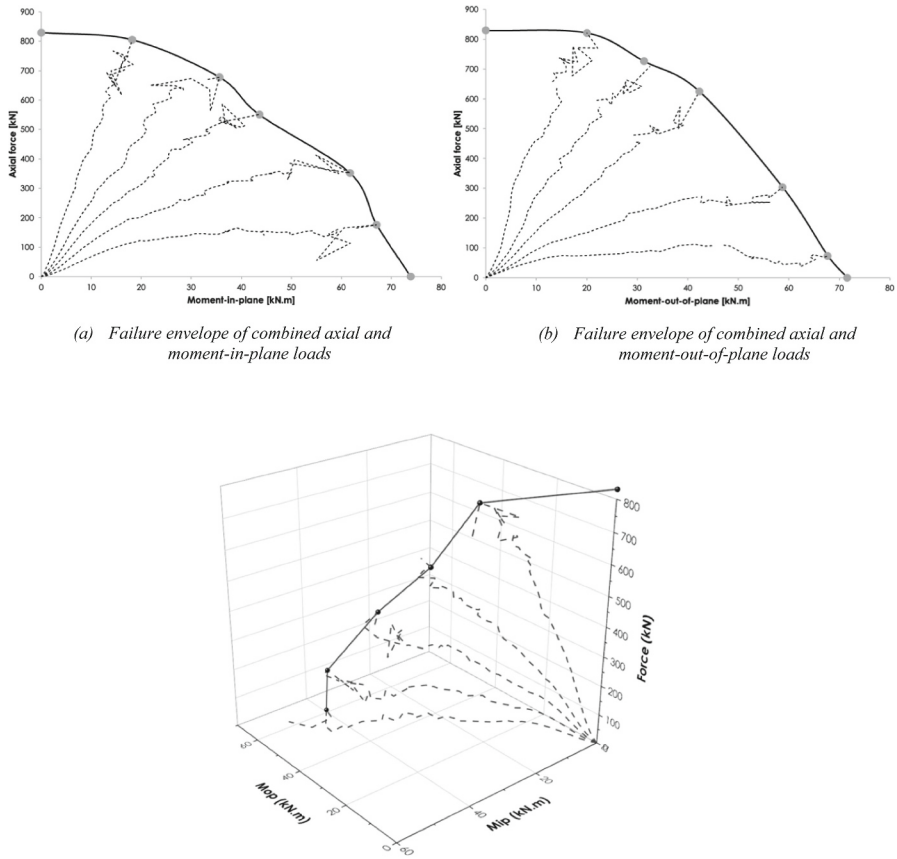
Simulating the X90-medium scale joint in Abaqus/Explicit involved restraining one end of the joint from all translations and rotations. On the other end, depending on the type of loading condition, displacement and/or rotation is applied (see Table 1) to the reference point at the end of the flanges kinematically coupled to the corresponding surface of the flanges. To avoid substantial inertia forces, a smooth amplitude step was chosen with an artificial time period of 300 s in combination with mass scaling to achieve a quasi-static test. The assembly of X90 medium-scale joint is shown in Fig. 4.

3 Results

As mentioned in Table 1, several combinations of loading were applied on the X90 medium-scale joints with the intention of deriving the interaction exponents. According to ISO 19902:2020 [12], each brace in a joint subjected to an axial force or a bending moment alone, or to an axial force combined with bending moments, shall satisfy:

$$U_j = \left|\frac{P_B}{P_d}\right| + \left(\frac{M_B}{M_d}\right)^2_{ipb} + \left|\frac{M_B}{M_d}\right|_{opb} \leq 1.0 \tag{1}$$

In the above equation, P refers to the axial force, M refers to the bending moments either out-of-plane bending (opb) or in-plane-bending (ipb). The subscripts 'B' refer to the moment (or) axial force in the brace and 'd' refers to the design value of the joint's axial strength (or) bending moment strength. The results from the simulations of all quasi-static scenarios allow for the development of failure envelopes and are presented as shown in Fig. 5.



(a) Failure envelope of combined axial and moment-in-plane loads

(b) Failure envelope of combined axial and moment-out-of-plane loads

(c) Failure envelope under full multiaxial loads

Fig. 5. Load curves from combined loading simulations

All the failure envelopes shown in Fig. 5 exhibit a characteristic erratic response in the force-moment curves preceding the final fracture that can be attributed to crack initiation and propagation within the composite wrap. Notably, under bending-dominated loading, the fracture occurs more abruptly, as evidenced by the reduced erratic behaviour in these scenarios. Figure 6 illustrates an axial versus out-of-plane moment case, highlighting the stages of crack initiation, propagation, and final failure within the noisy region of the envelope. Crack initiation corresponds to the onset of irregularity, propagation spans the intermediate phase, and the final fracture marks the termination point on the envelope.

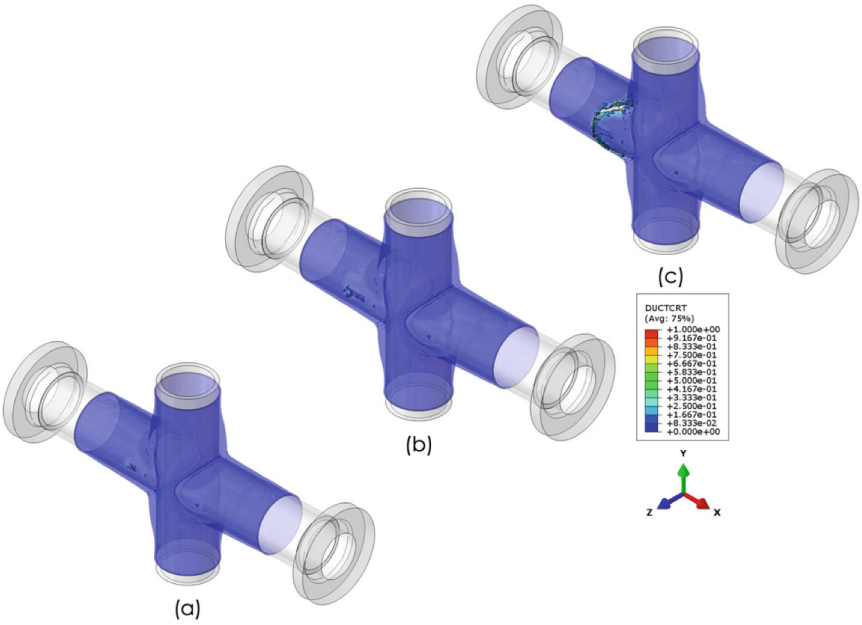


Fig. 6. Graphical insight of erratic behaviour observed in the failure envelope curves; (a) initiation of crack; (b) propagation of crack; (c) final fracture in the composite

The failure modes under all three combined axial and bending loading conditions are represented in Fig. 7. For each loading type, the failure mode remained consistent, irrespective of the axial-to-bending moment ratio.

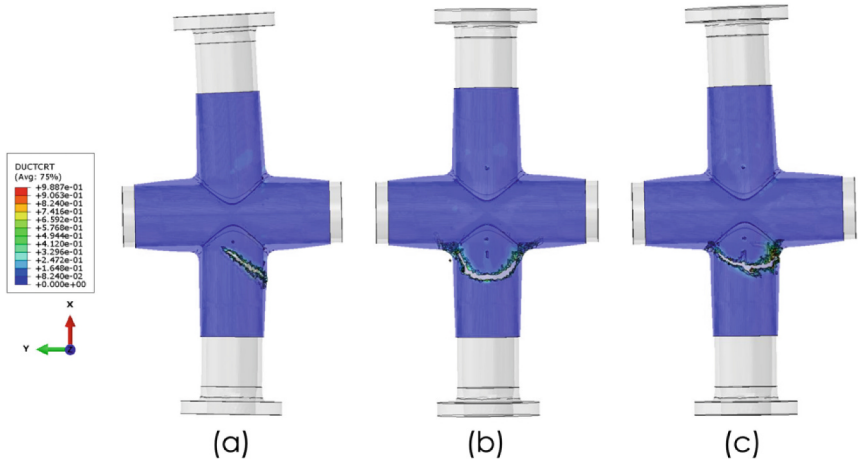


Fig. 7. Observed failure modes in the composite wrap under different combined axial and bending loads; (a) axial + moment-in-plane; (b) axial + moment-out-of-plane; (c) axial + moment-in-plane + moment-out-of-plane

From the failure envelopes, it is evident that no linear interaction exists between the axial and bending components. In addition, for welded CHS joints, the interaction criterion mentioned in Eq. 1 indicates a linear interaction for a combination of axial and moment-out-of-plane scenario, and a quadratic relation between axial and moment-in-plane components. Since this equation cannot be used for wrapped composite joints, a different criterion is proposed to quantify these interactions between bending moments and axial force, as presented in Eq. 2. This approach mainly allows for adjusting the influence of bending moment interaction.

$$U_j = \left|\frac{P_B}{P_u}\right|^{\alpha} + \left(\left[\frac{M_B}{M_u}\right]_{opb}^{\beta} + \left[\frac{M_B}{M_u}\right]_{ipb}^{\gamma}\right)^{\zeta} \leq 1.0 \tag{2}$$

The subscript 'u' in the above equation refers to the ultimate limit strengths in pure axial, moment in-plane and moment-out-of-plane scenarios.

In order to derive the interaction exponent values to arrive at a good fit for the design of wrapped composite joints inducing material failure, the parameters α, β, γ *and* ζ were obtained by non-linear regression, fitting a curve to the numerical data points through the least square method adopted that works by minimizing the sum of offsets from the plotted curve. A good fit was achieved for wrapped composite joints inducing material failure with $\alpha = 1$, $\beta = 2$, $\gamma = 1.9$ *and* $\zeta = 1.3$.

4 Conclusions

This study investigates the fracture resistance of steel-composite wrapped joints for tubular structures under combined axial and bending loads, emphasizing the potential of wrapped composite joints as an alternative to traditional welded connections. Through a detailed numerical analysis, this research develops a framework for understanding the interaction between axial forces and bending moments, providing critical insights into the failure mechanisms and ultimate strength of these joints. The key findings are summarized below:

- The current design recommendations according to ISO 19902:2020 for welded CHS joints are not valid for wrapped composite joints. Hence, an alternative criterion was proposed, one that is a good fit that aids in the design of wrapped composite joints.
- From the interaction coefficients derived, it is observed that the quadratic relationship holds for moments in-plane and out-of-plane. This indicates that using a linear interaction would underestimate the resistance.
- A good fit for wrapped composite joints inducing material faiure was achieved by using $\alpha = 1$, $\beta = 2$, $\gamma = 1.9$ *and* $\zeta = 1.3$.

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