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Proceeding Paper

Numerical Investigation of Crack Mitigation in Tubular KT-Joints Using Composite Reinforcement †

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Abstract: Recently, fiber-reinforced polymers (FRP) have begun to be used for steel structure reinforcement, following decades of successful utilization for the reinforcement of concrete structures. However, rehabilitation of tubular joints with a crack at the interface of mating members using FRP has rarely been investigated. A tubular KT-joint having a semi-elliptical crack subjected to axial tensile load is explored in this study. The joint was simulated using the fracture tool of ANSYS Structural, and the effect of crack size, location, and FRP reinforcement on stress intensity factor (SIF) was evaluated. The numerical simulations show that FRP reinforcement reduces the SIF, decreases the likelihood of crack growth, and may increase the fatigue life. A 4–12% reduction per millimeter thickness of unidirectional FRP was recorded.

Keywords: crack mitigation; crack growth; composite reinforcement; fracture analysis; tubular joint

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1. Introduction

Offshore structures are subjected to various environmental and service loads, in addition to aging and corrosion. Possible defects can occur anywhere, including the joining point of tubular members, reducing the load-bearing capability of the entire system, with the weld line of the tubular joints being the most critical portion of an offshore structure and prone to crack initiation and rapid growth. Routine inspection identifies such deteriorations and evaluates their effect and possible remedies [1]. Various rehabilitation techniques can be adopted to recover or enhance the load capacity of tubular joints [2]. Replacement or repair of these cracks is vital for safe operation. However, replacement may be costly and practically impossible, with repair being the only viable option. Traditionally, repair was accomplished by welding or clamping extra plates to reinforce damaged areas. Hot work such as cutting and welding are required to replace the corroded structures or add extra thickness, which increases the risk of disasters [3]. Techniques utilizing cold work are preferred for restoring oil and gas structures. Among these, fiber reinforcement of a defective joint has many competitive advantages [2].

Fiber-reinforced polymers (FRP) have been used for the reinforcement of steel structures after decades of successful utilization for civil structures [4–6]. ASME PCC-2 [7] and ISO 24817 [8] covers the repair of pipelines using FRP as a legitimate repair technique. It can be applied without hot work (due to ambient temperature curing). Even structures under the water can be reinforced, as various specialized epoxies can cure in the aqueous environment. FRP reinforcement of joints does not need load isolation; hence, shutdown of the platform is not required. Reinforcement layup can be customized for specific strength and stiffness requirements at different joints, locations, and directions, and minimal repair materials suffice for various geometric shapes and load requirements [2]. Various researchers have investigated FRP reinforcement of tubular joints in recent years, both numerically and experimentally [9–15]. However, these studies focused on enhancing load capacity and fatigue-life enhancement using FRP reinforcement. Most of these studies were on the reduction of stress concentration factors due to FRP, which can be used to determine the increase in fatigue life. Besides enhancing the load capacity, FRP reinforcement can mitigate crack propagation when a joint crack has been identified. Until now, the effect of FRP reinforcement on tubular joints with cracks at the interface has never been reported in the open literature.

The stress intensity factor (SIF) is an important parameter for the failure assessment of cracked structures. It can predict crack initiation and propagation. Stresses at the crack tip are proportional to SIF. The crack will grow further if the SIF exceeds the material's fracture toughness (FT) limit, but if the SIF is lower than FT, the crack will not propagate. Various two and three-dimensional fatigue crack problems have been investigated, and more than 600 formulae have been used for calculating SIF for different crack base geometries, cracks, and loading conditions [16–25]. Depending on the load, the crack can be mode I, II, or III. Practical structures are subjected to various loads simultaneously, including tension, shear, and torsion, resulting in a mixed-crack mode [26]. The fracture tool of ANSYS gives SIF for all three modes. The maximum of these shows the dominant mode of crack propagation. This paper investigates a cracked KT-joint using the fracture tool of ANSYS. The effect of crack size, crack location, and FRP reinforcement on SIF is evaluated.

2. Methodology

A typical KT-joint based on the dimensions of Ahmadi et al. [27] was modeled, as shown in Figure 1. A semi-elliptical crack was assumed at the weld line of the central brace–chord interface of a typical KT-joint. After sensitivity analysis, the model was meshed using 791,644 tetrahedral elements. An arbitrary crack was incorporated using the built-in fracture tool of ANSYS. The numerical model was simulated using the static structural module of ANSYS Workbench 21 R1. The ends of the chord and inclined braces were constrained in all degrees of freedom (fixed constraints), as shown in Figure 2. An axial tensile load of 30 MPa was applied on the central brace. Static structural analysis was performed using an HP Zbook Core i7-1185G7 workstation with 16 GB RAM. SIF was computed for all three modes of cracks, but only K1 was significant, as tensile loading was causing mode I to be dominant.

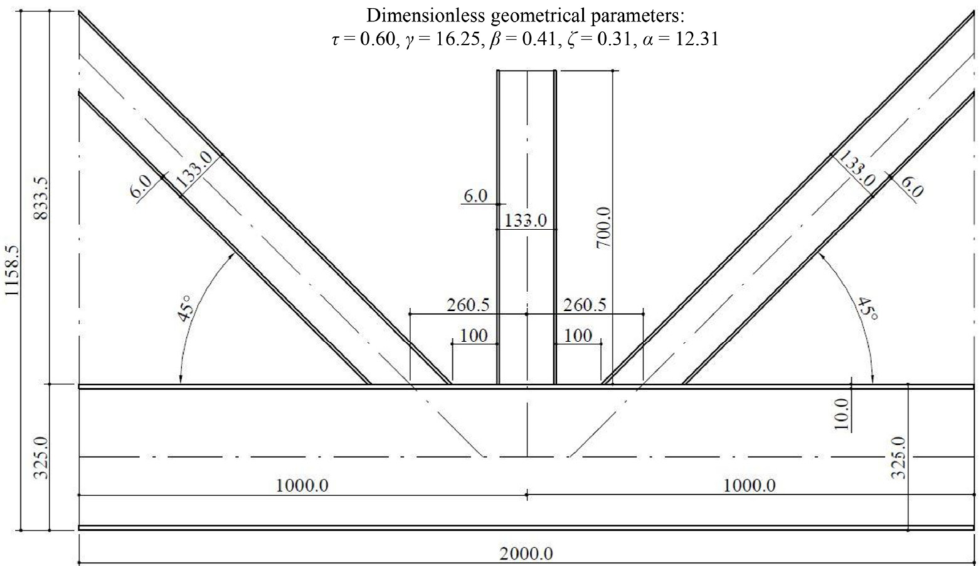


Figure 1. Geometry of the KT-joint used for simulations [27].

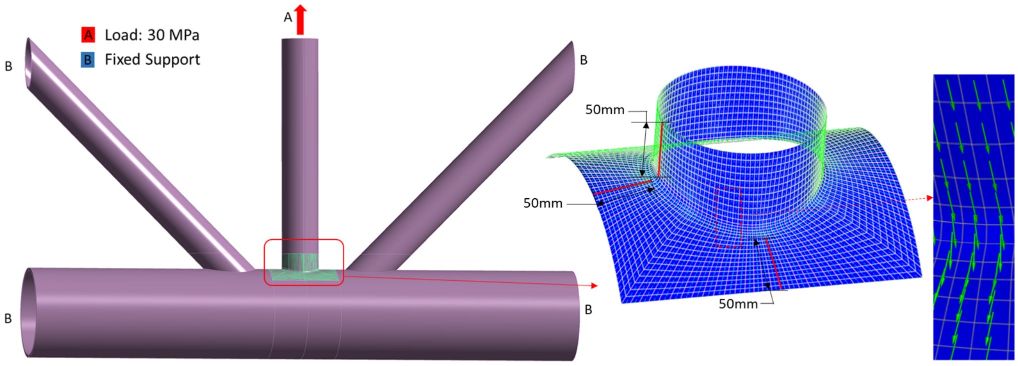


Figure 2. KT-joint with a crack at the chord and central brace interface, reinforced with CFRP UDs.

The effect of crack location was investigated by simulating cracks of the same dimension at different locations around the brace axis, namely the saddle, crown, and an arbitrary position in-between the saddle and crown, as shown Figure 3. A 1/4th model was assessed as a 1/4th symmetry can be assumed for a KT-joint with an axial tensile load on the central brace [28]. The effect of cracks at other positions can be approximated from these three positions. The interface region of the joint having the crack was reinforced with unidirectional Carbon FRP (CFRP), with a lamina thickness of 0.2 mm. The mechanical properties of CFRP are listed in Table 1 [29]. A minimum overlap of 50 mm was assumed to be sufficient around the chord–central brace interface.

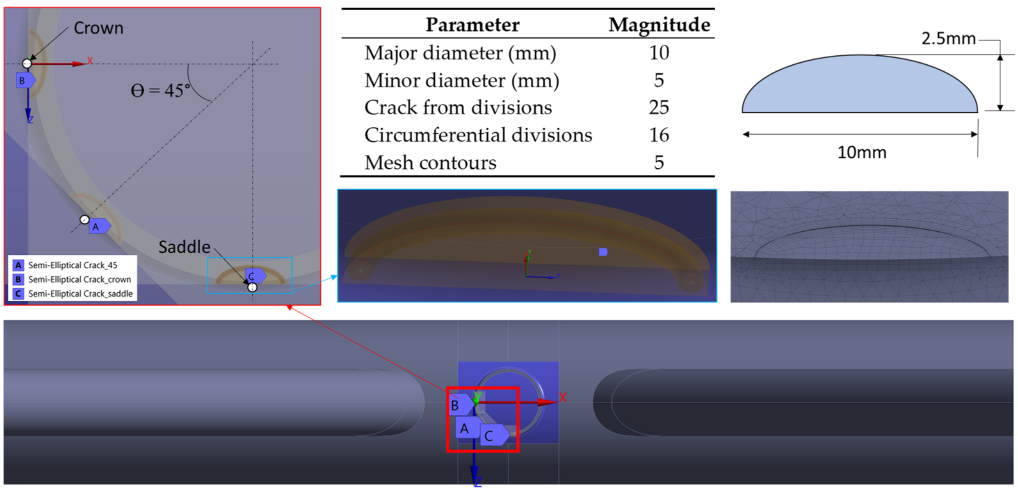


Figure 3. KT-joint with a semi-elliptical crack.

Table 1. Parameters of Semi-elliptical cracks [29].

	Parameter	Magnitude
CFRP UD	Young modulus, E_x (GPa)	134
	Young modulus, E_y (GPa)	10.3
	Young modulus, E_z (GPa)	10.3
	Shear modulus, G_{xy} (GPa)	5.5
	Shear modulus, G_{yz} (GPa)	5.5
	Shear modulus, G_{xz} (GPa)	3.2
	Poisson's ratio, ν_{xy}	0.33
	Poisson's ratio, ν_{yz}	0.53
	Poisson's ratio, ν_{xz}	0.33
Steel pipe	Young modulus, E (GPa)	211
	Poisson's ratio, ν	0.3

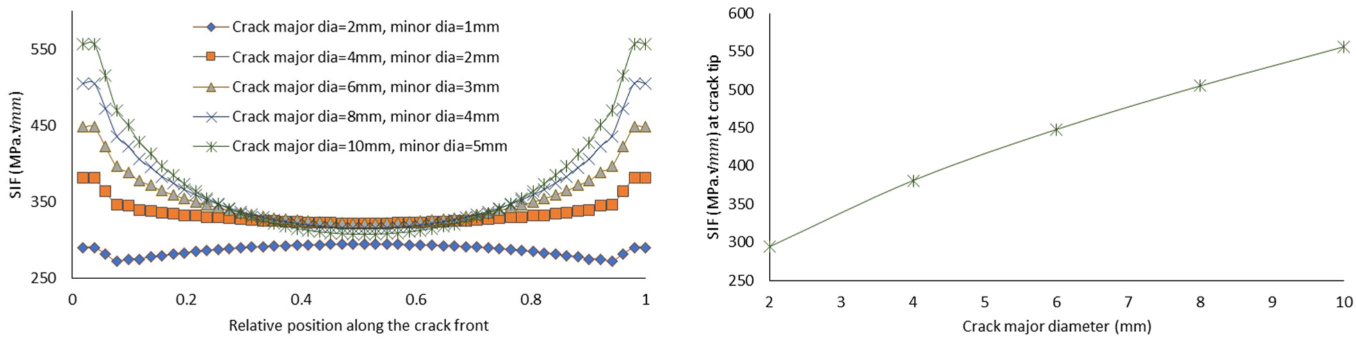
The effect of reinforcement thickness could be investigated either through varying the number of layers for a given lamina thickness or selecting a fixed number of layers and varying the lamina thickness, with the lamina thickness depending on the thickness of the dry fabric, the layup process, and the curing method. Once the base material and fabrication process were selected, the number of layers and their orientation were varied for optimum response. The lamina thickness was fixed in the current study, while the effect of the number of layers was investigated. Different reinforcement layers were applied to the crack region, and the corresponding SIF was determined. Reinforcement layers can be oriented in different directions, and selecting the optimum orientation is vital [30,31]. For tensile load on the central brace, the best direction of reinforcement was orthogonal to the weld toe, as shown in Figure 2. Hence, the optimization of orientation was not investigated in the current study.

3. Results and Discussion

The analyzed problem was mode-I dominant; hence, only results of SIF-K1 are presented. However, SIF reduction was noticed for all three modes. The numerical simulations show the effectiveness of FRP reinforcement for reducing SIF and mitigating cracks, thus decreasing the chances of crack growth and increasing fatigue life.

3.1. Effect of Crack Size

The physical size of the crack has an obvious effect on the SIF. A semi-elliptical crack with different major and minor diameters was simulated. The major diameter was fixed at twice the minor diameter to limit the variables, and a comparison of SIF as a function of the major diameter is shown in Figure 4. It was found that SIF increases with an increase in crack size. A similar effect of crack size was revealed by Subbaiah and Bollineni [32], for unreinforced pressurized cylinders, and by Wang et al. [33] for rectangular plates reinforced with FRP. SIF is usually high at the crack tips and reduces along the crack front towards the center. However, SIF is higher at the center for a relatively small crack.

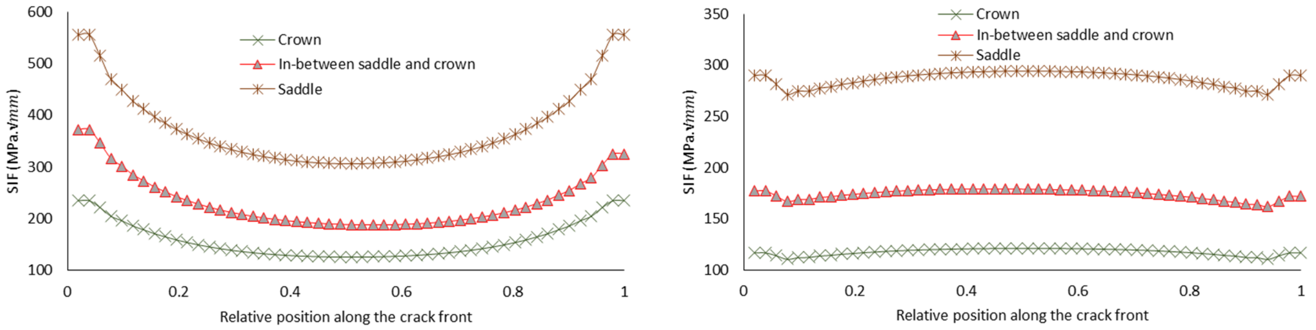


(**a**) (**b**)

Figure 4. SIF variation with crack size (for a crack at the saddle position without reinforcement): (**a**) SIF along the crack front; (**b**) SIF at the crack tip.

3.2. Effect of Crack Position

The criticality of a crack depends on its location. A saddle-point crack causes relatively higher SIF than other positions, as shown in Figure 5. This effect is due to a higher stress concentration at the saddle point than at the crown when a KT-joint is subjected to axial compressive load. When a tubular joint is subjected to combined load, the location of maximum stress depends on the direction and relative magnitude of load components [34]. For such situations, knowing the crack location would be critical for assessment. A specific size crack may be ignorable at one position and fatal for the same structure at another.

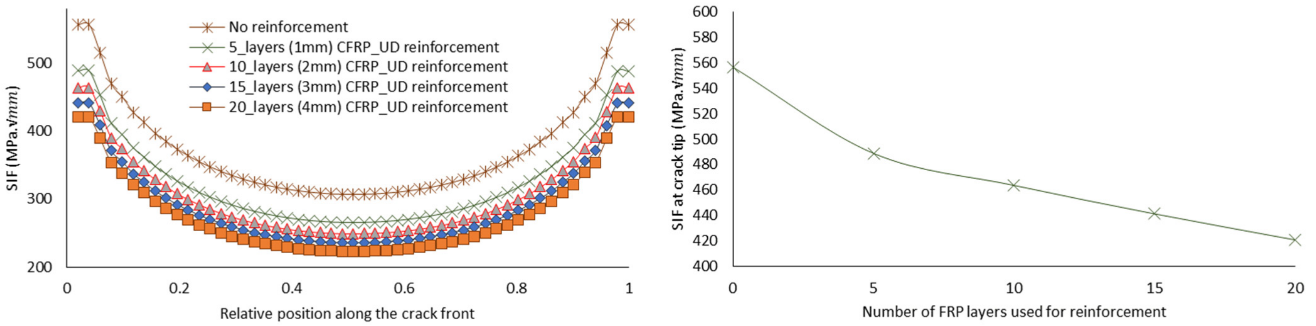


(**a**) (**b**)

Figure 5. Effect of crack position on SIF (without reinforcement): (**a**) crack major diameter = 10 mm, minor diameter = 5 mm; (**b**) crack major diameter = 2 mm, minor diameter = 1 mm.

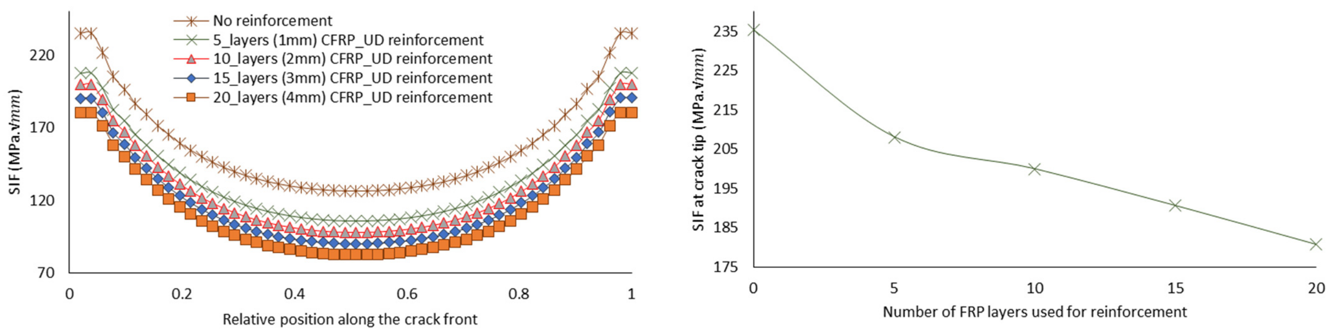
3.3. Effect of Thickness of FRP Reinforcement

It was found that the greater the number of reinforcement layers, the lower the SIF. A similar correlation of SIF with the thickness of FRP reinforcement was revealed by Wang et al. [33] for rectangular plates. Hence, the number of reinforcement layers should be decided based on the reduction in SIF required, as it would impart dead weight and cost. Figure 6 shows the reduction behavior of SIF with an increase in the number of reinforcement layers for a crack having its center at the saddle position. Similarly, Figure 7 shows the same for a crack at the crown position. For cracks at both locations, the reduction of SIF at the crack tip was 4–12% per millimeter of CFRP reinforcement.



(**a**) (**b**)

Figure 6. SIF variation due to FRP reinforcement (for a crack at saddle position, major diameter = 10 mm, minor diameter = 5 mm, reinforcement = CFRP-oriented orthogonal to weld, mechanical properties [29]): (**a**) SIF variation along the crack; (**b**) SIF at the crack tip.



(**a**) (**b**)

Figure 7. SIF variation due to FRP reinforcement (for a crack at crown position, major diameter = 10 mm, minor diameter = 5 mm, reinforcement = CFRP-oriented orthogonal to weld, mechanical properties [29]): (**a**) SIF variation along the crack; (**b**) SIF at the crack tip.

4. Conclusions

Crack propagation at the weld toe of a tubular KT-joint has been studied using fracture analysis. A semi-elliptical crack was introduced, and the effect of crack size, position, and fiber-reinforced polymer (FRP) reinforcement on stress intensity factor (SIF) was investigated. An increase in the size of the crack was found to increase the SIF. It was revealed that the magnitude of SIF depends on the location. SIF was maximum at the point where stress was maximum. Hence, the knowledge of a joint's stress behavior is vital for assessing the criticality of a crack in a joint. The simulation proved the capability of FRP reinforcement for reducing the SIF at the crack and mitigating crack propagation. Empirical modeling of the SIF in FRP-reinforced tubular joints with a crack will benefit from quick assessment. Experimental verification of these findings and investigation of joints under combined loads can be carried out in the future.

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References

1. Martinez, J.L.; Ramalho, J.C.; Murilo, C.; Irving, A.V.; Victor, D.H.; Perrut, V.A.; Gomes, G. CFRP-Patch repair characterization for compressive capacity recovery of perforated steel tubular members. *J. Braz. Soc. Mech. Sci. Eng.* **2023**, *45*, 421. [CrossRef]
2. Iqbal, M.; Karuppanan, S.; Perumal, V.; Ovinis, M. Rehabilitation Techniques for Offshore Tubular Joints. *J. Mar. Sci. Eng.* **2023**, *11*, 461. [CrossRef]
3. Nichols, N.W.; Khan, R. Remediation and Repair of Offshore Structures. *Encycl. Marit. Offshore Eng.* **2017**, 1–15. [CrossRef]
4. Dehghani, A.; Aslani, F. A review on defects in steel offshore structures and developed strengthening techniques. *Structures* **2019**, *20*, 635–657. [CrossRef]
5. Tafsirojjaman, T.; Ur Rahman Dogar, A.; Liu, Y.; Manalo, A.; Thambiratnam, D.P. Performance and design of steel structures reinforced with FRP composites: A state-of-the-art review. *Eng. Fail. Anal.* **2022**, *138*, 106371. [CrossRef]
6. Siddika, A.; Mamun, M.A.; Al Ferdous, W.; Alyousef, R. Performances, challenges and opportunities in strengthening reinforced concrete structures by using FRPs—A state-of-the-art review. *Eng. Fail. Anal.* **2020**, *111*, 104480. [CrossRef]
7. *PCC-2–2011*; Repair of Pressure Equipment and Piping—ASME PCC-2. American Society of Mechanical Engineers: New York, NY, USA, 2011; pp. 1–216.
8. *ISO 24817*; Petroleum, Petrochemical and Natural Gas Industries—Composite Repairs of Pipework—Qualification and Design, Installation, Testing and Inspection. International Organization for Standardization: Geneva, Switzerland, 2017.
9. Sadat Hosseini, A.; Bahaari, M.R.; Lesani, M.; Hajikarimi, P. Static load-bearing capacity formulation for steel tubular T/Y-joints strengthened with GFRP and CFRP. *Compos. Struct.* **2021**, *268*, 113950. [CrossRef]
10. Hosseini, A.S.; Bahaari, M.R.; Lesani, M. SCF distribution in FRP-strengthened tubular T-joints under brace axial loading. *Sci. Iran.* **2020**, *27*, 1113–1129.
11. Xu, G.; Tong, L.; Zhao, X.L.; Zhou, H.; Xu, F. Numerical analysis and formulae for SCF reduction coefficients of CFRP-strengthened CHS gap K-joints. *Eng. Struct.* **2020**, *210*, 110369. [CrossRef]
12. Nassiraei, H.; Rezadoost, P. Stress concentration factors in tubular T/Y-joints strengthened with FRP subjected to compressive load in offshore structures. *Int. J. Fatigue* **2020**, *140*, 105719. [CrossRef]
13. Sadat Hosseini, A.; Bahaari, M.R.; Lesani, M. Experimental and parametric studies of SCFs in FRP strengthened tubular T-joints under axially loaded brace. *Eng. Struct.* **2020**, *213*, 110548. [CrossRef]
14. Tong, L.; Xu, G.; Zhao, X.L.; Zhou, H.; Xu, F. Experimental and theoretical studies on reducing hot spot stress on CHS gap K-joints with CFRP strengthening. *Eng. Struct.* **2019**, *201*, 109827. [CrossRef]
15. Sadat Hosseini, A.; Bahaari, M.R.; Lesani, M. Stress concentration factors in FRP-strengthened offshore steel tubular T-joints under various brace loadings. *Structures* **2019**, *20*, 779–793. [CrossRef]

16. Ullah, H.; Harland, A.R.; Silberschmidt, V.V. Characterisation of mechanical behaviour and damage analysis of 2D woven composites under bending. *Compos. Part B Eng.* **2015**, *75*, 156–166. [CrossRef]
17. Ullah, H.; Silberschmidt, V.V. Analysis of impact induced damage in composites for wind turbine blades. *2015 Power Gener. Syst. Renew. Energy Technol. PGSRET* **2015**, *2015*, 1–6.
18. Ullah, H.; Harland, A.R.; Silberschmidt, V.V. Dynamic bending behaviour of woven composites for sports products: Experiments and damage analysis. *Mater. Des.* **2015**, *88*, 149–156. [CrossRef]
19. Ahmed, M.; Ullah, H.; Rauf, A. Fracture mechanics based fatigue life estimation of axial compressor blade. *Proc. 2016 13th Int. Bhurban Conf. Appl. Sci. Technol. IBCAST* **2016**, *2016*, 69–74.
20. Iqbal, M.; Alam, K.; Ahmad, A.; Maqsood, S.; Ullah, H.; Ullah, B. An enriched finite element method for efficient solutions of transient heat diffusion problems with multiple heat sources. *Eng. Comput.* **2022**, *38*, 3381–3397. [CrossRef]
21. Ullah, H.; Alam, K.; Iqbal, M.; Husain, A.; Silberschmidt, V.V. Simulation of buckling-driven progressive damage in composite wind turbine blade under extreme wind loads. *Eng. Fail. Anal.* **2022**, *140*, 106574. [CrossRef]
22. Ullah, H.; Silberschmidt, V.V. Numerical analysis of the interactive damage mechanisms in two-dimensional carbon fabric-reinforced thermoplastic composites under low velocity impacts. *J. Compos. Mater.* **2015**, *49*, 3127–3143. [CrossRef]
23. Ahmed, T.; Choudhry, R.S.; Ullah, H.; Hassan, F. Numerical Modelling of Carbon Fibre Reinforced Polymer Composites for Hole Size Effect. *NUST J. Eng. Sci.* **2015**, *8*, 1–9.
24. Ullah, H.; Harland, A.R.; Lucas, T.; Price, D.; Silberschmidt, V.V. Finite-element modelling of bending of CFRP laminates: Multiple delaminations. *Comput. Mater. Sci.* **2012**, *52*, 147–156. [CrossRef]
25. Ullah, H.; Harland, A.R.; Lucas, T.; Price, D.; Silberschmidt, V.V. Analysis of nonlinear deformations and damage in CFRP textile laminates. *J. Phys. Conf. Ser.* **2011**, *305*, 012045. [CrossRef]
26. Qi, S.; Cai, L.X.; Bao, C.; Chen, H.; Shi, K.K.; Wu, H.L. Analytical theory for fatigue crack propagation rates of mixed-mode I–II cracks and its application. *Int. J. Fatigue* **2019**, *119*, 150–159. [CrossRef]
27. Ahmadi, H.; Zavvar, E. Degree of bending (DoB) in offshore tubular KT-joints under the axial, in-plane bending (IPB), and out-of-plane bending (OPB) loads. *Appl. Ocean Res.* **2020**, *95*, 102015. [CrossRef]
28. Iqbal, M.; Karuppanan, S.; Perumal, V.; Ovinis, M.; Nouman, H. An artificial neural network model for the stress concentration factors in KT-joints subjected to axial compressive load. *Mater. Sci. Forum* **2023**, *1103*, 163–175. [CrossRef]
29. Zhang, Y.; Zhang, K.; Zhao, H.; Xin, J.; Duan, M. Stress analysis of adhesive in a cracked steel plate repaired with CFRP. *J. Constr. Steel Res.* **2018**, *145*, 210–217. [CrossRef]
30. Iqbal, M.; Khan, A.; Iqbal, M.; Azam, K. Layup Optimization of Laminated Structures. *Int. Conf. Model. Simul.* **2013**, *2013*, 259–262.
31. Iqbal, M. Weight Optimization of UAV Wing. Master's Thesis, University of Engineering and Technology, Peshawar, Pakistan, 2013.
32. Subbaiah, A.; Bollineni, R. Stress Intensity Factor of Inclined Internal Edge Crack in Cylindrical Pressure Vessel. *J. Fail. Anal. Prev.* **2020**, *20*, 1524–1533. [CrossRef]
33. Wang, H.T.; Wu, G.; Pang, Y.Y. Theoretical and numerical study on stress intensity factors for FRP-strengthened steel plates with double-edged cracks. *Sensors* **2018**, *18*, 2356. [CrossRef]
34. Iqbal, M.; Karuppanan, S.; Perumal, V.; Ovinis, M.; Nouman, H. Empirical modeling of stress concentration factors using FEA and artificial neural networks for the fatigue design of tubular KT-joints under combined loading. *Fatigue Fract. Eng. Mater. Struct.* **2023**, *46*, 4333–4349. [CrossRef]