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Research paper

2-D Strength Prediction of Single-row Multi-bolted Joints Woven Fabric Kenaf Composites

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Abstract

Implementation of multi-bolts arrangements in structures connections are commonplace in steel design to allow for joint efficiency and stronger connections. Woven fabric kenaf fibers are potentially used as reinforcement in composite materials due to excellent specific strength, renewability and less hazardous during handling as compared to commercial fibers. A two-dimensional Extended Finite Element Method (XFEM) framework of single-row multi-bolted joints has been developed to study the stress distribution and predict the joint bearing stress at failure. Stress distribution among adjacent bolts were compared along the hole boundary and net-tension plane, suggesting net-tension failure occurred at end-bolt. The predicted bearing strength from finite element modelling are validated against experimental framework. The testing series under investigated consists of four datasets from single-row 2 bolts and 3 bolts single-lap joints. Current study showed that the XFEM models demonstrated good agreements with the experimental results.

Keywords: *Multi-bolt; Woven fabric; Kenaf fibers; XFEM.*

1. Introduction

Implementation of kenaf fibers as composite reinforcement in epoxy polymers has been reported worldwide and excellent mechanical properties were reported [1]. Kenaf fibre is recognized as raw materials in manufacturing sector that has economic and environmental benefits, able to be harvested up to three times a year [1]. Kenaf are cultivated in some countries such as Bangladesh, Australia, Thailand, parts of Africa, Indonesia and Malaysia. Comparison with synthetic fibres counterparts, it demonstrates advantages such as superior specific strength (and stiffness), biodegradable, renewable, excellent tensile and impact properties, less hazardous during fabrication handling [2].

There are three prominent failure modes occurred in bolted joints, i.e., net-tension, shear-out and bearing failures. Net-tension is associated with development of stress raisers at the vicinity of the hole edge, previous works in single-bolt joints gives critical plate width/bolt diameter (W/d) approximately four in quasi-isotropic lay-up and six in cross-ply lay-ups [3]. On the other hand, net-tension failure modes prone to occur in multi-bolts joints due to by-pass loading transfer within adjacent bolts [4]. Few strength prediction works in multi-bolted has been reported, based on analytical approaches [5] and numerical approaches such as progressive damage modelling [6]. The progressive damage modelling used in McCarthy work was based on ply-by-ply basis and three steps were implemented, i.e. stress analysis, implementation of failure criteria and degradation of material properties. Their work is somewhat complex due to large combinations of failure criteria and degradation law models available, various precisions were obtained with model combinations and computational effort is time-consuming. Moreover, these works were conducted within in-house subroutine program and not available to public domains.

Ahmad has implemented cohesive zone model [7] and extended finite element framework [8] to predict notched strength and bearing stress at failure in bolted joint respectively. Reasonable predictions were obtained, both approaches used constitutive modelling based on traction-separation constitutive law and implementing independently determined material properties. Present work was carried out to implement a simplified 2-dimensional approach to study a parametric stress distribution within adjacent bolts and predict bearing stress at failure in multi-bolted woven fabric kenaf composite joints. Tangential stress and radial stress are associated with net-tension and bearing failures respectively and stress transfer are slightly contrary in multi-bolted joints compared to single-bolt joints. The study of multi-bolts configurations is essential to optimize joining efficiency under applied loading. Two-dimensional finite element analysis framework using ABAQUS CAE Version 6.13 software package were conducted using XFEM approach to include proper surface interaction and friction coefficient to allow joint load transfer. The strength prediction works were validated against experimental datasets, subsequently discussed in discussion section.

2. Experimental Set-up

Fabrication of woven fabric kenaf composite panels were carried out at Fabrications Laboratory, Universiti Tun Hussein Onn Malaysia (UTHM). Kenaf yarn has a nominal diameter of 0.7 mm were weaved by using weaving handloom machine combined with epoxy resin (and hardener) to produce woven fabric kenaf composite panels. Woven fabric kenaf composite laminate used was cross-ply plain weave architectures with a stacking sequence of

$(0/90)_s$. The composite panels were allowed to harden for 24 hours under high pressure and visible voids were inspected. Open holes were drilled according to specified geometric dimension, care should be taken to ensure there was no hole break-out.

Single-lap bolted joints with two and three bolts in single row were understudied respectively. Woven fabric kenaf composite plates has a constant end distance to hole diameter, *e/d* = 4 and corresponding normalized plate width is given as *W/d* = 5. The fastener systems used in this joint configuration system are steel washers and steel bolts. M5 bolts and washers were installed as the fastener system prior to mechanical testing. Two steel washers are provided below the bolt head and above the nut. Figure 1 shows schematic of single-lap joint configuration used in current experimental framework. The installation torques studied were a finger-tight condition (equivalent to about 0.5 Nm) and a clamped condition of 5 Nm. A total of four datasets were taken based on testing series as given in Figure 2, consisting of two and three bolts with two different applied torques respectively.

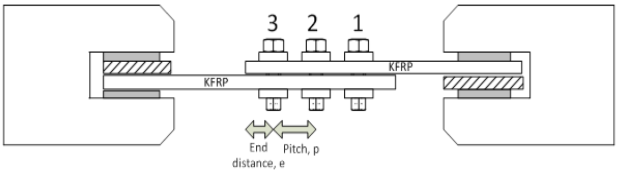


Figure 1. Schematic of single-lap joint configuration used in this experiment

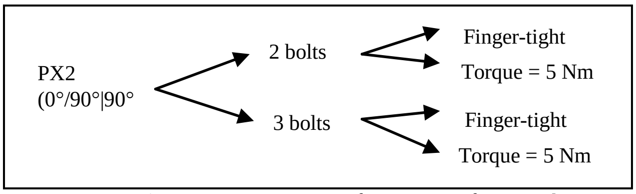


Figure 2. Testing series of experiment frameworks

Mechanical testing of testing coupons were carried out under quasi-static tensile loading using an Instron Universal Testing Machine (UTM) with 100 kN load cell and crosshead speed of 0.5 mm/min, following ASTM standard D3039. Load and displacement datasets were recorded at one-second intervals using a PC data-logging package from Instron. The plate thickness were measured and recorded by using micro-meter.

3. Finite Element Modelling

3.1 Modelling Techniques and Approaches

Figure 3 shows two-dimensional multi-bolt model developed in ABAQUS CAE Version 6.13 software following experimental framework configurations. Generally, the bolt/hole contact surface were lies between $80° \leq \theta \leq 85°$ and not along net-section plane as observed in notched plate case. The boundary condition and applied loading were properly assigned, displacement was assigned on the right edge with fixed boundary steel bolts. The model is modelled as half-symmetry to save time and cost effort as shown in Figure 3. Interaction properties between contacting bolt and inner surface of bore hole were assigned as a "master-slave" interaction and assumed as frictionless contact.

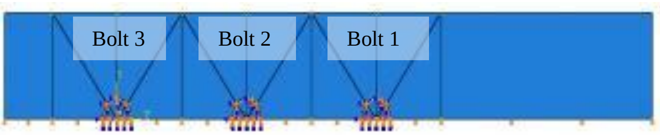


Figure 3. Boundary condition and loading applied of 2-D multi-bolted joints model

From Figure 4, meshing refinement was assigned at the vicinity of the notch edge as these areas were taken as interest area due to dense micro-cracks were taken place. A sensitivity study on damage stabilization coefficient and meshing refinement for 2-D multi-bolted joints were carried out, sufficient damage stabilization coefficient and meshing to ensure strength prediction was free of these parametric effects. In current work, a value of was 1 x 10-5 was implemented in the model. XFEM region is assigned within the net-tension plane of bolt 1 due to failure exhibited in experimental observations. First-order plane stress element with element designation of CPS4 in ABAQUS element library was used as element type. These elements were chosen as only first-order elements were compatible in current ABAQUS Version 6.13 with XFEM framework.

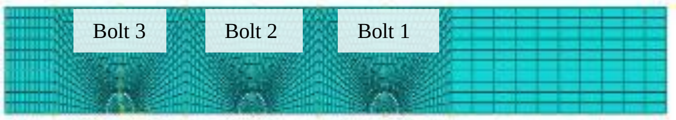
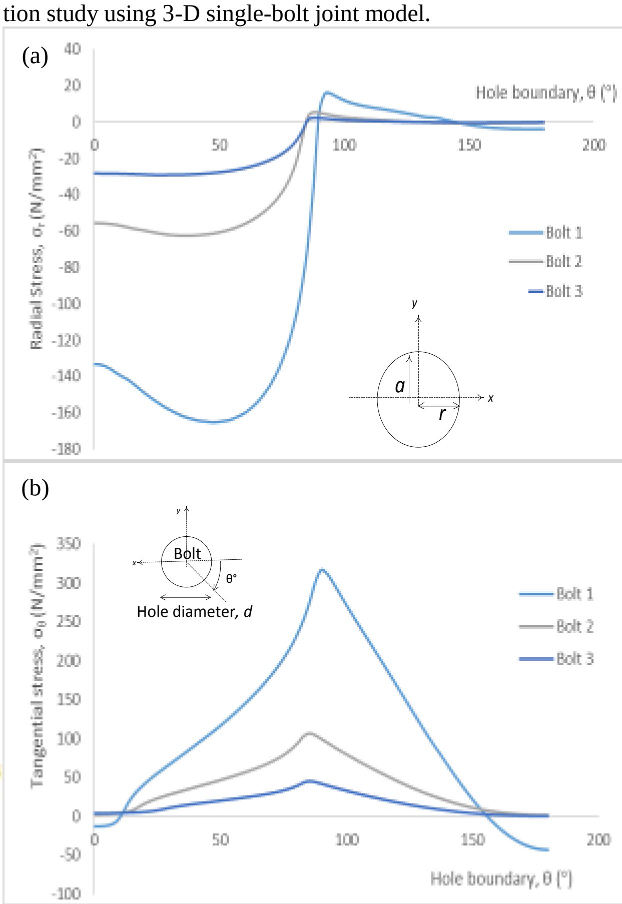


Figure 4. Meshing of 2-D multi-bolted joints model based on experimental plate geometry

3.2 Stress Distributions of Multi-Bolts Joints

Figure 5 showed variation of stress distribution at the hole boundary of three adjacent bolts. Radial stress, σ_r is associated with bearing failure mode as a result of matrix compression and fiber kinking due to the compression of composite plate behind the bolt shaft. On the other hand, tangential stress is associated with stress concentration due to discontinuity of stress profile. It is clearly seen from Figure 5(a) that zero radial stress is exhibited at hole boundary more than 87° (direction of angle is shown in Figure 5(a)) due to non-contact between bolt and plate bore. Correspondingly, largest stress concentration occurred at angle of 87° to signifies of crack formation at the hole boundary. Similar trends were obtained by Ahmad [9] carried out 3-dimensional stress distribution study using 3-D single-bolt joint model.



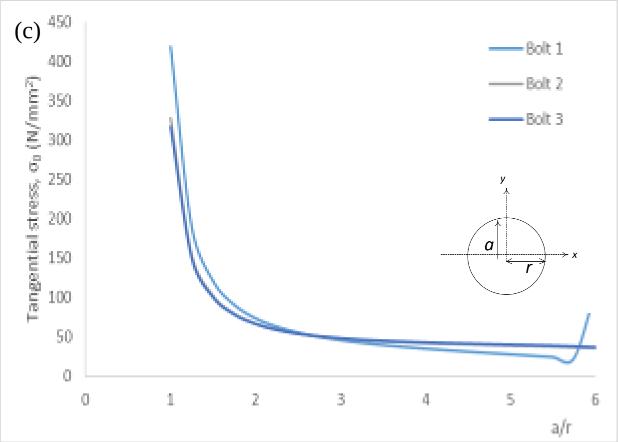


Figure 5. Stress distribution in single-row 3-bolts joints (a) Radial stress at hole boundary (b) Tangential stress at hole boundary (c) Tangential stress with *a/r*

From Figure 5, it was observed that three adjacent bolts produced different stress distribution due to ability of adjacent bolts to transfer stress which is known as "by-pass loading". It is expected that similar stress distribution occurred at top and bottom plates respectively as both joining plates were woven fabric kenaf composite plates, different stress behaviour may exhibit if using dissimilar joining materials as reported by [10]. Bolt 1 demonstrates substantially higher radial stress and tangential stress than other adjacent bolts, it carries largest load at the beginning of loading history [11] compared to other bolts. This subsequently reduced the loading capacity of Bolt 1 and transfer the load to Bolt 2 and 3. Current model implemented 2-D modelling framework, therefore bolt load and secondary bending effect is not explicitly exhibited.

4. XFEM Predictions

4.1 Material Properties

Table 1 shows the elastic and material properties of PX2 laminate used in current experimental work. The elastic properties includes in-plane tensile modulus, (E_x/E_y), shear modulus, G_{xy} and Poisson's ratio, v_{xy}. These properties were determined experimentally and the values obtained were taken as "smeared-out" properties. The constitutive model used was traction-separation relationship, requires material properties parameter i.e.,unnotched strength, σ_o and the fracture energy, G_c, similar approach was used previously in single-bolted CFRP joints [12]. These material properties were determined independently in the laboratory following relevant code of practice. The isotropic steel bolts and steel washers were assigned with elastic modulus, E_s = 210 GPa and Poisson ratio, v = 0.3.

Table 1. Elastic and material properties for PX2 laminate

Lay-ups	E_x/E_y (MPa)	G_{xy} (MPa)	v_{xy}	σ_o (MPa)	G_c (kJ/m2)
PX2	2260.33	565.08	0.07	54.70	5.3

4.2 Material Properties

Figure 6 showing a representative testing coupon of net-tension failure with three bolts joint as observed after mechanical testing. As previously discussed, the largest tangential stress occurred at Bolt 1 and gives approximately three times tangential stress at net-tension plane (about 87°) than the other two adjacent bolts. Compressive radial stress showed lower value than corresponding tensile tangential stress at Bolt 1 (both radial and tangential stress are highest at Bolt 1), suggesting dominant failure is net-tension failure at Bolt 1. All testing series are showing the same trends; net-tension failures were exhibited in Bolt 1.

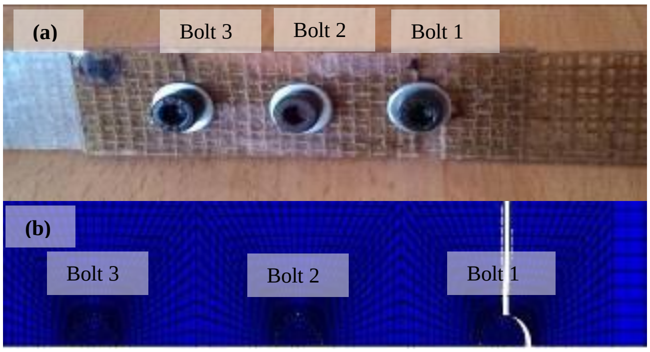


Figure 6. Comparison of (a) experimental observation and (b) XFEM of three-bolt joint

XFEM region were assigned within net-tension plane of bolt 1 as pre-defined failure path to allow easier convergence within XFEM framework. This is consistent with experimental observations where fracture and failure takes place at Bolt 1 as described above. Current 2-D modelling work used smeared-out properties and ignored the definition of out-of-plane properties. However, as the plate is sufficiently thin (all plates has approximately 2 mm thickness) the out-of-plane properties were assumed as negligible. All XFEM models showed crack initiation and propagation along net-tension plane, which is within the enriched XFEM region assigned prior to job submission.

Figure 7 displayed associated damage plots along net-tension plane at specified applied loading. Crack is initiated at around 87° hole boundary due to contact interaction between bore hole and bolt shaft. This had been explained in stress distribution section above. Corresponding damage plots at specific points on the loading history indicated in Figure 7, are illustrated in Figure 8. At point A, it is assumed that micro-damage event i.e., matrix cracking, delamination and fiber fracture progressively occurred until reaching of point B. At point B which is approximately a hole radius size, catastrophic failure occurred. The distance from hole edge prior to catastrophic failure is also known as damage zone length which comprised of self-similar localized crack due to stress concentration. At point C, the crack is fully separated.

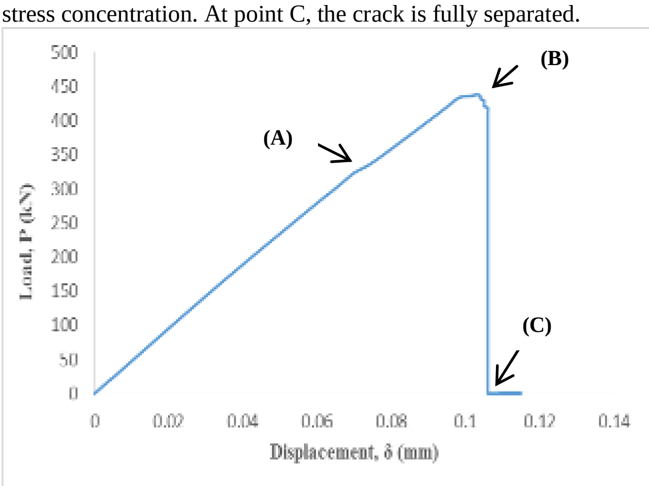
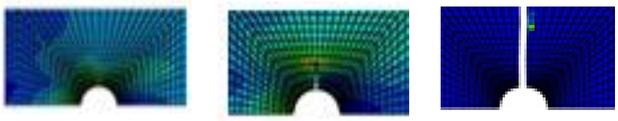


Figure 7. Load-displacement curve and associated damage plot in XFEM framework.



(A) (B) (C)

Figure 8. Associated damage plots at specified location given in Figure 6.

The limitation of 2-D approach is that frictional load transfer effects are not explicitly captured. From load-displacement curve given in Figure 9, as applied load, P was surpassing bolt load, P_{bolt}

the friction load was overcome and both plates started to slip within shear plane. This is usually characterised by a load drop, even this feature was more apparent in some P-δ curves than others [13]. From Figure 9, the sliding load is taken as 860 N, this value is equivalent to the stage when applied load fully overcome the friction from clamp-up (torque). This value was added to the bearing stress from XFEM strength prediction work, this was assumed as a simplistic way to take into account for friction load.

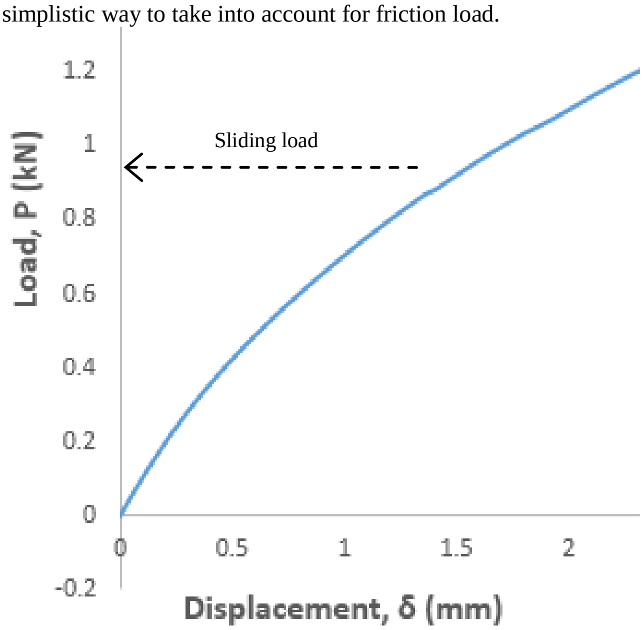


Figure 9. Sliding load taken from load-displacement profile

Table 2 gives comparison between experimental results and modelling predictions of bearing stress at failure for all testing series understudy. As expected, KFRP plates with 5 Nm bolt load is higher than finger-tight condition. From Table 2, discrepancy in finger-tight condition of 2 bolts and 3 bolts model is smaller (less than 10%) than bolt-load condition. Current model implemented 2D modelling framework, therefore the load transfer due to friction and bolt load effect is not explicitly modelled. Therefore, larger discrepancy in torque condition is not surprising. Sliding load is taken from experimental load-displacement profiles (average from three datasets) which showed a slight plateau to indicate slipping of joining plates. Present study can also be expanded to other engineering problem such as concrete beam specimen [14] and composite floor system [15].

Table 2. Comparison between experimental and numerical bearing stress at failures

Multi-bolts		2 bolts		3 bolts	
Torque		FT	5 Nm	FT	5 Nm
Exp. bearing strength ($\sigma_{b, exp}$)		110	148	124	159
Numerical Predictions (N/mm^2)	**2-D XFEM**	86	86	113	113
	Sliding load	19	86	19	86
	Bearing stress at failure ($\sigma_{b, pred}$)	105	172	132	199
Error (%)		4.5	16.2	6.5	25.2

5. Conclusion

Experimental set-up has been carried out and showed that net-tension occurred in all testing series investigated. From the experimental observation, a simplistic 2-D modelling of single-row 2-bolt and 3-bolt configurations has been implemented within XFEA framework. Good agreement were found (especially in finger-tight condition of less than 10% discrepancy). However, the predicted can be further improved by implementing 3-D model by explicitly includes clamping load, friction and secondary bending effect.

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References

[1] N. Saba, M.T. Paridah, and M. Jawaid, “Mechanical properties of kenaf fibre reinforced polymer composite”: a review. Constr. Build. Mater, 76, 2015, pp. 87–96.

[2] J. George, M.S. Sreekala, and S. Thomas, “A review on interface modification and characterization of natural fiber reinforced plastic composites”, Polymer Engineering & Science, 41, 2001, pp. 1471–1485.

[3] J.H. Crews, C.S. Hong, and I.S. Raju, “Stress Concentration Factors for Finite Orthotropic Laminates with a Pin-loaded Hole”. 1-40, 1981: NASATechnology Paper 1862, 1981.

[4] D. Cunningham, K.A. Harries, and A.J. Bell, “Open-hole tension capacity of pultruded GFRP having staggered hole arrangement”. Engineering Structures, 95, 2015, pp. 8–15.

[5] C.T. McCarthy, and P.J. Gray, “An analytical model for the prediction of load distribution in highly torqued multi-bolt composite joints”. Composite Structures, 93(2), 2011, pp. 287–298.

[6] C.T. McCarthy, M.A. McCarthy, and V.P. Lawlor, “Progressive damage analysis of multibolt composite joints with variable bolt-hole clearances”. Compos Part B – Eng ;36(4), 2005, pp. 290–305.

[7] H. Ahmad, A.D. Crocombe, and P.A. Smith, “Strength Prediction of Notched Composite Plates using a Cohesive Zone Approach”, Advanced Material Research, Vol. 845, 2014, p. 199-203.

[8] H. Ahmad, A.D. Crocombe, and P.A. Smith, “Strength Prediction in CFRP Woven Laminate Bolted Double-Lap Joints under Quasi-static Loading using XFEM”. Composites Part A :56, 2013, pp. 192-202.

[9] H. Ahmad, “Stress Distribution in Composite Double-Lap Bolted Joints Incorporating with Clamp-Up″. Applied Mechanics and Materials, Vol: 660, 10, 2014, pp. 152-156, ISSN:16627482.

[10] H. Ahmad, “Stress Distribution of Secondary Bending in Single-Lap Bolted Joints with Dissimilar Joining Plates and Plate Types″, Journal Teknologi, Vol: 78, 6, 2016, pp. 1-7, ISSN:2180-3722.

[11] C.T. McCarthy, and P.J. Gray, “A global bolted joint model for finite element analysis of load distributions in multi-bolt composite joints”, Composite : Part B, 41, 2010, pp. 317-325.

[12] H. Ahmad, A.D. Crocombe, and P.A. Smith, "Physically Based Finite Element Strength Prediction in Notched Woven Laminates under Quasi-static Loading". Plastics, Rubber and Composites :42(3), 2013, pp. 93-100.

[13] A. Kontolatis, “Failure of Composite Bolted Joints Made from Woven Fabric GFRP Composite”, MSc dissertation, Guildford: University of Surrey, 2000.

[14] N.A. Rahman, Z.M. Jaini, and N.N.M. Zahir, “Fracture Energy of Foamed Concrete by Means of the Three-Point Bending Tests on Notched Beam Specimens”, APRN Journal of Engineering and Applied Sciences, Vol: 10, 2015, pp. 6562-6570.

[15] L.Y. Fong, H.A. Ghafar, N.A. Rahman, and D. Yeoh, “Connection Performance for LVL-Concrete Composite Floor System”, Applied Mechanics and Materials, Vol: 773-773, 2015, pp. 954-963.