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Static Strength of Adhesively-bonded Woven Fabric Kenaf Composite Plates

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Abstract. Natural fibers are potentially used as reinforcing materials and combined with epoxy resin as matrix system to form a superior specific strength (or stiffness) materials known as composite materials. The advantages of implementing natural fibers such as kenaf fibers are renewable, less hazardous during fabrication and handling process; and relatively cheap compared to synthetic fibers. The aim of current work is to conduct a parametric study on static strength of adhesively bonded woven fabric kenaf composite plates. Fabrication of composite panels were conducted using hand lay-up techniques, with variation of stacking sequence, over-lap length, joint types and lay-up types as identified in testing series. Quasi-static testing was carried out using mechanical testing following code of practice. Load-displacement profiles were analyzed to study its structural response prior to ultimate failures. It was found that cross-ply lay-up demonstrates better static strength compared to quasi-isotropic lay-up counterparts due to larger volume of 0^o plies exhibited in cross-ply lay-up. Consequently, larger overlap length gives better joining strength, as expected, however this promotes to weight penalty in the joining structure. Most samples showed failures within adhesive region known as cohesive failure modes, however, few sample demonstrated interface failure. Good correlations of parametric study were found and discussed in the respective section.

1. Introduction

Over the past few decades, there has been a growing interest among material engineers and scientists to develop high-performance engineering materials made from natural fibres to produce composite materials. Natural fibres are potentially used in manufacturing lightweight composites and coupled with lower costs (as compared to synthetics fibres) leading to excellent constituents in engineering materials production. Natural fibers composites also offers advantages such as low tool wear, low density, less hazardous, renewability and biodegradability. Kenaf fibres contain numerous elongated individual fibers which ranging within 6 - 30 μm in diameter and was found that the diameters of the natural fibres has irregular shape and unicircular, demonstrates inconsistency of fibre cross-section along the width. Most researchers assumes natural fibres cross-section as circular shape and average diameter across the fiber width was taken (Roa and Roa, 2007). Munawar *et al.* (2007) determine the cross sectional area of several natural fibres using SEM and obtained an average tensile strength and modulus of 357 MPa and 9.1 GPa, respectively.

CFRP and GFRP are widely used in various sectors as these materials have excellent specific strength to density compared to other engineering materials. Malaysia had limited applications on these materials in engineering sectors as these materials are regarded as imported goods. In civil engineering sector, these materials (particularly CFRP) are commonly used in repair and strengthening works but have limited applications due to high cost. Kenaf fiber is not a new material, it is used in furniture manufacturing industry and paper pulp productions. In Ninth Malaysian Plan (RMK9), government concentrates on biotechnology research to develop aggressive agricultural growth in Malaysia including massive kenaf plantations. The most challenging part in producing natural fiber composites is to combine and provides good bonding between hydrophilic natural fiber and hydrophobic polymer, but with proper treatment, a transparent and good bonding composite material can be obtained (Lee and Ahmad, 2016).

Composite structures components require reliable joining method to assemble composite parts to form a stable structure. Mechanically fastened joint is the most conventional method in structures assembly, but introduction of hole lead to stress concentration, weight penalty, etc. Supar and Ahmad (2016) has reported that complex fracture path were exhibited in different hole configurations of multi-holes GFRP plates. His work were then expended to determine bearing strength at failure of hybrid bolted-bonded joints which were dependent upon various parameters such as applied bolt load, lay-up types, overlap length, and plate thickness (Lee and Ahmad, 2017). Bolted joints and hybrid joints leading to weight penalty and highly stress concentration at the notch tip that may reduce loading capacity of composite plates.

Alternatively, adhesive joint method can be opted but joining strength is largely dependent upon variables such as adhesives and adherends strength, adhesive thickness, overlap length etc. Among the drawback in implementing later method are it requires surface preparations, large peel stresses at far edge, etc. Joint type chosen (i.e., single-lap or double-lap joints) also attributes to different phenomenon in structures response. There is lacking of literatures reported to study the behaviour of any natural fiber composite material subjected to tensile loading. Experimental works were carried out to study static strength of adhesive joint in woven fabric kenaf plates of as a function of identified variables.

2. Experimental Set-Up

2.1 Fabrication of Composite Panels

Fabrication is conducted in the textile laboratory, Universiti Tun Hussein Onn Malaysia (UTHM). A mixture SP84 epoxy and SP76 hardener were used as matrix binder with a ratio of 2:1 respectively. Thin silicon was applied on the formwork to provide smooth surface of finishing plate. A layer of woven fabric kenaf fibre was laid on fabrication aluminium mould and epoxy matrix were poured and smeared carefully to remove the void and air from laid woven fabric layers. The process is then carefully repeated to overlaid woven fabric layers according to stacking sequence desired. Most thermoset systems have one fixed mixing ratio that must not be varied if the optimum cured properties need to be obtained. Then, the fabrication panels were allowed to compress under pressure in order to provide the uniform surface using hydraulic compression machine in 24 hours. The fabricated panels were sectioned with a slow cutting speed water-cooled diamond saw to produce required number of testing coupons. The coupons are numbered and labelled accordingly to the respective series using a designated code.

2.2 Testing Series and Mechanical Testing

There are two different woven fabric architecture types investigated in current study, two sets of plain weave cross-ply and quasi-isotropic KFRP respectively as given in Table 1. The nominal thickness of laminated one layer and two layer kenaf fabric is approximately 2.4 mm and 4.8 mm respectively.

Table 1. The requirement of the sample for the testing

Lay-up	Joint type	Overlap length	Adhesive thickness (mm)
$(0/90)_s$ $(0/90)_{2s}$	Single & Double Lap	10,20	0.2
(0/90/+45/-45) (0/90/+60/-60)	Single & Double Lap	10,20	0.2

Two types of joint types were investigated as shown in Figure 1, i.e., single-lap bonded joint and double-lap bonded joint. Testing coupon with overlap length of 10 mm and 20 mm has nominal gauge length of 145 mm and 150 mm respectively. The end-tab is provided to give better gripping with the testing machine to avoid any slipping during testing. Surface preparations at the end-tab are required by polishing the edge laminate with sandpaper to give good bonding with attached spacer.

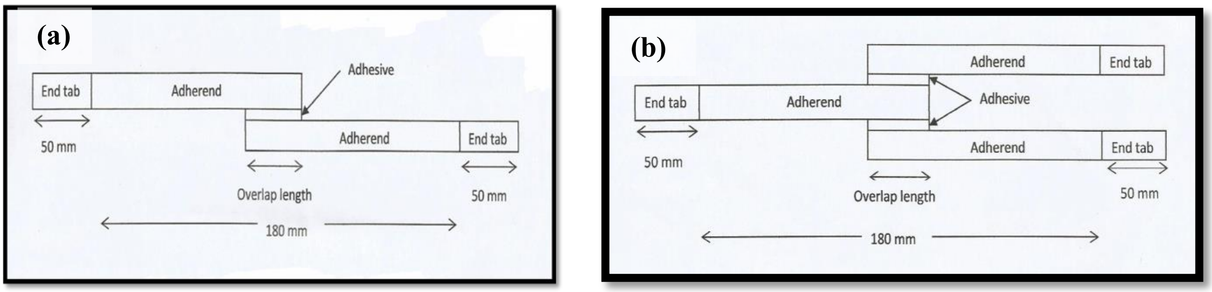

Figure 1. The geometry and dimension of (a) adhesively single-lap bonded joint (b) adhesively double-lap bonded joint.

Two-component of epoxy adhesive Araldite was coated over the lapped region with adhesive thickness of approximately 0.2 mm and allowed to cure for 3 hours at room temperature to reach maximum strength as recommended by the manufacturer. The surface area of the joining adherend is treated with sufficient roughness and a fillet is provided in order to reduce stress concentration due to exhibited peel stress at the plate edge as tensile load applied. The mechanical tests were carried out using Instron 1175 Universal Testing machine (UTM) machine 3369. A crosshead speed of 0.5 mm/min, and a load cell of 100 kN was used. Load and strain data were recorded at one-second intervals using a PC data-logging package from Instron. The ASTM standard D 3039 was followed wherever possible in determining the in-plane tensile properties of the laminates investigated. A minimum of three testing coupons for each joint configuration were tested and demonstrated good reproducibility.

3. Results and Discussions

3.1 Load-displacement Profiles

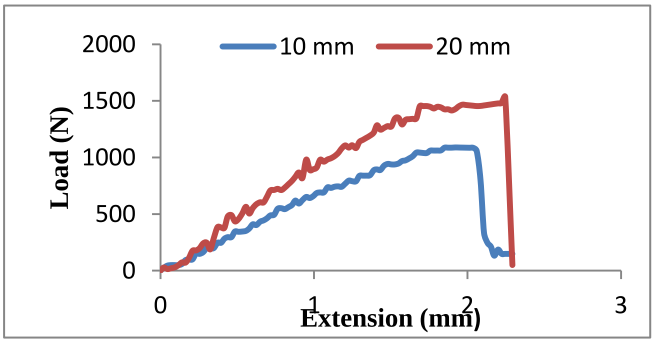

Figure.2. Load-displacement of 10 mm and 20 mm overlap length of single-lap joint of $(0/90)_{2s}$

From Figure 2 above, bonded joint demonstrates fairly linear behaviour from initial phase to ultimate failure and failed immediately as has it reached its maximum load. Woven fabric kenaf composite plate will not experienced any plastic deformation as subjected to tensile loading composite material and considered to fail in brittle manner. Prior to the ultimate failure, it was observed that the coupons were started to crack within the adhesive region. A screeching crack sound of brittle failure was heard prior to joint failure. It is observed that single-lap joint with 20 mm overlap length can withstand a

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larger peak load compared to 10 mm overlap length counterparts. As a failure are predominantly occurred within the adhesive layer, it is expected that larger overlap joint gives better joint strength. For the single-lap joint of 10 mm and 20 mm overlap, the failure mode occur is regarded as cohesive failure. Cohesion bond failures result in fracture of the adhesive and are characterised by the clear presence of adhesive material on the matching faces of both adherends. Failure is usually by shear, but peel stresses or a combination of shear and peel may also cause a cohesion failure.

3.2 Static strength of adhesive joints of all configurations

Table 2. The maximum load at failure at different variables

Lay-up	Maximum load at failure, P_{max}			
	Single-lap		Double-lap	
	10 mm overlap	20 mm overlap	10 mm overlap	20 mm overlap
$(0/90)_s$	977.48	1213.5	1231.25	1703.1
$(0/90)_{2s}$	1110.85	1607.85	1332.37	2167.8
(0/90/+45/-45)	787.53	956.8	1053.06	1225.25
(0/90/+60/-60)	912.62	1172.3	1186.19	1562.2

Table 2 shows the maximum loads at failure in all testing configurations as investigated in testing series. The largest peak load is shown in double-lap cross-ply $(0/90)_{2s}$ lay-up with 20 mm overlap length while the least value of joint load demonstrated by quasi-isotropic (0/90/+45/-45) lay-up with 10 mm overlap length. Even though double-lap joints leading to weight penalty, but some joint design requires more lapping joint especially in tension joint configurations.

3.1.1 Static strength of adhesive joints as a function of joint type. The single-lap joint is the most common joint used mainly due to its simplicity and efficiency. However, major problem associated to this joint type is the fact that the higher stress concentration (shear and peel) is concentrated at overlap far edge. On the other hand, stress concentration has been reduced in double-lap joints due to the applied load were transferred symmetrically to the loading path. Double-lap joint configuration of $(0/90)_{2s}$ has the largest strength while the least strength is single-lap joint of $(0/90)_s$. This is well understood as single-lap joints exhibits secondary bending that may decreased its carrying capacity compared with double-lap joint counterparts. Similar behaviours are also reported by Ahmad et al. (2014) on bolted joint study. Although double-lap joint exhibited lower peak load, however due to design constraint and client requirement, single-lap joint is unavoidable in structures assembly.

3.1.2 Static strength of adhesive joints as a function of overlap length. As loading were applied, plastic deformations in adherends took place when the strength of bonded joints is larger than proportional limit of adherend. In small overlapping length, bonded area is reduced. Joint is exposed to shear stresses induced as adherend deforms and leading to smaller bending stress. With increasing applied load, adhesive stresses can overcome the elastic limit values in adhesive/adherend interface. Therefore failure initiation and crack propagation occurred within overlapped region. By increasing overlap length, stresses through the overlapping region are decreased. As overlap length increased, joint strength increases due to larger bonding area. The larger overlap length will cause the crack propagation become slower and sustained more load than smaller overlap joints counterparts.

Although larger overlap length contributes to higher joint load, but it may lead to weight penalty and architectural unpleasant. Depending on design requirements, shorter overlap length is more favourable.

3.1.3 Static strength of adhesive joints as a function of lay-up types. It was apparently that adherend (composite) plate with larger volume of 0^o plies can bear higher joint load, as expected. This is because the tensile load is applied longitudinally with joining adherend and tensile stress is therefore captured by 0^o plies. Bear in mind that woven fabric layer comprised of equivalent two uni-directional layers, each woven fabric layer comprises of two sets or orthogonally unidirectional layer with crimping region. Equal numbers of woven fabric layer in composite plate showed that cross-ply lay-up has larger volume fraction of 0^o plies than quasi-isotropic lay-up counterparts. The fiber orientation has a prominent influence on the joint strength to resist applied load where arrangement of fiber direction (0^o) parallel to applied loading direction give optimum strength. When the surface fiber direction coincides with the loading direction, the strain on the surface of the laminate is limited due to the presence of the reinforcing fibers. From the experimental findings, it shows that the cross-ply lay-up can sustain higher load than equivalent quasi-isotropic lay-up. Since the quasi-isotropic lay-up has low volume fraction of 0^o ply in loading direction, it failed at relatively lower load.

Conclusions

Testing series and associated effects were investigated and careful measurements have been made. It was found that by increasing overlap length promotes to better joint strength. However, from material design perspective, large overlap length contributes to weight penalty and this reduce the advantages of applying composite material that offers excellent strength to density ratio. Adhesive joints configuration and lay-up types also gives significant contribution to the tensile load applied during mechanical testing. Secondary bending occurred in single-lap joint that alter the stress distribution profile and significantly reduce the single-lap joint strength compared to double-lap joint counterparts. This explains less good joint strength in single-lap joint configurations. Cross-ply lay-up demonstrated better joint strength than equivalent quasi-isotropic lay-up. It is suggested that due to higher volume fraction of 0^o plies in cross-ply lay-up offer better resistance to applied tensile load.

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