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ORIGINAL ARTICLE

Strength predictions of single-lap woven fabric Kenaf composites bolted joints

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ABSTRACT – Application of woven fabric kenaf fibers in production of polymeric composites (known as woven fabric kenaf reinforced composite (WKRP)) were readily available in the literatures due to excellent tensile strength and elongation at break. Nevertheless, there are less reported work and information regarding to performance of these materials in bolted joints problem. Bolted joints demonstrate complicated damage morphologies either net-tension, shear-out or bearing failure modes dependence upon combination arrays of lay-up/joint variables. XFEM approach has been reported in the literature, yet the agreements are limited to net-tension failure resulting from stress concentration problem. The aim of this paper to carry out strength prediction work of single-lap WKRP/aluminium bolted joints by using Hashin formulation within 3D finite element framework. Hashin formulation which based on ply-by-ply basis seen to perform better prediction to bearing failure modes. The material properties incorporated within Hashin formulation was taken from a single-ply of woven fabric. Strength prediction from Hashin formulation showed a difference of less than ±25% in net tension-bearing failure mode, but less good predictions (some lay-up showed discrepancies of 50%) in smaller *W/d* to give net-tension mode. Good prediction in net-tension-bearing failure were exhibited in Hashin formulation than XFEM approach as bearing failure is based on ply-by-ply basis due to fiber kinking and matrix compression.

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INTRODUCTION

High demand for lightweight and high-performance materials in engineering sectors leading to drastic increase over the last twenty years due to superior specific stiffness and strength. In early years, application of commercial composite materials such as carbon fiber reinforced polymer (CFRP) were limited to aerospace and defense sectors. In mid- 1990's, production of composites was evolved extensively in manufacturing and construction sectors due to their price drop. Recently, with significant awareness of utilizing green materials, natural fibers were employed in composite production to offer comparable specific stiffness and strength to commercial fibers, in particular GFRP. These natural fiber composites also possessed low tool wear, cheaper, availability, and biodegradability [1].

Incorporation of kenaf fibers as reinforcing composite materials in production of woven fabric kenaf polymer composites (WKRP) were found in the literatures [2–4]. Good engineering properties of WKRP especially fracture toughness and lightweight favours material engineers and scientists to utilize them as structure components. Bolted joints are favorable due to ability of joining parts to dismantle for inspection and repair purposes. Formerly, Romanye et. al. [2] used XFEM approach in their strength prediction, however, good agreements were limited in bolted joint series with net-tension failure mode. They used traction-separation relationship as constitutive model which derived from stress concentration problem. XFEM is based from state-of-the-art fracture mechanics fundamental and nature of net- tension which is based on stress concentration developed at the vicinity of the hole edge. Ahmad [5] attempts to incorporate bearing failure with XFEM models that occurred behind the bolt to capture the bearing-net-tension mode in woven fabric CFRP plates. The increase of failure strength with percentage of softening increases however, insignificant. The softening in bearing will not affect the predicted net-tension strength to a great extent.

Tsujimoto and Wilson [6] created a 2-D elasto-plastic finite element model with rigid pin assuming a cosine load distribution which also included the effects of friction and non-linear shear stress-shear strain behaviour. A combination of an elastic-perfectly plastic constitutive model and the Hill yield criterion (flow rule) for orthotropic materials was used. It was found that net-tension failures were insensitive to friction effects and this particular type of failure mode was predicted imprecisely. On the other hand, increasing friction, shear-out and bearing strengths increased. Since cosinusoidal loads were idealized for an isotropic lay-up, the application to modelling non-isotropic lay-ups was limited.

Progressive damage approach is a numerical approach comprised of three steps, stress analysis, failure criterion and damage softening law, many researchers developed subroutines within FEA framework that is not accessible to public use. Hashin [7] has formulated discrete micro-damage event to predict bolted joints failures and usually coupled with Yamada-Sun [8] softening law, limited success was reported with mixture of failure model and damage softening law used. Failure in bolted joints problems are complex and damage morphologies are dependent of various factors such as

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lay-up types, normalized plate width, *W/d*, joint types etc [9]. Typically, the primary failures modes in bolted joint problem occurs in net-tension, shear-out and bearing failures. A numerical study to predict secondary mode of net-tension-bearing failure in bolted joint need to be carried out.

The aim of current work is to predict the bearing strength in bolted joint of WKRP/aluminium plates by using Hashin criterion [7] which is based on ply-by-ply basis that may improve prediction in bearing mode by incorporating more intrinsic micro-damages features. The strength prediction from Hashin formulation is then validated against experimental datasets and compared to XFEM modelling approach [2].

HASHIN FORMULATIONS AND MODELLING TECHNIQUES

From stress analysis at the hole boundary, the peak local stresses were used within a failure criterion to predict laminate strength and associated mode of failures. Early works including Waszak and Cruse [10] who applied the maximum stress, maximum strain and distortional energy criteria around the hole. Oplinger and Ghandhi [9] used the Hoffman criterion. Chang et. al. [11] assumed frictionless contact and a co-sinusoidal boundary radial stress distribution and applied progressive failure model. A particular ply was removed from further analysis on a ply-by-ply basis once the failure criterion in any ply was achieved, the new stress distribution (as a result of load redistribution to other plies) was recalculated and the procedure repeated until the total laminate failed. However, predicted strength was consistently conservative.

The strength of a single layer of composite material can be predicted using a micromechanics approach or using experimental data. Hashin's macro-mechanical analytical models [7] considered independent fiber and matrix failure modes, generally leading to a very conservative solution to satisfy the criterion, and hence non-cost effectiveness predictions. Table 1 shows the Hashin failure criteria associated with respective failure modes which are embedded within (ABAQUS CAE Version 6.13, SIMULIA Corp) software. Dano et. al. [12] has includes non-linear shear stress-shear strain relation and given as;

$$\gamma_{12} = \frac{\tau_{12}}{G_{12}} + \alpha\tau_{12}^3 \tag{1}$$

Table 1. Hashin failure criterion [6] with associated failure modes

Failure modes	Hashin Criteria: Non-linear	Hashin Criteria: Linear
	$\sigma_2 > 0$	
Matrix Tensile Failure	$\left(\frac{\sigma_2}{Y_t}\right)^2 + \frac{\frac{\tau_{12}^2}{2G_{12}} + \frac{3\alpha\tau_{12}^4}{4}}{\frac{S^2}{2G_{12}} + \frac{3\alpha S^4}{4}} > 1$	$\left(\frac{\sigma_2}{Y_t}\right)^2 + \left(\frac{\tau_{12}}{S}\right)^2 > 1$
	$\sigma_2 < 0$	
Matrix Compression Failure	$\left(\frac{\sigma_2}{Y_c}\right)^2 + \frac{\frac{\tau_{12}^2}{2G_{12}} + \frac{3\alpha\tau_{12}^4}{4}}{\frac{S^2}{2G_{12}} + \frac{3\alpha S^4}{4}} > 1$	$\left(\frac{\sigma_2}{Y_c}\right)^2 + \left(\frac{\tau_{12}}{S}\right)^2 > 1$
	$\sigma_1 < 0$	
Fiber/matrix Shear Failure	$\left(\frac{\sigma_2}{X_c}\right)^2 + \frac{\frac{\tau_{12}^2}{2G_{12}} + \frac{3\alpha\tau_{12}^4}{4}}{\frac{S^2}{2G_{12}} + \frac{3\alpha S^4}{4}} > 1$	$\left(\frac{\sigma_2}{X_c}\right)^2 + \left(\frac{\tau_{12}}{S}\right)^2 > 1$
	$\sigma_1 > 0$	
Fiber Tensile Failure	$\left(\frac{\sigma_2}{X_t}\right)^2 + \frac{\frac{\tau_{12}^2}{2G_{12}} + \frac{3\alpha\tau_{12}^4}{4}}{\frac{S^2}{2G_{12}} + \frac{3\alpha S^4}{4}} > 1$	$\left(\frac{\sigma_2}{X_t}\right)^2 + \left(\frac{\tau_{12}}{S}\right)^2 > 1$
	$\sigma_1 < 0$	
Fiber Compression Failure	$\left(\frac{\sigma_1}{X_c}\right)^2 > 1$	

In this study, three-dimensional FEA models were carried out to incorporate explicitly frictional load transfer, bolt load applied and surface interactions between adjacent parts by using (ABAQUS CAE Version 6.13, SIMULIA Corp). Only half-model of single-lap bolted joint were modelled to save the computational and time efforts. The geometries of composite plate used in current modelling work are schematically given in Figure 1, following tested joining plates of WKRP plates [2] given in Table 2. A more detail test parameters of bolted joint assembly system is given in Table 3. Each single-lap bolted joint model has a constant hole diameter (d = 5mm) and *e/d* ratio with a finger-tight condition, but the variation of normalized plate width *W/d* ratios were in the range of 2- 5. The testing series includes WKRP system comprised of two stacking sequences of a four layer plain weave with cross-ply (PX4) and quasi-isotropic (PQ4) arrangements.

The elastic properties of a single woven fabric ply composite plate (reported as PX1 from [2] which comprised of an equivalent two orthogonal plies arrangement) used in recent model were given in Table 4. These properties were independently determined from uniaxial tensile testing following ASTM D3039-76 to determine Young Modulus (E_1, E_2), Poisson ratio (v_{12}), longitudinal tensile strength (X_t) and transverse tensile strength, (Y_t). Shear modulus and strength was determine following ASTM3518. All bolted joint components were assembled and master-slave contact interactions were assigned as surface contact interactions. According to tensile testing conditions, the boundary conditions and applied loads were also included. The joining aluminium plate geometry was following the adjacent joining composite plates and composite plate demonstrate larger secondary bending deformations as shown experimentally compares to similar joining plate materials.

The modelling technique is following woven fabric CFRP bolted joint models, described comprehensively in [13]. A sensitivity study on mesh refinement has been carried out to make sure the model is independence of mesh. The mesh was refined in the vicinity of the hole (under washers), while away from the hole, the mesh was made coarser. Mesh refinement of 30 x 30 were made on the notched regional area while 10 x 10 mesh on other regions. Shell planar was chosen within composite plate and 3D brick element used in bolt and washers. Far-left edge was held fixed and far-right edge was assigned with applied traction, this to simulate the plates was subjected to quasi-static tensile loading as tested experimentally. Aluminium plates are restrained in all degrees of freedom at left end of the model, while displacement of 3 mm is applied to the composite plate at the other end of the model as shown in Figure 2. The procedure used to model the bolt load was suggested by (ABAQUS CAE 6.10, SIMULIA Corp), whereby the bolt is pre-tensioned prior to the application of the far-field tensile load.

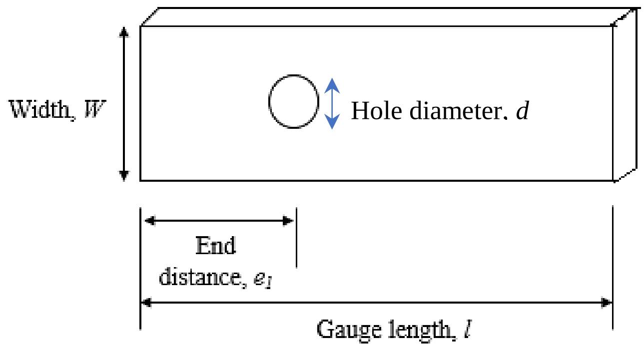

Figure 1. Geometries of composite plate used

Table 2. Geometry of the joining plates

Laminate	*e/d*	*W/d*	Nominal kenaf plate thickness (mm)	Nominal aluminium plate thickness (mm)
PX4	6	2,3,4,5	4	3
PQ4	4	2,3,4,5	4	3

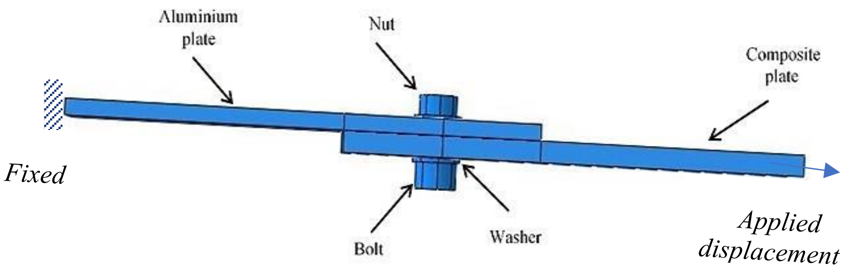

Figure 2. Components in single-lap joint implemented in FEA model

Table 3. Range of test parameters investigated for WKRP single lap joints tests [2]

Lay-ups sequences	Stacking	*e/d*	*W/d*	Hole size, *d* (mm)	Clamp-up torques (Nm)
PX4	$(0/90)_{2S}$	6	2,3,4,5	5	FT
PQ4	$(0/90/\pm45)_S$	4	2,3,4,5	5	FT

*FT=finger-tight

Table 4. Elastic and material properties of a single woven fabric kenaf ply composite plate investigated [2]

Elastic Properties				Material Properties				
E_1	E_2	G_{12}	v_{12}	X_t	X_c	Y_t	Y_c	S
1773	1773	177	0.07	40.39	40.39	40.39	40.39	4

*All units are *GPa* except Poisson's ratio is dimensionless.

LOAD-DISPLACEMENT PROFILES

The load-displacement profile of tested single-lap bolted joint woven fabric kenaf composite from post-processing results available from (ABAQUS CAE, SIMULIA Corp) is depicted in Figure 3. The curve showed that initially, the relationship of applied load and displacement is linear corresponds to elastic deformation within un-lapped region of composite plates. It is depicted that the composite coupons show a linear elastic behavior resemble to stresses are proportionately to plate displacement. As the slippage occurred, friction is taking over by individual plate which demonstrate by small plateau on load-displacement curve. This occurred when the bolt load applied has surpassed by the applied traction load. Then, the contact between bolt and hole induce large bearing stress until ultimate stress.

From Figure 3 below, it was indicated the initiation of matrix cracking and delamination were taken place at point (a), however, at this point the plate is still able to carry more applied loads until it reached the ultimate load at point (b). Point (b) showed the WKRP plate has reached the maximum load prior to catastrophic failures, this point associated to fiber fracture has exceeded the damage zone length [most researchers predicted the damage zone length is equivalent to a hole radius]. Beyond this point, WKRP plate unable to resist more load, ultimate load has reached and typically given as symbol P_{max} and the bearing stress at failure can be obtained by dividing ultimate load, P_{max} with a product of cross-sectional WKRP plate area [plate width, W x plate thickness, t]. At point (c), the plate performed catastrophic fracture. Finally, at point (d), the composite plate is fully separated, point (c) to (d) occurred in an infinitely small interval time. This load displacement-curve has good agreement with the experimental load-displacement curve as reported by Romayne [2] as showed in Figure 4.

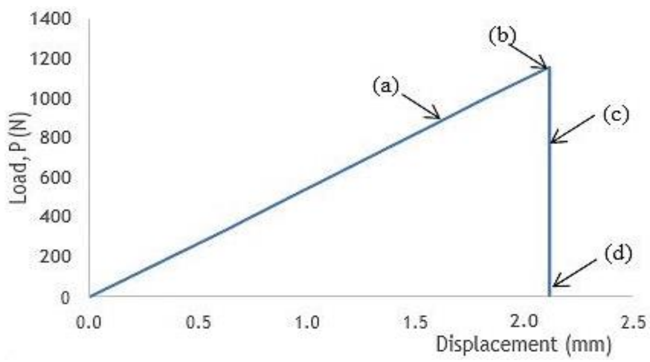

Figure 3. Load-displacement curve profile of PQ4 plate in *W/d* = 5, *e/d* = 4

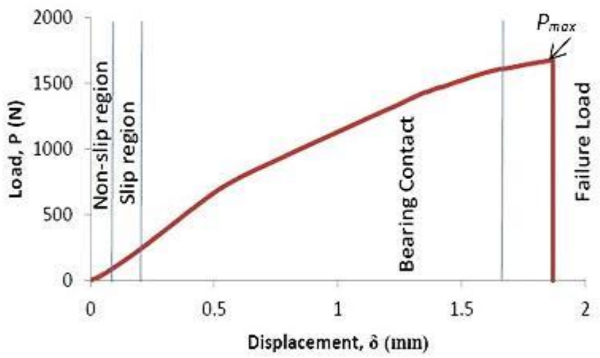

Figure 4. Load-displacement curve profile of PX4 plate in *W/d* = 5 (taken from [2])

Validation Works and Comparison with XFEM Modelling

Similar trends in strength predictions work with experimental datasets where bearing stress at failure in all testing lay-up series increased with *W/d* of joining plates increased. The strength prediction works of WKFRP single-lap bolted joints by using Hashin criterion framework were given in Table 5, validated against experimental datasets from Romanye [2]. It was clearly seen that less than 50% discrepancies were given between strength prediction results and experimental datasets. Overall, good agreements were found where most testing series gives discrepancy of less than 20%. Less good agreement was found in both PX4 and PQ4 of *W/d*=2, partially due to the washer penetrating to the composite plates is not captured properly in the current modeling work as observed experimentally [2].

Table 5. Bearing strength prediction of single lap bolted joint woven fabric kenaf

Designation	*W/d*	Experimental Bearing Strength (N/mm^2)	Prediction using Hashin Criterion (N/mm^2)	Error (%)	Prediction using XFEM (N/mm^2)	Error (%)
	2	38 (N)	57	50	51	33
PX4	3	65 (N)	81	25	82	26
$(0/90)_{2s}$	4	83 (N-B)	93	13	99	21
	5	102 (N-B)	103	2	113	11
	2	30 (N)	38	27	43	35
PQ4	3	53 (N)	72	26	75	34
$(0/90/\pm45)_s$	4	79 (N-B)	95	16	107	31
	5	97 (N-B)	116	20	120	27

*N = net-tension mode
N-B = combination net-tension and bearing failure mode

The discrepancies of bearing stress at failure between the prediction works and experimental datasets may cause by several factors. Although the agreement is acceptable (mostly within 20%), however there were several modelling assumptions made in the modelling framework. Unavailability of kenaf ply properties in the literatures (to the lesser extent on woven fabric kenaf composites), therefore these properties are regarded as predictive values. Nevertheless, woven fabric kenaf ply properties are independently measured by crude estimation from experimental dataset from one-ply WKRP plates (given as PX1) from Romanye [2] testing series. Bear in mind that Hashin formulation input was taken as ply properties (in this case, a ply of woven fabric kenaf layer is implemented). The bearing stress at failure provides better predictions if the material properties of composite materials were measured independently with good validation with other findings.

XFEM formulation is no longer suitable for bearing failures, nevertheless Hashin formulation is more realistic material model in modelling bearing failure as it focused on micro-damage event-based ply-by-ply basis. From Romanye work, testing series of WKRP plates with $W/d \leq 4$ demonstrated combination of net-tension and bearing failures in both lay-up types. Table 5 showed the bearing strength prediction using XFEM formulation. Better predictions in WKRP plates that demonstrates combination of net- tension and bearing failure, partly because Hashin formulation able to capture ply-by-ply failure which is bearing failure nature due to fiber kinking and matrix compression beneath the bolt shank.

Generally, XFEM formulation used [2] measured “smeared-out” plate properties in their strength prediction works. Material properties such as fracture energy and un-notched strength were measured independently by small-scale experimental set-up tested as a plate thickness. On the contrary, Hashin formulation used in-plane ply properties and current work used “predictive” one woven fabric kenaf ply value as material input in Hashin formulations.

Secondary bending usually occurred in single-lap joints due to unsymmetrical loading path, leading to lifting of plate edges and introduce additional tensile stresses in joining plates. Figure 5 showed the secondary bending in composite plate, it changes the stress gradient when the bolt tilting and reduce the strength of the composite plate.

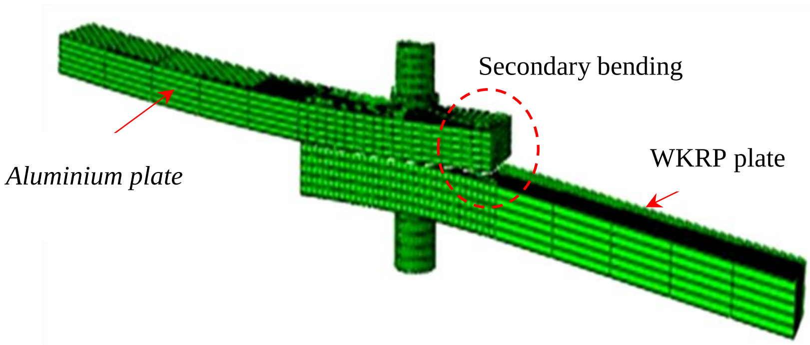

Figure 4. The effect of secondary bending in single-lap bolted joints

Romanye [2] observed that the failure started to crack at the washer edge which is tend to penetrate to composite surface as pressure from bolt tilting and give premature failure. The effect of secondary bending causes the crack started from the bottom plane through the plate thickness to the top plate as it bent across its plate thickness. It was predicted that Hashin model able to capture secondary bending better than XFEM formulation as bending behavior is better represented by local ply stress than global plate deformations. However, the study of secondary bending behavior is outside the scope of this paper. As the discrepancy between the predicted strength with the experimental strength is in good agreements, therefore the modelling technique can be adopted in future study of strength prediction work with improvements as suggested.

CONCLUSIONS

Bearing failure is related to damage beneath the bolt shank (resulting to fiber kinking and matrix compression) leading to ply-by-ply failure, the latter can be predicted well within net tension-bearing failure modes. XFEM formulation is based on stress concentration, therefore it provides good prediction in net- tension failures than bearing failures. Hashin formulation is based on ply-by-ply failure where it provides good prediction in WKRP plate in net-tension-bearing failures modes. Strength prediction from Hashin formulation showed a difference of less than ±25% in net-tension-bearing failure mode, but less good predictions (some lay-up showed discrepancies of 50%) in smaller *W/d* to give net-tension mode. Despite of good agreement, the effect of secondary bending should be investigated in a more proper manner.

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