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Research paper

Strength and Interface Adhesion Properties of in-Plane Shear Loaded Thick Adhesive Joint

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Abstract

This paper addresses the quality of the interface bonded joints in layers of timber elements. The shear performance was studied to assess the suitability of adhesive to bond timber with different thickness of glueline and timber densities. Since there is absolute test method in establishing the shear strength of the surface bonds between layers timber elements, two test methods were used namely Thick Adherend Shear Test [TAST] and Lap Shear Test. The adhesived used is Sikadur-30 and timber used are Sesendok, Bintangor and Kempas with average densities 400-600kg/m3, 600-800kg/m3 and 800-1000kg/m3 respectively. Obtained results suggest that the interface stress distribution are related to the thicknesses of adhesive and densities of timber.

Keywords: *Shear strength; timber; adhesive*

1. Introduction

In Malaysia, a wide range of timber species is available in its tropical forest with approximately over than 3000 species all over the country. It has many excellent properties of timber species including high strength to weight ratio, it is easily worked, the price is usually competitive and it has comparatively good heat-insulation properties. On top of that, since Malaysian's timber species is a fully renewable building material which does not contribute to the greenhouse effect, it is widely used as structural material especially in modern industry. Over the years, several amount of timbers engineered material component have been developed. The product is produced using the same basic approach such as cutting solid wood into smaller pieces and putting them together by pressing and gluing them.

Adhesives have been associated with changing timber into a product to be used for timber structure connection, both for repairing and new building application. The availability for bonded timber and wood-based products is substantial in the market. An efficient method of making joint such as bonded in rods or dowels or bonded into pre-drilled holes in timber elements can be used to bond two or more timber component and other materials together for transferring structural loads between such elements.

The performance of bonded-in joints depends on the properties of the timber, rod and adhesive and the interfaces between the components. Structural adhesives and bonding have been reviewed by Kinloch[1] and Mays and Hutchinson[2]. Studies on bonded-in connections are still limited and the focus of these studies is mainly on the design of the connections with variation in rod type and size, glueline thickness, type of timber and type of connections [3-7].

The capacity of the bonded structure and its serviceability is basically influenced by the bond integrity. Therefore, the type of adhesive and adherend, cure cycle, bondline thickness and the environment are among of the factors that contribute to the bond integrity. For further adherence, timber works as a better substrate for adhesion. The adhesive and bond strength when bonding to timber will be controlled by the surface condition, as compared to any other substrate. As a matter of fact, timber is a cellular, natural organic material in which its porosity can influence its characteristic as a substrate. According to Frisch, [8], when two pieces of timber are glued together for structural purpose, the basic objective is to hold the two pieces in a fixed position, so that when stress is applied and exceeds the wood's strength, the failure is expected to occur in the timber rather than with adhesive.

In order to achieve this goal, both of the molecular attraction of the adhesive throughout its mass [cohesive forces] must be greater than the strength of the timber. Chemical interaction; hydrogen bonding and covalent bonds give major contribution to adhesion. For two timber adherence to be held together with maximum strength, the adhesive must flow onto and wet the wood before the adhesive reaches a rigid state and produce an intimate contact. An overview of strength theories for the design of adhesively bonded lap joints with composite adherends and wide range of diverse references review adhesive bonding of timber [1, 3, 9] is provided by [10].

The bond strength depends on how well the adhesive wet the adherends and the lower the viscosity, the more easily the adhesive will penetrate the adherend. Therefore, this study was conducted to to determine the strength and interface adhesion properties of in plane shear loaded thick adhesive joints of three timber species for each density [400-600kg/m3 Sesendok, 600-800kg/m3 Bintangor and 800-1000kg/m3 Kempas] bonded with high viscosity adhesive; Sikadur 30

2. Literature Review

2.1. Timber Characteristics on Adhesive Bond

Timber as a substrate acts as a good base for adhesion. When timbers are bond together with any other substrate, the bond strength and adhesion are influenced by the surface condition. The characteristic of the substrate will affect its porosity by its cellular and natural organic material [3]. However, the joint strength and adhesion are varied based on the methods on how the timber are being produced by means such as sawn, dried and stored. Present study defined bondline as the region between two solid adherends, which is subdivided into the adhesive bulk and two interface regions one in the vicinity of each adherend.
Figure 1 provides the definition of the components of a bondline. The thickness of the interface region is small but finite and related to the penetration of the adhesive into wood. Due to being exposed to compressive stresses during curing, the interface region is generally considered as being part of the adherend rather than being part of the adhesive bulk.

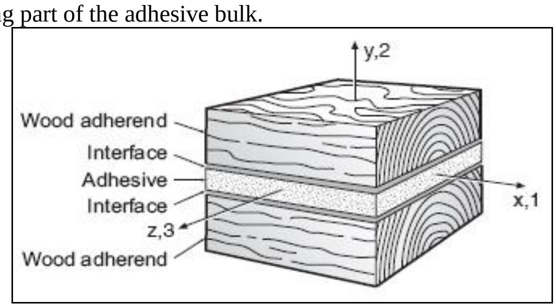


Fig. 1: Definition of Bondline Component

2.2. Mechanism of Adhesion

Adhesion is based on the attraction between the substances and it does not only occurs during adhesive joints applications but happens whenever solids are brought into contact as in coatings, paints and varnishes. The various types of intrinsic forces, which may operate across the adhesive/substrate interface, are commonly known as the mechanism of adhesion.
It is a crucial for these forces to be sufficiently strong and stable in order to ensure that the interface does not act as the weak link in the joint. A number of mechanical, physical, and chemical forces played a desired role to form the bonding of an adhesive to an object or a surface, which are these forces are overlap and influence one another and it is not possible to separate these forces from one another.
Based on the research conducted by Cherry and Thomson [11], they argue that the utmost cause of the environmental failure of some adhesive joint is the stresses induced at the interface as the polymeric adhesive solidifies and not the thermodynamic instability of the joints. Any flaws, which may be present at the interface due to the inadequate wetting of the substrate by the adhesive will led to this failure. It is necessary to consider the wetting condition and also the adhesion strength, In order to assess the ability of a given adhesive/substrate combination to meet the criteria of good and strong bonding. Wetting condition and the adhesion strength are the utmost matter to be put to the consideration, in order to assess the ability of a given adhesive/substrate combination to meet the criteria of good and strong bonding.
Wetting plays great importance for achieving good interaction and adhesion between two phases. Wetting appears to validate that it involves the interaction of a liquid with a solid. When the liquid makes contact with a surface, it is due by wetting. For this reason, when combining wood, which involve a solid with liquids such as paint, glue and lacquer, the liquid will perforate to the rough porous surface of the wood to different extents. These liquids will later on become solids by different mechanism, for example, drying or cross-linking.
Johnson *et al* [12] reported that wettability determined by the balance interaction between adhesive forces existing in liquids and solids; and cohesive forces existing in liquids. Generally, adhesive forces cause a liquid to drop while cohesive forces cause the drop to ball up. The angle between adhesive and cohesive forces is known as contact angle.
Adhesion is defined as joining of two surfaces where the stresses can be transmitted between the phases. Several different adhesion mechanisms have been proposed by [9]. Today the absorption theory has been received considerable attention to be the most powerful and it can be concluded that this theory requires intimate contact and the development of physical forces at the interface. As the result, this theory provides the basis for the formation of mechanical interlocking, inter diffusion and chemical bonding. The methodologies for adsorption theory and wetting are discussed, followed by the other mechanism.

2.3. Testing and Performance of Adhesive Bonding

An adhesive is expected to undergo the phase of holding materials together and transmit design loads from one adherend to another within a given service environment for the life of the structure. It is a must to analyse the engineering structure of the joints by identifying the stresses and strains under the given loading, and to foresee the probability of failure. However, to get an accurate analysis, it is important to take into account the distinction between the basic mechanical properties and the occurrence of high stress gradients in certain regions of the joints.
Quantification of the structural loads and stresses is premised as the strong emphasis. Hence, to make sure that the adhesive bonds will not deteriorate before they can meet the requirements of their design is recommended to run the joints performance analysis. There is considerable diversity in the style of methods to test bonding performance, particularly for bonded assemblies. In general, these performance tests are intent to predict how bonded joints are likely to perform in a specific loading mode [i.e shear, tensile, creep, fatigue, etc.] in an assembly at specific temperature and moisture conditions. Therefore, the knowledge of the basic engineering properties of the adhesive and also the rheological properties of curing and cured adhesive is essential in order to analyse the stresses in the adhesive.
The common measures such as strength, the nature of wood or adhesive failure and delamination have been utilised in the estimation on the potential performance of bonded wood joints. Okkonen and River, [13] have propounds the view that bond strength is preferably be greater than the wood while wood failure should have over more than 75% over the bonded area. Along similar line Okkonen and River, [13] claimed that the delamination of the joint through the wood material should be less than 5% for softwoods and 8% for hardwoods, under severe service conditions. These performance values demonstrate how the wood adherend, the adhesive bond and environmental exposure have interacted in response to loading. In the event of failure of an adhesive bonded joints can be interfacial [adhesive] and cohesive while the fracture of the adhesive [cohesive failure] will leave adhesive residues on both surfaces of the adherend as shown by Figure 2[a]. The cohesive fractured surfaces are complex where the crack propagates within the adhesive layer resulting to the presence voids and obvious defects such as cracks and impurities. Adhesive strength tests such as lap shear or peel tests can be utilised to monitor the cohesive and adhesive failure. It will be a situation where the adhesive remains on only one of the adherend surfaces, with the matching surface being free of adhesive; is known as an adhesive failure which is a further type interfacial failure shown in Figure 2[b].

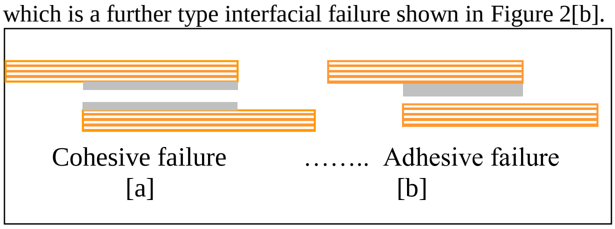


Fig. 2: Types of Failure in Adhesive Bonds [a] Cohesive Failure and [b] Adhesive Failure

Davis and Bond [14] claimed that the contamination will literally lead to these interfacial failures. The poor environmental durability is the cause of in-service adhesive failures. This will happen due to the insufficiency of the surface preparation used at the time when the bond was formed. An adhesive has the ability to influences the fracture behaviour of the joint by the following ways [13], If the adhesive is formulated, applied, or cured improperly, its cohesive strength and toughness may be lower than that of the wood and If the adhesive does not properly wet or penetrate the wood, the adhesion strength may be lower than the cohesive strength of the wood.

Based on the previous findings, it indicates that the type of failure will lead to the formation of bond strength and it is often more important than the measured shear strength of the bond. Additionally, a percentage of the area of the bonded joints is determined by the amount of wood that fails in a joint. [15] proclaimed that the higher the wood failure and deeper the fracture into the grain of the wood established the stronger and more durable the bond, especially with durable types of adhesive. Davis[3] simplified the typical failure modes in adhesive connections are as follows:

i. Adhesive failures
ii. Cohesive failures
iii. Delamination
iv. Failure in the connector – when using bonded-in connector
v. Failure in timber member itself – meaning the joint is at least as strong as the timber.

There is a rapidly growing literature on the factors affecting bond strength. It was classified that the main factor affecting the bond strength is the adhesive thickness. There are numerous references that lead to an extensive review of adhesive bonding [1, 3, 9]. Evidence for the factors affecting joint strength is borne out by the previous research and successfully outlined a number of factors are as below:

i. Joint design - Geometrical configuration bondline thickness
ii. Adherends - Mechanical properties, susceptibility to deterioration, linear coefficient of thermal expansion permeability.
iii. Adherend surface - Surface chemistry, surface topology and surface cleamliness
iv. Nature of adhesive- rheology – Viscosity, chemical composition, mechanical properties and linear coefficient of thermal expansion
v. Bonding conditions - temperature of substrates, humidity, cure time and pressure
vi. Internal stress - cure shrinkage, temperature, environmental conditions, nature of adherends and nature of adhesive
vii. Service/environmental conditions – stress, moisture and temperature
viii. Testing conditions, strain rate, cyclic frequency and temperature

3. Materials and methods

Following are material used for the current study

3.1. Adhesives

The adhesive used in this research is Sikadur-30. Sikadur-30 is a thixotropic adhesives which consisted of two part; Part A [white colour] and Part B [black colour] as shown in Figure 3. The adhesives were mixed with ratio 3:1 and turned to light grey colour after mixing. This adhesive was obtained from Sika Kimia Sdn Bhd which it has the speciality in producing products for bonding, sealing, damping, reinforcing and protecting in the building sector and the motor vehicle industry. Sikadur-30 is a commercial product uses for bonding structural reinforcement particularly in structural strengthening works including; Sika CarboDur plates to concrete, steel plates to concrete, brickwork and timber. It is designed for use at normal temperatures between +8°C and +35°C and can give best performance under permanent load due to its high creep resistance

Fig. 3: Sikadur-30 [Part A: White & Part B: Black]

3.2. Timber specimens

Three timber species were selected namely Kempas [*Koompassia malaccensis*], Bintangor [*Calophyllum spp.]* and Sesendok [*Endospermum malaccensis*]. These timbers were chosen from three different strength group with different range of density in order to see the effect of density on the bonding properties. The properties of those timber is shown in Table 1.

3.3. Specimens Preparation and Measurements

3.4. Thick Adherend Shear Test [TAST]

Each type of timber was cut into specific size to prepare for TAST. Two timber planks of size, 5mm x 20mm x 150 mm were laid side by side. Two Perspex shims of 1mm thickness were placed at the end of the beam for use as thickness guide. The adhesive was poured and spread slowly onto one of the plank. The other plank then was placed on top and clamped together to secure bonding. The wood composite was left to cure in room temperature for three days. After curing, the bonded section across the grain was cut approximately 2mm as a notch. The notch of the specimens was cut up to the glue line. These steps were repeated with different adhesive thickness of 2 mm and 3 mm. Figure 4 shows the schematic diagram of the spesimens.

3.5. Lap Shear Test [Single Lap Joint]

For Lap Shear Joint, two pieces of timber planks size; 5mm x 20mm x 80 mm from three different species were prepared. Spacers which are taken from the remainder timber planks are used as a guide to control bondline thickness of 1mm, 2mm and 3mm. The adhesive was applied on the overlap area of the specimens [Figure 5]. A load is put on the top in order to secure the bond between these two specimens and left

Table 1: Timber Properties

Standard Name of Species	Botanical Name	Family	Density at 19% Moisture Content [kg/m3]	Strength Group [SG]	Description
Kempas	Koompassia malaccensis	Leguminosae	910	SG 2	Brick-red or orange - red
Bintangor	Calopyhllum spp	Guthiferea	750	SG 5	Deep red, red brown, pink brown or orange
Sesendok	Endorpermum malaccensis	Euphorbiaceae	508	SG 7	Bright yellow turning to pale brown on exposure

Table 2: Characterisation of Failure Type of the Adhesive Bonds: TAST

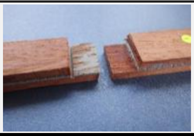
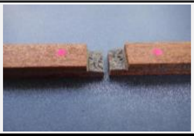
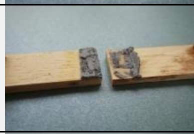
Timber Species	No. of Samples	Bondline Thickness [mm]	Example Picture of Failure Mode [Major Failure Mode]	Percentage of Failure Modes [%]		
				Adhesive Failure	Cohesive Failure	Wood Failure
Kempas	8	1		30	70	-
	8	2		40	50	10
	8	3		40	50	10
Bintangor	8	1		40	50	10
	8	2		40	40	20
	8	3		40	-	20
Sesendok	8	1		40	-	
	8	2		50	-	
	8	3		80	-	

Table 3: Characterisation of Failure Type of the Adhesive Bonds: Single Lap Joint

Timber Species	No. of Samples	Bondline Thickness [mm]	Example Picture of Failure Mode [Major Failure Mode]	Percentage of Failure Modes [%]		
				Adhesive Failure	Cohesive Failure	Wood Failure
Kempas	7	1		90	-	10
	8	2		100	-	-
	9	3		90	-	10
Bintagor	9	1		50	-	50

	8	2		50	-	50
	8	3		90	-	10
Sesendok	9	1		30	70	-
	8	2		10	90	-
	8	3		100	-	-

to cure at room temperature for seven days. These steps were repeated with different adhesive thickness of 2 mm and 3 mm.

3.6. Testing Method

Both test were conducted according to same standard which is BS EN 205:2003. A tensile force was applied for TAST and Lap Shear Test using a tensile testing machine equipped with 50kN load cell at a crosshead rate of 1.0 mm/min. The maximum force is recorded and type of joint failure was identified.

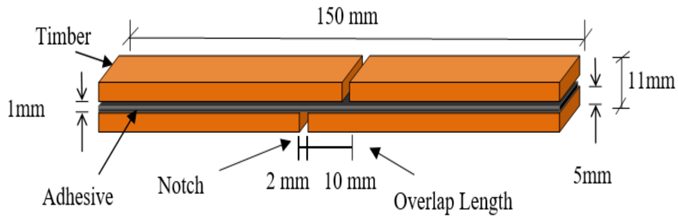


Fig. 4: Schematic Diagram for Thick Adherend Shear Test

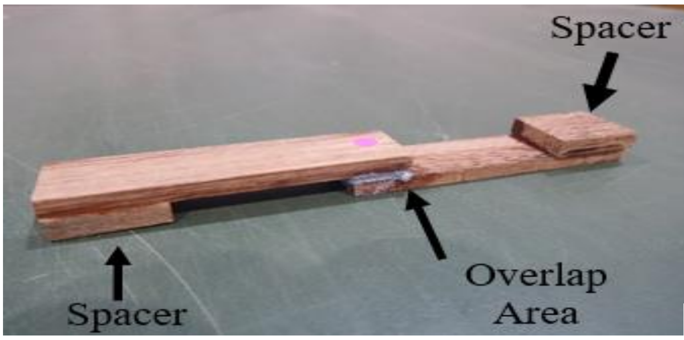


Fig. 5: The specimen for Lap Shear Test

4. Results and Discussion

4.1. Thick Adherend Shear Test Results

Shear Strength for the Thick Loaded Adhesive Joint.

Thick Adherend Shear Test method is applied to determine the load displacement properties of an adhesive in shear and to establish the proportional-limit of the shear stress and the mode of failure. Based on Load versus Deflection graph displayed in Figure 6, the value of the ultimate load will be used to calculate compressive strength of the specimen as mentioned in BS EN 14869-2:2011. Generally, the entire graph shows [Figure 6] a ductile behaviour as the specimens did not fail abruptly once it reached the maximum load.

For Kempas species with bondline thickness of 1mm, the beginning of the graph illustrates the displacement is directly proportional to the load. As force increased, the specimens reached its elastic limit of stability until it arrives to the point of maximum load. At this point, the material begins to yield and fracture.Through this experiment, it depicts that, bondline thickness of 1mm experienced very little plastic deformation as compared to 2mm and 3mm thick [for Kempas]. For these two thicknesses, once it reached its ultimate strength, a longer range of plastic deformation takes place before it fractures which signifies a cohesive failure mode.

Meanwhile for Bintangor, the test result is doubtful and ambiguous as the shear strength for each different thickness are almost the same. For Sesendok, the adhesive bondline thickness of 1mm has the maximum peak load which is 1595N. The elastic limit of the adhesive for this bondline is much larger as compared to 2mm and 3mm as can be seen in Figure 6. It shows that deformation occurs much longer before it reached the peak load or maximum shear stress until it drastically drop to zero. It can be seen from graph [Figure 6], Sesendok has the largest apparent shear strength out of the other two species, meanwhile Kempas 3mm bondline thickness being the least strongest according to the result from this test.

Overall, for all specimens the extensive plastic deformation takes place before fracture. This behaviour explains on the major failures mechanism that occurs in most of the specimens. Most of these specimens failed at the adhesive itself and adherend where its relate to the result of shear strength for each type of timber with different adhesive thickness [Figure 7].

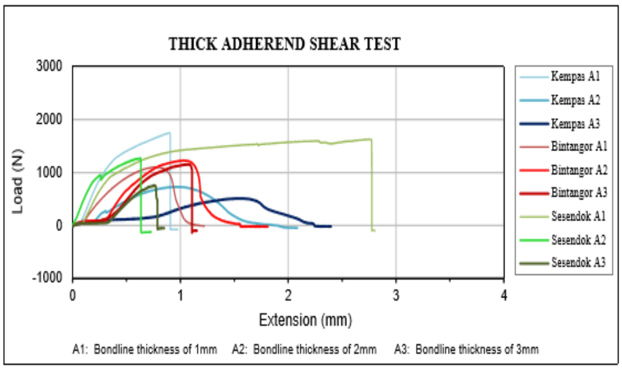


Fig. 6: Load vs Displacement Curve for All Type of Timber Specimens and Adhesive Thickness. The Thicker Line Represent the Thickest Bondline

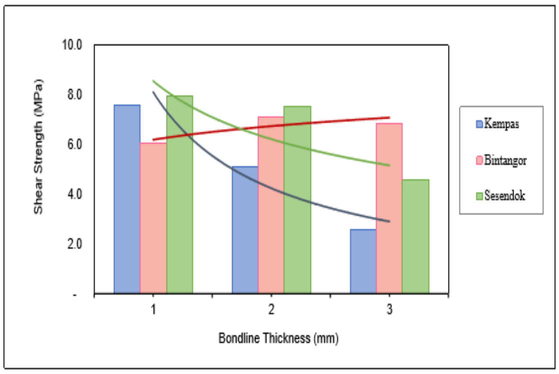


Fig. 7: Influence of Bondline Thickness on Shear Strength of Different Timber Species

The average shear strength, τ were calculated using Equation 1;

$$\tau = P/bL \qquad [1]$$

Where τ the shear stress [N/mm2], P is the force applied [Newton, N], L is overlap length [mm] and b is the specimen width [mm]. The specification for bL is the cross-sectional area of material with area parallel to the applied force vector [mm2]. Based on Figure 7, generally it can be shown that the curve performance strength for Kempas and Sesendok bondline thickness drop gradually from 1mm to 3mm except for Bintangor specimens. The curve pattern of the average shear strength increased slightly from 6.07MPa at 1mm bondline to 7.13MPa at 2mm bondline thickness until to a point where it remain constant in average

According to Wake [16] has found out an argument in favour of the weakness of thicker joints based on his previous study. This happens due to the stresses that built into the joints by the contraction of the adhesive on setting. Moreover, this also happen when there are differences in contraction between the adhesive and adherend after curing at an elevated temperature. These circumstances suggest the linear relationship between strength and thickness. Additionally, obtained from the curve performances strength result between the specimens, that behaviour of bond strength is highly influenced by the various different thickness of the adhesive. In the previous research, it is stated that lower density timber has higher bond strength compared to higher density timber [Ahmad et al, 2013]. In regards to the relationship between wood density and its shear strength show in the graph, lower wood density consists of higher bond strength. However this does not apply to Bintangor with bondline thickness 1mm and 3mm. This may be caused by errors during sample preparation, spreading of the adhesive and pressure during bond assembly. A study conducted by Custodio et el. [17], also explained that the damaged wood cells due to improper machining might lead to compression wood damage. Moreover, it is discovered from this study that the cutting of the notch for the specimens might not penetrate enough into the bond-line of the joint but remain in the adhesive. This can cause the test to fail mostly in wood.

4.2. Characteristic Failure

For each specimen, the type of failure was identified and recorded throughout the test. Table 2 summarize the data analysis for failure mode occur during the test for each species with different adhesive thickness.

For Kempas, it appears that 1mm adhesive thickness specimens tend to fail mainly in adhesive failure. In fact, this failure mode is also represented in all three bondline thickness. However, for bondline thickness of 2mm and 3mm, the connection bond between wood surface and adhesive appears to be strong and failure occurs mostly in cohesion. It is identified that cohesive failure primarily occurs in bonded joints for Kempas specimens. Hence, it shows that the strength of adhesive is weaker than the adhesion bond to the adjacent joint surfaces.

Meanwhile, it implies that cohesive failure appears to be the highest type of failure for Bintangor species. For 2mm bondline thickness, the test specimens fail partly in cohesive and wood failure which is 40% for each failure and the remaining 20% is the wood failure. 3mm of bondline thickness on the other hand only indicates a small percentage of wood failure which is 20% while the remaining of 80% refers to adhesive failure. Hence, Bintangor 3mm is most likely to fail in adhesive failure while 1mm and 2mm of bondline thickness tend to fail more in the material.

For Sesendok, the failure mode have a bit differents from the other two species. From the observation made, the mechanical interlocking of adhesive and wood cells is more obvious for bondline thickness of 1mm. According to Pizzi [8], in order for the intermolecular forces of attraction between adhesive and timber to become more effective, the molecules of the adhesive must diffuse over and into each surface to make contact with the molecular structure. Hence, this explains the high percentage of wood failure mode of 60% for 1mm bondline thickness. The similarity occur for 2mm bondline thickness where it shows almost 50% of wood failure but bondline thickness 3mm shows that only 20% of the specimens fail in wood. In general, the specimens fail in wood failure and adhesive failure.

4.3. Lap Shear Test Results

4.4. Shear Strength and Characteristic Failure for the Lap Shear Test; Single Lap Joint.

Single lap joint test method is one of the commonly occurring test to determine the shear strength in practice. Figure 8 presents the load versus displacement for all type of timber specimens and adhesive thickness used. The graph pattern for most of the sample shows that the specimens dropped steeply after it reached its ultimate load and raptured.

The strength for Bintangor SG5 and Kempas SG2 with 1mm adhesive are significantly higher than the rest of the specimens. The mode of failure for most of the samples in this test mainly occur in adhesive failure except for Bintangor SG5 and Sesendok SG7 with 1mm bondline thickness. An adhesive failure is identified by a joint failure at the adhesive interface. Meanwhile, Bintangor SG5 failed largely in wood failure while cohesive failure occurs in Sesendok SG7.

Figure 9 shows the result of the bondline thickness which represents the average shear strength for three species. These average of shear strength value were also determine from the Equation 1. It is clear that as the bondline thickness increase, the shear strength of the adhesive decreases gradually. According to Adams et al. [18] increasing the adhesive thickness and adherend stiffness, or decreasing the overlap length and shear modulus of adhesive, it will decrease the shear stress capacity in the adhesive so providing a stronger bonding joint. Bryant and Dukes [19] have performed a study to measure the strength of joints. Based on this study, they discovered that thinner joint has a stronger bond.

Meanwhile, referring on the graph [see Figure 9], the relationship between shear strength and density of the timber turn out to be doubtful and ambiguous especially Sesendok. The loss of joint strength may be affected by the moisture content and surface preparation of the wood samples prior to gluing. It is determined that the percentage of moisture content in Sesendok specimens is 12.04%. As mentioned by Vick [20] there are several factors that can impact the bond formation including particularly density, porosity, moisture content and dimensional stability, in fact, the surface properties of wood adherends also effect the bond formation. But the relationship between the bond quality of adhesive in Kempas and Bintangor shows an influence of the density. This relationship can be supported with the study conducted by Widsten et al. [21] to identify the impact of various factors in adhesive bond. The study was conducted by performing the tensile strength of cross lap joints. Based on the study, they found out that density contributes highly to the quality of glue joints of the species. Hence, high-density wood have a weaker adhesive bond.

Goland and Reissner[22] put the effect of the bending moment factor applied to the joint in addition to the adherend, at the end of the overlap in plane load. This can cause the adherend to bend and rotate alters the direction of the load

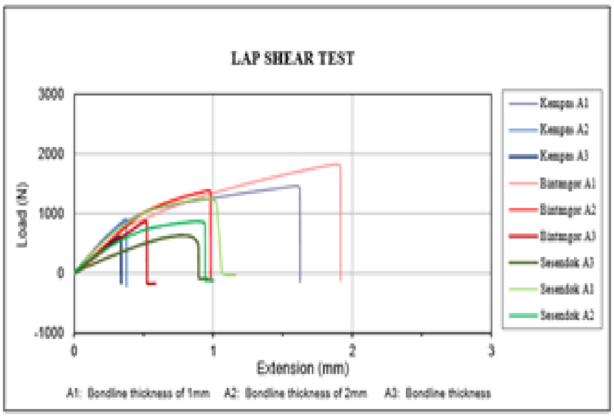


Fig. 8: Load - Displacement Curve for All Type of Timber Specimens and Adhesive Thickness. The Thicker Line Represent the Thickest Bondline

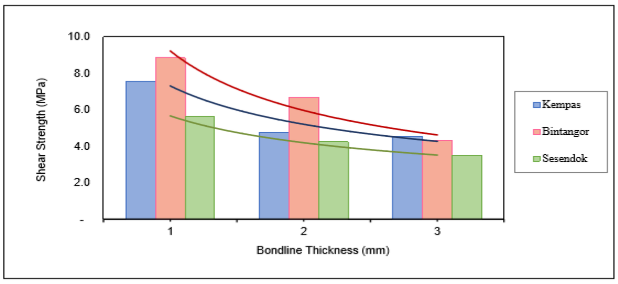


Fig 9: Influence of Bondline Thickness on Shear Strength of Different Timber Species

4.5. Failure Characteristics

Adhesion failures are categorised by the absence of adhesive on one of the bonding surfaces. Failure occurs along the interface between the adhesive layer and the adherends and is due to the impact on the chemical bonds and the ability of the adhesive to penetrate into the wood substrate. For Kempas species, most of the failures occurred in the substrates while the adhesive remained undamaged. Wood with high density as this Kempas with density range between 850 - 1000 kg/m^3 consist of a thicker cell walls. This finding was found similar to Frihart and Hunt[23] which commented that denser woods tend to be stronger with thicker cell walls and smaller cell lumens.

Hence, the ability of the adhesive to penetrate into the substrate will negatively impact the bond strength. Table 3 conclude that most Kempas specimens failed in adhesive failure.

For Bintangor, two categories of failure were found, the percentage of wood failure for a single lap joint test appear mainly between adhesive thicknesses of 1mm to 2mm. The bond strength of adhesive and cohesive is great enough that the cohesive strength of the substrate fails before the adhesive bond. In woods, this occurs when the adherend yields. However, as for 3mm test specimens, the specimens seem to fail generally in adhesive failure.

It can be seen in Table 3, the level of wood failure found are more than 50% of at the adherend for 1mm and 2mm adhesive thickness. The bonding joint indicates that the adhesive are stronger than the wood. On the other hand, for 3mm adhesive thickness, the obvious adhesive shows that the specimens fail mostly adhesive and only a small amount of wood fibers spotted at the surface of the adhesive. In the same Table [Table 3], it can be seen that the typical failure surface of joints that mostly failed cohesively in the middle of the adhesive for 1mm bondline thickness. Meanwhile in 2mm and 3mm bondline thickness the mode of failure indicates cohesive failure in the adhesive but close to the inter facially between the adhesive and one of the adherends. As simplified for Sesendok, there is no occurrence of wood failure in this test whereas the result shows 70% cohesive failure in 2 mm adhesive, 90% for 3 mm thickness and a 100% of adhesive failure for 3mm bondline thickness. The adhesive bond are likely to fail in adhesive failure in 3 mm specimens where it is clearly show that the adhesive separate from the substrate.

5. Conclusion

5.1. Thick Adherend Shear Test [TAST]

The result show that the highest ultimate shear strength value obtained from Sesendok SG7 with 1 mm adhesive thickness for timber of the lowest density.

The strength value of Bintangor SG5 reveal a lack of relationship between timber density and the joint strength. But Sesendok SG7 with the lowest density has higher bond strength compare to Kempas SG2.

The same timber species were compared in bond strength value with different thickness, no linear relation was perceived in Bintagor SG5 in the range of 1 mm to 3mm bondline thickness. However, it can be seen that the strength for Kempas SG2 and Sesendok SG7 decrease as the bondline thickness increases.

The type of failure of the specimens appears too failed in a combination of modes. Higher thickness tends to fail in between interface of adherend and adhesive, while lower thickness fails in wood or adhesive itself. On the other hand, Kempas showed a variation of mode failures over the different range of bondline thicknesses.

5.2. Lap Shear Test

The test results show that the influence on low density of Sesendok SG7 do not seems to strengthen the bonded joints. It turn out that the optimum shear strength was identified in Bintangor SG5 specimens with 1 mm adhesive thickness.

A small different of shear strength between Kempas SG2 and Bintangor SGS in density was noted between this two species, that joint strength increases as the density decrease.

Obtained from this test result proved that the bondline thickness affect directly on the joint strength. It is clear that as the bondline thickness increase the shear strength of the adhesive decreases gradually.

As for failure characteristics, it appears that the specimens for the test tend to fail mainly in adhesive failure. But for Bintangor SG5 specimens bonded with 1 mm and 2 mm thickness fail mostly in wood failure.

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References

[1] Kinloch AJ. Fracture behaviour of polymers: Springer Science & Business Media; 2013.
[2] Mays GC, Hutchinson AR. Adhesives in civil engineering: Cambridge University Press; 2005.
[3] Davis G. The performance of adhesive systems for structural timbers. International Journal of Adhesion and Adhesives. 1997;17[3]:247-55.
[4] Broughton J, Hutchinson A. Adhesive systems for structural connections in timber. International journal of adhesion and adhesives. 2001;21[3]:177-86.
[5] Azlan HM, Ahmad Z, Ibrahim A, Hassan R, editors. Behaviour of kempas timber beam strengthened with CFRP and steel plates under bending. Business Engineering and Industrial Applications Colloquium [BEIAC], 2013 IEEE; 2013: IEEE.

[6] Ahmad Z, Ansell M, Smedley D. Fracture toughness of thixotropic and room temperature cured epoxy-based adhesives for in situ timber bonding. International Journal of Adhesion and Adhesives. 2010;30[7]:539-49.

[7] Azlan HM, Ahmad Z, Hassan R, Jamadin A, editors. Shear strength of steel and CFRP to timber interface. Humanities, Science and Engineering Research [SHUSER], 2012 IEEE Symposium on; 2012: IEEE.

[8] Frisch K, Rumao L, Pizzi A. Wood Adhesives: Chemistry and Technology. NY: Marcel Dekker. 1983:287-317.

[9] Schultz J, Nardin M, Pizzi A, Mittal K. Handbook of adhesive technology. Marcel Decker, New York. 1994.

[10] Carpenter WC. A comparison of numerous lap joint theories for adhesively bonded joints. The Journal of Adhesion. 1991;35[1]:55-73.

[11] Cherry B, Thomson K. Crack Tip Processes and the Adhesive-Cohesive Transition in the Environmental Fracture of Adhesive Joints. International Journal of Polymeric Materials. 1980;8[1]:13-24.

[12] Johnson R, Dettre RH. Wetting of low-energy surfaces: Marcel Dekker: New York; 1993.

[13] River BH, Okkonen EA. Delamination of edge-glued wood panels: Moisture effects: US Dept. of Agriculture, Forest Service, Forest Products Laboratory; 1991.

[14] Davis M, Bond D. Principles and practices of adhesive bonded structural joints and repairs. International journal of adhesion and adhesives. 1999;19[2-3]:91-105.

[15] Handbook W. Wood engineering material. Gen./twch. Rep. FPF-GTR-113, Madison, WI, USA, 1999.

[16] Wake WC. Adhesion and the Formulation of Adhesives. 1976.

[17] Custódio J, Broughton J, Cruz H. A review of factors influencing the durability of structural bonded timber joints. International Journal of Adhesion and Adhesives. 2009;29[2]:173-85.

[18] Adams RD, Comyn J, Wake WC. Structural adhesive joints in engineering: Springer Science & Business Media; 1997.

[19] Bryant R, Dukes W. The measurement of the shear strength of adhesive joints in torsion. British Journal of Applied Physics. 1965;16[1]:101.

[20] Vick CB. Adhesive bonding of wood materials. Wood handbook—wood as an engineering material. Gen Tech Rep FPL–GTR–113 Madison, WI: USDepartment of Agriculture, Forest Service Forest Products Laboratory. 1999.

[21] Widsten P, Gutowski VS, Li S, Cerra T, Molenaar S, Spicer M. Factors influencing timber gluability with one-part polyurethanes–Studied with nine Australian timber species. Holzforschung. 2006;60[4]:423-8.

[22] Goland M. The stresses in cemented joints. J Applied Mechanics, Trans ASME. 1944;66:A-17-A-27.

[23] Frihart CR, Hunt CG. Adhesives with wood materials: bond formation and performance. 2010.