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XFEM Modelling of Single-Lap Woven Fabric Kenaf Composites Bolted Joints with Temperature Action

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Abstract: Kenaf fibers as reinforcing fibers and combined with epoxy polymers matrix to develop a sustainable composite materials were reported and it has excellent specific tensile modulus (and specific strength), renewable, relatively cheap and less hazardous during handling as compared to synthetic fibers composites counterparts. Present experimental work investigates bearing stress at failure of single-lap bolted joint woven fabric kenaf composite plates under finger-tight condition of room and elevated temperature actions, respectively. Other parametric studies include variation of lay-up types and normalised plate width W/d as specified in testing series. Present work concentrates on opening mode (Mode I) fracture associated with stress raisers ahead of notch tip. Experimental flow includes weaving of kenaf yarns using handloom weaving machine, composite panels fabrication using wet hand lay-up techniques, cutting into testing coupons and hole drilling prior to mechanical testing. The experiment results showed small increase of bearing stress under temperature action (120°C) due to of matrix toughening. Strength prediction works of bolted joints problem were implemented using 3-dimensional XFEM framework and validated against experimental result datasets. The constitutive model used were based on physically based traction-separation law by implementing independently determined unnotched strength, σ_0 and fracture energy $G_{.c}$ Good agreements between experimental work and finite element modelling results were achieved in most cases.

Key words: Woven fabric, bolted joint, natural fibres, bearing stress, XFEM

INTRODUCTION

Polymer composites have emerged as important structural engineering materials in automotive, transportation, infrastructure applications as well as in civil engineering sector, mainly due to excellent specific strength and stiffness. Composite materials are one of a new class of advanced materials that are strong, low densities and non-corrosive. Recently, natural fiber has attracted attention in composite material research due to advantages such as renewable, environmental-friendly and cheaper option (Mittal *et al*., 2016). Kenaf fiber exhibits superior specific strength and stiffness, less abrasive during handling and biodegradability (Jeyanthi and Rani, 2012). Woven reinforcement fibers are 2-dimensional fiber consisting of interlaced orthogonal tows which consist of two sets of interlaced yarns, warp (0°) and weft (90°). Abot *et al.* (2004) found that reinforcing composite with fiber layup in general offers good dimensional stability in both warp and weft direction but low in-plane shear stiffness. A comprehensive literature review relating to the damage and fracture behaviour of composite laminates containing a stress raiser has been reported extensively in the form of a circular hole (Agarwal, 1980) or mechanically fastened joint (Ahmad *et al*., 2014).

The major issue that hinders the widespread use of Fiber Reinforce Polymer (FRP) in structure engineering is the degree of fire resistance of material and limited amount of information regard of these material behaviour in high temperature. As reported by Smith (2000) with increasing temperature, the matrix dominated properties of composite will be influenced by softening of the matrix in particular as temperature approach the matrix glass transition temperature. An experiment study by Azwa and Yousif (2013) on unnotched kenaf fiber/epoxy subjected to thermal degradation concludes that composites demonstrates fine cracks initiated at 150°C which is attributed to the fiber-matrix debonding and the kenaf fiber/epoxy composites will suffer a great reduction of its mechanical properties at this temperature. On the other hand, Vieille *et al*. (2011) works on mechanical behaviour of woven fabric carbon fiber reinforce Poly Phenylen Sulfied (PPS) laminate under elevated temperature and

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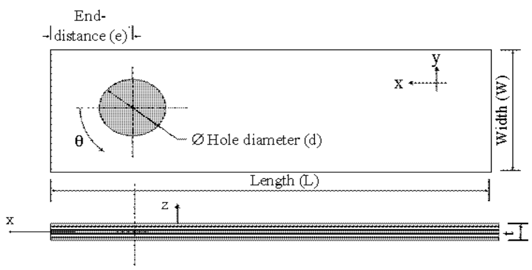

Fig. 1: Geometry of single-lap bolted joint required in 3D modelling

found that heat degraded the fiber/matrix interface as temperature deteriorate the surface of composite material to slip micro-crack formation and therefore react as reinforcing system. Such complex behaviour of composite materials with elevated temperatures requires further experimental framework.

There are lacks of numerical tools to predict the strength of plates associated with stress concentration problems. Due to numbers of parameters involved especially in bolted joint problem, analytical approaches seems unrealistic as huge array of parameters involved. Numerical approaches able to reduce laborious experimental framework and effective in designing composite joint structures effectively. Ahmad *et al*. (2014) has successfully conducted Extended Finite Element Method (XFEM) framework approach in predicting joint strength of woven fabric CFRP composites with single-lap bolted joints. Santiuste *et al*. (2011) conducted progressive damage modelling where good predictions were found with correlation with bearing failure mode however, this approaches used in-house subroutines program and not available to public domain. There was no reported literature found to extend XFEM framework to predict the strength of composite materials subjected to the effect of temperatures. This research can be extended to structures response prediction of concrete strength under temperature (Mokhatar *et al*., 2016) and blast loading (Santiuste *et al*., 2011).

Experimental frameworks: Reinforcing fibers used in current experimental work was kenaf fiber yarns with a diameter of 0.75 mm and weaved byusing handloom weaving machine, combines with epoxy resin (SP-84) and hardener (SP-76) as matrix binder with a mixture ratio of 2:1. Woven fabric type used in the present study was cross-ply and quasi-isotropic plain weave lay-up. The fabricated panels were compressed under hydraulic compression moulding machine under room temperature for a minimum of 24 h then cut into testing coupons as shown in Fig. 1 and assembled to single-lap bolted joints configurations as given in Fig. 2 prior to mechanical testing.

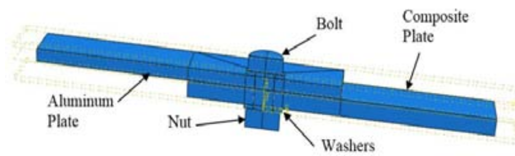

Fig. 2: Part components in single-lap joint implement in XFEM

The temperature control system including oven and a temperature controller provides a stable temperature environment during oven-drying process with operating temperature ranges from room temperature to 120°C. Prior to that, all testing coupons were dried in designated oven at 70±5°C for 48 h and were cured under dry condition. The mechanical testing was carried out on the testing coupons within 8 h after oven drying. The bearing stress at failures were given as:

$$\sigma_b = P_{max}/d\times t$$

where, σ_b, P_{max}, d and t are given as bearing stress at failures, peak load, hole diameter and plate thickness, respectively. The in-plane elastic properties and material properties (unnotched strength σ_0 and fracture energy, G_c) were determined independently. Elastic properties and unnotched strength properties were tested under quasi-static loading following ASTM Standard D3039B and fracture energy were measured using Single-Edge Notch (SEN) technique following ASTM Standard E399-90.

MATERIALS AND METHODS

Finite element modelling: Three-dimensional models were implemented to incorporate explicitly the frictional load transfer, clamped force applied and surface interactions between adjacent parts generated by using ABAQUS CAE version 6.13. The generation of composite plate geometries used in current modelling work shown in Fig. 2, following experimental framework of bolted joint system as given in Table 1 with various geometry dimensions. The single-lap bolted joint model were finger-tight condition has a constant hole diameter (d = 5 mm) and e/d ratio but variation of normalized plate width W/d ratios were in range of 2-5. The elastic properties of woven fabric kenaf composites used in recent model were determined independently and considered as “smeared-out” elastic properties given in Table 2. All bolted joint components were assembled and master-slave contact interactions assigned as surface contact interactions.

Only half-model of actual single-lap bolted joint configurations were modelled to save computational cost and efforts. The boundary conditions and applied loads

Table 1: Range of test parameters investigated for WKRP single lap joints tests

Designation	Laminate (sec)	e/d (fixed)	W/d	Hole size d (mm)	Clamp-up torques (Nm)	Temperatures (°C)
PX2	(0/90)	6	2-5	5	FT	RT, 120
PX4	(0/90)2	6	2-5	5	FT	RT, 120
PQ4	(0/90/±45)	4	2-5	5	FT	RT, 120
PA4	(90/0/±60)	4	2-5	5	FT	RT, 120

*RT = Room Temperature

Table 2: Elastic and material properties of woven fabric kenaf composites investigated

Lay-up	E_x (MPa)	E_y (MPa)	E_z (MPa)	v_{xy}	v_{yz}	v_{zx}	G_{xy} (MPa)	G_{yz} (MPa)	G_{zz} (MPa)	σ_0 (MPa)	G_c (kJ/m^2)
PX2	2260	2260	565	0.07	0.10	0.10	198	182	182	54.70	5.30
PX4	2291	2291	572	0.07	0.10	0.10	201	184	184	55.47	10.50
PQ4	2115	2115	661	0.30	0.33	0.33	755	220	220	50.38	7.75
PA4	2583	2583	850	0.30	0.33	0.33	971	283	283	42.33	6.75

were also included according to tensile testing conditions. The joining aluminium plate geometry was following the joined composite plates and composite plate may demonstrate more secondary bending behaviour as shown experimentally. Current model implemented physically-based traction-separation constitutive model, two material parameters, i.e., unnotched strength, σ_0 and fracture energy, G_c were assigned as material input and determined independently as described in earlier study, the values are given in Table 2. The thermal coefficients in longitudinal direction, α_1 and transverse direction, α_2 were given as 1×10^{-6} and 26×10^{-6}, respectively under elevated temperature model.

RESULTS AND DISCUSSION

Experimental observations found that all single-lap joint configurations demonstrate net-tension failures in all W/d ratios. Larger normalized plate width (W/d) provides larger process zone failure prior to catastrophic failure and this contributes to higher bearing stress at failure (Kontolatis, 2000). Table 3 showed that larger W/d gives higher prediction value of bearing stress at failure under both temperature actions similar to experimental findings. This agreement satisfies a research observations by Kontolatis (2000) with increasing W/d and e/d ratio tends to increase the bearing stress at failure and his interrupted test showed extensive micro-damage event occurred ahead of the notch edge. Current work controls the normalised plate width W/d = 5 to focus upon net-tension failure associated to stress concentration as found by Ahmad *et al*. (2014) on CFRP composite plates. This allows the implementation of physically based constitutive model in XFEM framework to predict bearing stress associated with stress raiser ahead of the notch edge.

The strength predictions were compared with experimental results shown in Table 3 under room temperature and elevated temperatures. In general, most of strength prediction showed <35% discrepancy in the WKRP single-lap bolted joint although some modelling results showed much lesser disagreement. Most of bolted joints overestimated the strength prediction in room temperature but mixed predictions under elevated temperature condition. Cross-ply lay-up has higher bearing stress at failure than quasi-isotropic lay-up due to higher volume fraction with 0° fiber in cross-ply compared to equivalent quasi-isotropic lay-up. This showed in Table 3 that XFEM strength prediction result of PX4 lay-up has higher bearing stress value than PQ4 and PA4 lay-ups as found in experimental results.

XFEM predictions and experimental results showed that thinner plate of PX2 has slightly higher bearing stress at failure compared to PX4 lay-up, thicker laminate shows slightly better prediction than thinner lay-up. Therefore, combination of thicker plate and cross-ply lay-up (showed by PX4 lay-up) give better prediction than other lay-up perhaps is perhaps not surprising. This may due smeared-out properties were better represented in the thicker plates as the plate is associated with secondary bending. Similar behaviours was also observed in Ahmad *et al*. (2014) of woven fabric CFRP single-lap bolted joint. The warping effect of secondary bending were given by constant $[D_{ij}]$ which was based on its constituent properties, current work averaged the material properties throughout the plate thickness known as "smeared-out" properties. However, as the composite plates thickness were sufficiently thin and plane stress formulations is still valid, the smeared-out properties giving a reasonable simplistic approach. On the other hand, cross-ply lay-up showed better strength predictions than equivalent quasi-isotropic lay-up both in room and temperature actions. Similar finding was reported in cross-ply lay-up to provide better strength prediction in bending behavior (Ahmad *et al*., 2014). It was found that 30 and 20% discrepancy under room temperature and elevated temperature were found, respectively as given in Table 3.

Temperature effects reported by Buxton and Baillie (1994) found that composite polymer increased bearing stress as temperature increased as a result of fiber matrix interface enhancement similar to fiber treatment and resin

Table 3: Comparison work of XFEM model with experimental works in single-bolt joint woven fabric Kenaf composites

Laminate designation	W/d	Failure mode	Room temperature Exp. results (N/mm²)	Room temperature XFEM (N/mm²)	Room temperature Error (%)	Elevated temperature Exp. results (N/mm²)	Elevated temperature XFEM (N/mm²)	Elevated temperature Error (%)
PX2	2	NT	39	43	9.8	48	44	-8.4
	3	NT	723	70	-4.4	86	70	-18.6
	4	NT	122	98	-19.3	129	106	-17.9
	5	NT	145	122	-16.1	151	129	-14.5
PX4	2	NT	38	51	33.2	45	52	14.2
	3	NT	65	82	26.2	75	83	10.1
	4	NT	83	100	20.7	117	102	-13.1
	5	NT	102	113	10.8	140	115	-18.0
PQ4	2	NT	32	43	34.9	38	48	25.4
	3	NT	56	75	34.1	73	80	8.9
	4	NT	81	107	31.4	106	109	2.7
	5	NT	95	120	26.6	135	121	-10.6
PA4	2	NT	30	31	29.5	33	44	32.7
	3	NT	53	59	23.8	59	75	26.5
	4	NT	79	95	29.2	95	109	14.4
	5	NT	97	132	25.0	132	119	-9.5

properties. The XFEM strength prediction gave smaller discrepancy under elevated temperatures. The temperature leads to thermal expansion on composite plates in longitudinal and transverse direction. The applied thermal expansion in XFEM were in good agreement with Santiuste *et al*. (2011) work under temperature action however they used lamina properties to be implemented in Hashin criterion and associated degradation model but the application towards stress concentration problem is found not suitable as most of his bolted joints failed in bearing failures.

Olmedo and Santiuste (2012) reported that the secondary bending increases tensile stresses exhibited due to lifting of joining plates and net-tension failure tends to occur as compared to double-lap bolted joints. Figure 3a showed the experimental observations of secondary bending behaviour where bolt tilting occurs in single-bolt bolted joint experimental test but ultimate failures demonstrated net-tension failure mode. The similar behaviour was demonstrated in XFEM strength prediction modelling as shown in Fig. 3b, occurs as contact pressure between hole edge and fasteners were non-uniform through the plate thickness. Secondary bending also changes the stress gradient when the bolt tilting and reduce the strength of composite plate (Ahmad *et al*., 2014). Therefore, crack was initiated at the washer edge tend to penetrate to composite surface as pressure from bolt tilting and give premature failure as observed in the experimental work. The effect of secondary bending causes the crack started from the bottom plane through plate thickness to the top plane due to plate bending. The current constitutive model implemented able to track the crack occurrence from bottom plate to predict the net-tension opening crack as shown in Fig. 4.

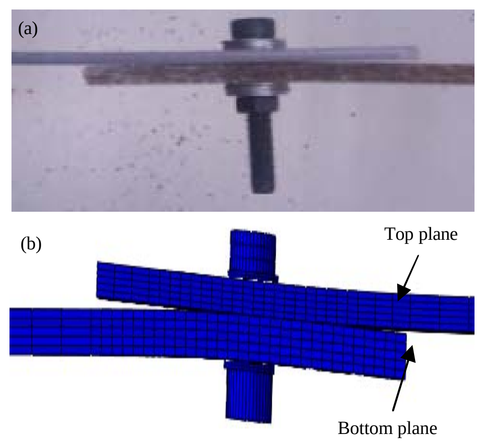

Fig. 3: Secondary bending in single-lap joint: a) Experimental observations and b) XFEM model

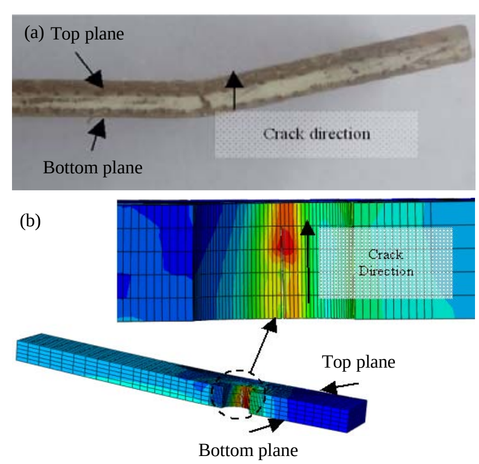

Fig. 4: Crack propagation through thickness from bottom plane to top plane in single lay-up: a) Experimentally and b) XFEM

CONCLUSION

The strength prediction of bolted joints was implemented within 3D XFEM modelling framework of single-lap bolted joint to incorporate explicitly contact surfaces interaction, friction load transfer, clamping load and temperature actions. This approach used a physically-based traction-separation relationship able to predict bearing stress at failure under room and elevated temperature in single-lap bolted joints associated with stress raisers ahead notch tip. Present work implemented elastic and material properties that were determined independently from experimental work following relevant code of practice and not calibrated from datasets available in the literatures. All testing series lay-up were failed in net-tension failure mode associated with stress raisers at the vicinity of the notch edge. Good agreement between experimental results and XFEM modelling work (most models give discrepancy in the range of 30-40%) on strength prediction of all testing coupons even less discrepancy were seen in elevated temperature case. The exhibition of secondary bending in single-lap bolted joint model may not be representing the bending behaviour properly in thinner lay-up but good predictions are given in thicker lay-up.

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