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Tensile and shear strength of four species of bamboo in Malaysia

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Abstract. As one of the fastest growing plants on earth, bamboo has a lot of species that range in size from a few centimeters to many meters tall. Bamboo is a unique plant where it can reach their full height up to 30m in a period of 2 to 4 months. Even though bamboo has been used traditionally as a construction material for thousands of years, there are not many studies about the mechanical properties of the bamboo itself. Thus, this paper presents an investigation on tensile and shear strength of four species treated bamboos that are available in Malaysia, which include *Bambusa Vulgaris*, *Dendrocalamus Asper*, *Gigantochloa Scortechinii* and *Shizostachyum Grande*. All the test was conducted according to the International Standard Organization (ISO-22157-2004). From the test result, *Bambusa Vulgaris* and *Dendrocalamus Asper* possess high tensile strength, meanwhile, *Gigantochloa Scortechini*i shows the highest value of shear strength compared with other species. Moreover, the test result also shows that *Shizostachyum Grande* possesses the lowest tensile and shear strength. Thus, with the available data on bamboo properties, structural engineers should take the advantages of bamboo to be used as a construction material in modern design buildings.

1. Introduction

At this present time, developing environmentally friendly with low-cost construction materials is a challenging issue especially for the rural area. Conventional construction material such as concrete, steel and timber are usually associated with high-cost materials due to the production and processing method. Construction industry starts to move to green construction especially in the rural area in which timber is needed as there are limited facilities to transport other conventional material such as concrete and steel. Even though timber is known to have environmentally compatibility, reusability and simplicity in fabrication, the main problem with timber is availability and cost of the material as the source of timber is getting low. Timber possesses intermediate strength and less flexible due to its grains pattern and natural defect. Other than that, timber required longer period up to 10 years before can achieve the strength and be harvested compared with bamboo which needs less period, about 3 years to achieve required strength. Non matured timber usually will cause the reduction of strength properties. Consequently, replacing it with bamboo in areas where the strength is the primary consideration is a practical alternative. Compared with all conventional construction material such as timber and steel, bamboo also exhibits excellent mechanical properties. As a natural and fibrous material, there is a just small study on the anatomical and physical characteristic as well as mechanical properties of bamboo that cause the utilization of bamboo being neglected especially in Malaysia. As being used traditionally since the ancient time, bamboo is generally known to have flexible, lightweight, tough and low-cost material. As well as timber and other construction materials, bamboo also required extensive testing on specific age in order to determine the strength achieved by the bamboo itself. Furthermore, even though there is small research on the mechanical properties such as compressive, tensile, shear for various species of bamboo all over the world, there is no specific design data on mechanical properties and design rules of bamboo. So, there is need to conduct the research on bamboo and prove that the bamboo will offer great potential as an alternative to other conventional construction materials and practices.

1.1. Bamboo Culm
Basically, the bamboo structure consists of culms with nodes, internode and diaphragm. In nodes, there is solid diaphragm inside the culm that separating the hollow internode region along its height of the culm. On the outside of bamboo culm, this nodes can be identified by a ring around the culm. The characteristics of bamboo are different with other plants as it has many nodes in one full culm which acts as axial crack arrester due to entangled fibres direction in nodes. The length of each internode depend on species but generally, the length of internodes increase from the base to the middle of the culm but decreasing when reaching the top [1]. Young bamboo usually protected by a series of the sheath which covered with very sharp tiny hairs. This sheath is very sharp enough to pierce human skin and depending on the species, this sheath also can cause skin irritation due to its toxicity. Bamboo is composed of unidirectional cellulosic fibres oriented parallel to the longitudinal axis that surrounded in lignin matrix. As shown in Figure 1, the density of the fibres increasing from the inner to the outer wall of the culm. Some species of bamboo show a natural capability use of bamboo to withstand overturning caused by wind while reducing gravity load due to the thickness of bamboo culm that large at the base and decrease along the height of the culm.

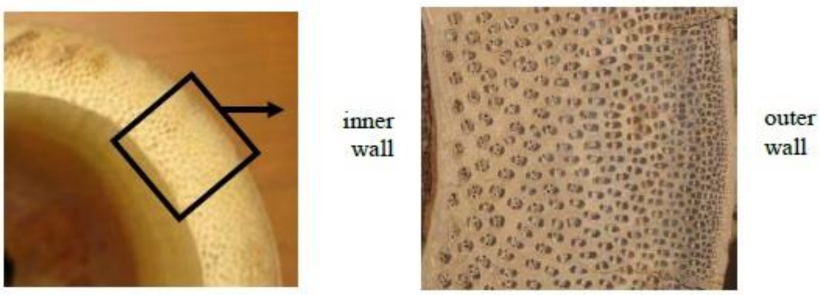


Figure 1. A functional gradation of cellulosic fibre [2].

The culm of bamboo provides structural support and conduit water and sap transportation when alive. Basically, the culm consists of approximately 50% parenchyma tissue, 40% cellulose fibre and 10% vessels [3]. Figure 2 shows the bamboo fibres (darker cells) capped around the conducting vessels and surround with parenchyma. Fibres and vessel are embedded in parenchyma tissue begin to harden over time. The fibres are very crucial to provide the strength of the bamboo culm and it grouped with vessels for sap and water transport in vascular bundle. This vascular bundle are less packed and large at the inner of the culm wall but densely packed and small at the outer wall of the culm.

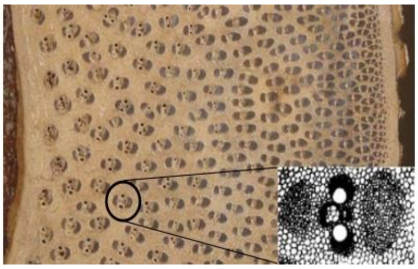


Figure 2. Bamboo vascular bundles [3].

Along the height of bamboo culm, the vessels size become smaller and the quantity also decrease. So the volume of the vessel is filled with fibres and this contributes to the addition strength and stiffness due to the reduction of wall thickness and diameter along the height of bamboo culm.

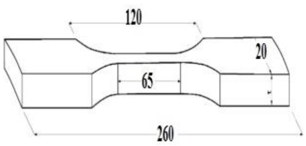
2. Materials and Methods

2.1. Preparation of the bamboo

Four species of bamboo are involved in tensile and shear test which known as Dendrocalamus Asper, Bambusa Vulgaris, Gigantochloa Scortechinii and Shizostchyum Grande. They were subsequently treated in order to increase their durability and ability against fungus attack. Combination of boric acid and borax in a ratio of 1:1.5 form an alkaline salt where this salt was obtained in ready mixed powder form. This powder was poured and mixed with water in the special rectangular tank and the bamboo was immersed into the tank for about 1 week before they were left to dry. A total of 36 specimens were prepared for tensile test and 36 specimens were prepared for shear test. All the specimens were cut to according to standards and the measurements were taken such as thickness and diameter. Based on the average wall thickness (t) and diameter (D) that measured and gross section dimensions, the value of the cross sectional area (A_{culm}) were determined.

2.2 Tensile Strength Test

The tensile strength test of specimens was conducted in accordance with ISO-22157-1 (2004) [4] procedure. The tensile strength test was carried out on adequately air-dried specimens in 1 months. The specimens were prepared in wedge-shaped as shown in Figure 3.



(a) Wedged-shaped test piece

(b) Real test specimens

c) Tensile test setup

Figure 3. Tensile strength test specimens.

The overall length of the test specimen was 260mm with a 20mm width of the specimens grip. The effective length of specimens was 65mm, 10mm width and the thickness was according to the thickness of the bamboo culms. The thin sides of specimens had been formed by using a chisel and smoothed by using sandpaper. Parameters such as width, the thickness at mid-span and the length of the specimens

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were measured and recorded. The measurement of width and thickness at mid-span were measured by using Vernier calliper. The purpose of this measurement was to determine the average cross-sectional area of the sample at mid-span. The universal testing machine was used for the tensile strength test. The specimens were placed on the tensile strength testing machine and both ends of the specimen were tightened on the provided grips flat. All the dimensions measured were key-in into the computer software such as sample name, width, thickness, lengths and loading rates. Pulling forces were applied at 0.05mm/sec at constant extent movement until maximum load achieved before the sample failed completely. All the data obtained were recorded through Bluehill software which is linked directly to the test machine.

The experiment was repeated for other samples within a set. Readings obtained for the top, middle and bottom part of the specimens were recorded and average reading for three sample each part were counted. In general, the tensile strength of bamboo specimens can be calculated by using the following Equation 1.

$$\sigma = \frac{P}{A} \tag{1}$$

Where,

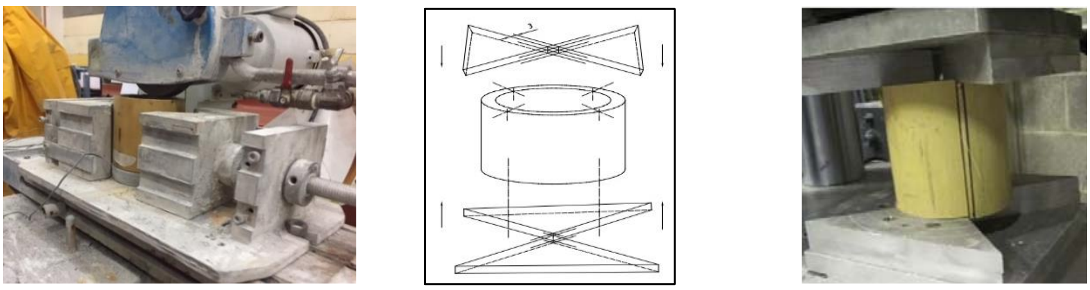
σ = Maximum tensile strength, in N/mm^2.

P = Maximum load at which the specimen fails, in N.

A = Cross-sectional area at the mid-span, in mm^2.

2.3. Shear Test

Shear test parallel to fibre was carried out by using the same machine that used for a compression test. The test also was carried out in accordance with ISO-22157-2 (2004) [5] procedure. The specimens were prepared same like a specimen for compression test where the length of the sample was equal to the outer diameter of the bamboo and the specimens were taken from the bottom part, middle part and the top part of the bamboo culm. Figure 4 shows the operational test set up for the shear test. The shear plate that had 3 mm distance between sides of the steel plates on top and bottom was used for safety precaution so that the shear area remained between the steel plates. Instead of steel plate, hardwood also can be used as stated in ISO-22157-1 (2004).



a) Grinding bamboo surface b) Shear plate for test set up c) Applied load to specimen

Figure 4. An operational test set up for the shear test.

All measurements such as the height, L, and the thickness, t, of the specimen were recorded at all four shear areas. The specimens were placed vertically in the centre of the movable head. The specimen also was centred with regard to the supporting and loading plate. The load was applied continuously at a constant rate of 0.01mm/s and the final reading of maximum load, F_{ult}, was recorded. Then, the ultimate shear strength was calculated using Equation 2.

$$\tau = \frac{F_{ult}}{\sum(t \times L)} \tag{2}$$

Where,

τ = Ultimate shear strength, in N/mm².

F_{ult} = Maximum load at which the specimen fails, in N.

$\sum(t \times L)$ = Sum of four product of t and L.

3. Results and Discussions

3.1. Tensile Strength

The overall experimental tensile strength results for the various species of bamboo can be referred to Table 1 while Figure 5 shows the average tensile strength for all bamboo species. The results show that Dendrocalamus Asper and Bambusa Vulgaris possesses the highest tensile strength among other species and followed by Gigantochloa Scotechinii and Shizostacyum Grande. Even though Dendrocalamus Asper and Bambusa Vulgaris showed higher tensile strength, there is the only small difference in strength between these two species. Considering the thickness of each specimen, Dendrocalamus Asper possesses more thickness, resulting in a large area of tested specimens compared with Bambusa Vulgaris in its natural form. Thus, Dendrocalamus Asper still show high tensile strength value.

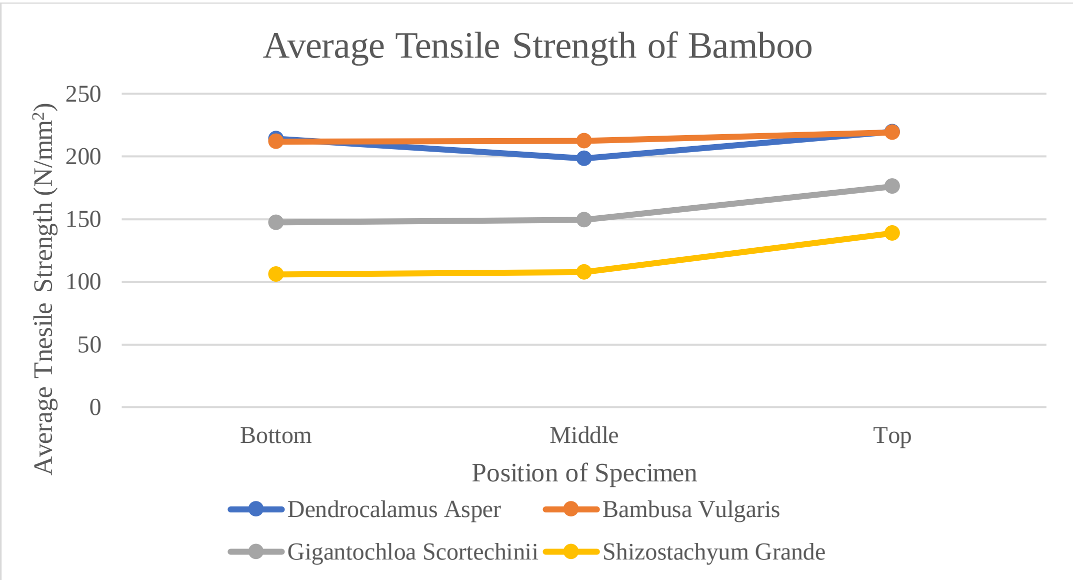


Figure 5. Average tensile strength of bamboo against the position of specimens.

It is also known that the tensile strength of the bamboo varied along the location of the specimen along the culm. The results obtained from this experiment show that the tensile strength generally increased along the culm height. The incremental trend of tensile strength values was clearly shown by Gigantochloa Scortechinii and Schizostachyum Grande. Even though Dendrocalamus Asper did not show a stable increment of tensile strength, the data still can be accepted because the specimen on top part gave higher value compared with the bottom part of the bamboo culm. The increase in tensile strength along the height of the culm for all species in this experiments is believed to be a function of a simple mechanism. Fibres material in the culm is basically constant or increase along the height of the culm [3] and the diameter and culm thickness decrease with the height, thus reducing the area over which the stress is determined. Since the tensile strength is primarily conveyed by the fibres, the apparent tensile strength of bamboo had increased. Thus, the fibres volume fraction increased along the height of the culm [1].

Table1. Tensile strength data of bamboo specimens.

Species	Part	Sample	Area (mm^2)	Max Load (N)	Tensile Strength (N/mm^2)	Average Tensile Strength (N/mm^2)
Dendrocalamus Asper	Top	DA 1A	96.35	25900	268.80	219.68
		DA 2A	94.63	17400	183.86	
		DA 3A	93.02	19200	206.39	
	Middle	DA 1T	99.45	27400	275.51	198.35
		DA 2T	98.47	18000	182.78	
		DA 3T	103.10	14100	136.75	
	Bottom	DA1B	122.54	28483	232.43	214.06
		DA 2B	112.32	21947	195.39	
		DA 3B	105.19	22546	214.33	
Bambusa Vulgaris	Top	BV 1A	56.10	12212	217.68	219.08
		BV 2A	56.56	11983	211.86	
		BV 3A	55.00	12523	227.69	
	Middle	BV 1T	61.48	13212	214.89	212.38
		BV 2T	60.90	13172	216.28	
		BV 3T	60.90	12543	205.96	
	Bottom	BV 1B	66.34	13424	202.35	211.76
		BV 2B	66.15	13824	208.97	
		BV 3B	65.92	14762	223.93	
Gigantochloa Scortechinii	Top	GS 1A	50.00	8842	176.84	175.98
		GS 2A	49.50	8744	176.64	
		GS 3A	49.50	8635	174.44	
	Middle	GS 1T	48.50	7042	145.19	149.29
		GS 2T	46.56	6924	148.71	
		GS 3T	47.04	7243	153.97	
	Bottom	GS 1B	54.06	7842	145.06	147.36
		GS 2B	52.52	8032	152.93	
		GS 3B	53.04	7643	144.09	
Shizotacyum Grande	Top	SG 1A	47.94	6292	131.24	138.72
		SG 2A	47.00	7323	155.80	
		SG 3A	48.36	6243	129.09	
	Middle	SG 1T	48.36	5273	109.03	107.83
		SG 2T	48.36	5231	108.16	
		SG 3T	48.36	5133	106.14	
	Bottom	SG 1B	49.82	4721	94.76	105.83
		SG 2B	49.82	4944	99.23	
		SG 3B	48.76	6021	123.48	

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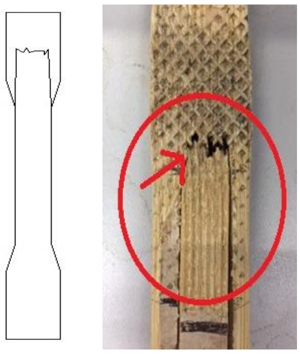
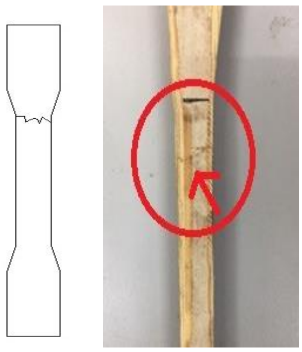
3.2. Mode of Tensile Failure

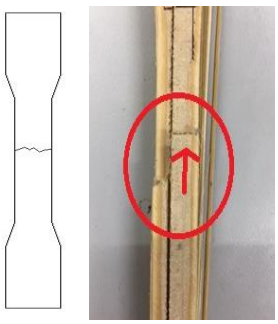
The bamboo tensile test specimens exhibited a few general categories of specimen failure as shown in Figure 6. Failure mode A shows specimen failed along the specimen grip length. Then, mode B involves failures at the interface of grip and gage length while mode C represents tensile rupture along the gage length of the specimen. Longitudinal splitting failure was identified through the gage length in modes D and E, where mode D was a single split and mode E known as ‘brooming’ failure which occurred to the entire of the cross section. As shown in schematically ways and by example in Figure 6, mode C, mode D, and mode E showed ‘good’ failures in way of being mostly unaffected by the gripping process of the testing machine. Meanwhile, failure mode D showed a single longitudinal splitting that resulted from uneven grip pressure and longitudinal bending of the specimen.



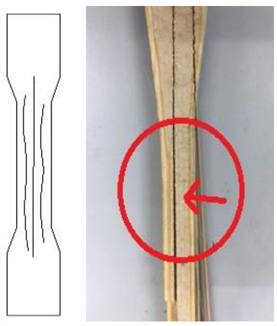
a) Mode A



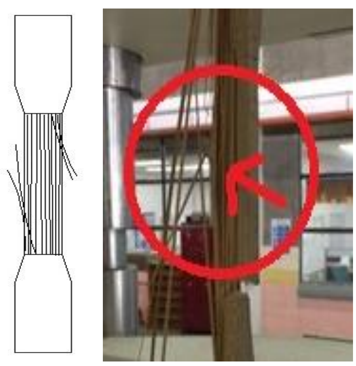
b) Mode B



c) Mode C



d) Mode D



e) Mode E

Figure 6. Failure modes of tensile specimens.

Uneven grip pressure occurred when the grip pressure applied to the grip area as the bamboo itself has varying material properties across the grip area and the apparent gripping pressure to that area may be uneven. Thus, it resulted in single longitudinal splitting associated with an area of greater grip pressure. Other than that, the longitudinal bending of the specimen occurred when the longitudinal shear was present as the specimen experienced flexure during the testing due to shape irregularities. During testing, it should be noted that many specimens experienced slip issues between the wedges grips of the machine and the grip length of the specimens. The slip occurred when there was not enough of gripping pressure to the grip area and cause the specimen to slip from the testing machine. This slip caused in the reduction of tensile strength value when compared with actual tensile strength value of the bamboo specimens. Therefore the slip was not considered as a failure and the testing was repeated until the slip issues were eliminated.

3.3. Shear Stress

Results of the shear test were shown in Table 2 and Figure 7 where the shear stress was calculated using Equation 2. From the shear strength test, Gigantochloa Scortechiniit possesses the highest shear stress and followed by Bambusa Vulgaris, Dendrocalamus Asper and Shizostachyum Grande. In this experiment, the value of ultimate shear stress was almost double from the value obtained from Abd. Latif (1990) [6] where the value ranged from 3.37 to 4.40 N/mm^2 for the same species (Bambusa Vulgaris) in green condition.

From Figure 7, the value of shear stress of bamboo increased along the height from the bottom to the top part of bamboo. The shear stress was correlated with moisture content and percentage of Sclerenchyma fibres that increased from bottom to top [7]. There is also a positive correlation between fibres thickness and shear where along the height, the amount and thickness of fibres increase. Thus, it increased the shear resistance of the bamboo [8].

A conclusion also had been drawn by Atrop and Suzuki [9] from their research in 1948 that the shear strength slightly increased from bottom to top part of a bamboo culm. Ultimate shear stress obtained from this experiment also clearly show an increment of shear stress value from bottom and top, thus, support the conclusion that has been made from previous research [6]. Generally, the failure of shear specimens occurred along the shear plane that created by the shear loading plates. Based on visual inspection in this experiment, the first failure occurred at the peak load and it was considered as an initial failure. After the initial failure occurred, the specimens still carried the additional load that caused the second failure that occurred in the shear plane as shown in Figure 8.

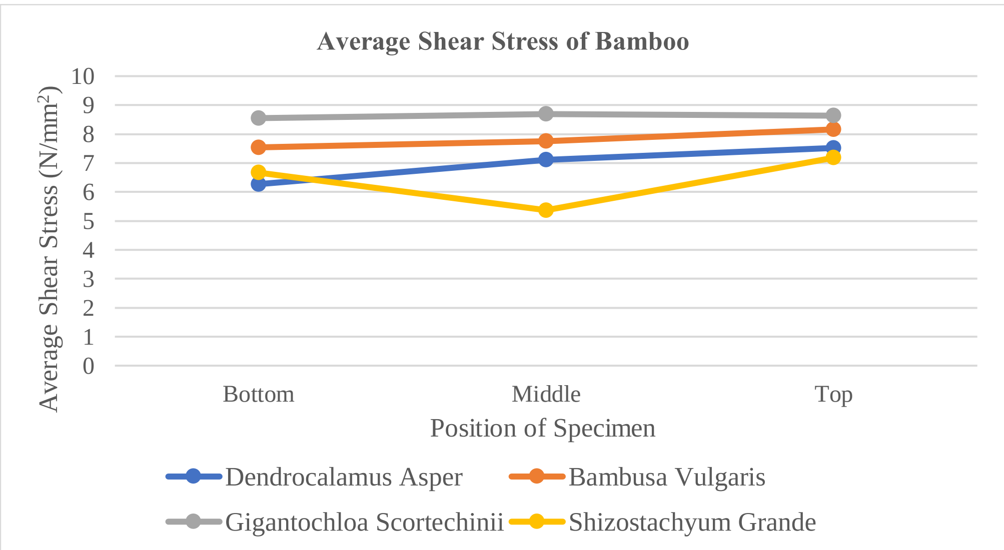


Figure 7. Average shear stress of bamboo against the position of specimens.

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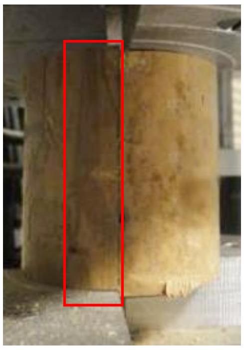
Table 2. Geometrical data and shear stress results.

Species	Part	Thickness (mm)				Length (mm)				Shear Area (mm^2)	Ultimate Load (N)	Shear Stress (N/mm^2)
		A	B	C	D	A	B	C	D			
DA	Top	10.40	10.60	11.40	9.50	96.00	96.00	95.10	94.80	4000.74	30100	7.52
	Middle	13.20	10.60	11.60	12.00	96.00	95.80	96.00	96.00	4548.28	32300	7.10
	Bottom	12.50	11.90	12.00	10.40	101.30	101.10	101.30	101.20	4737.42	29700	6.27
											Avg.	6.96
BV	Top	6.40	6.20	6.40	7.00	71.10	71.50	71.50	71.30	1855.04	15140	8.16
	Middle	7.40	8.00	7.50	7.70	71.00	71.00	71.30	71.00	2175.65	16890	7.76
	Bottom	7.30	7.50	7.60	7.50	70.00	69.70	69.70	69.20	2082.47	15700	7.54
											Avg.	7.82
GS	Top	6.50	6.00	6.20	6.40	64.60	63.80	63.80	64.30	1609.78	13900	8.63
	Middle	6.60	7.00	6.30	6.40	67.40	67.50	67.40	67.00	1770.76	15400	8.69
	Bottom	6.20	6.50	6.60	6.00	66.90	67.60	68.00	67.50	1707.98	14600	8.55
											Avg.	8.62
SG	Top	6.50	6.50	6.40	6.40	70.10	70.10	70.20	70.20	1810.51	13000	7.18
	Middle	6.80	6.90	6.60	6.50	71.50	71.40	71.50	71.50	1915.51	10300	5.37
	Bottom	7.10	7.20	7.10	7.30	73.20	73.20	73.30	73.20	2101.55	14000	6.66
											Avg.	6.40

DA = Dendrocalamus Asper
BV = Bambusa Vulgaris
GS = Gigantochloa Scortechinii
SG = Shizostachyum Grande

Most of the specimens failed at the shear plane initially but then, the specimens started to show multiple cracks that caused the specimen to split into few separates pieces. The additional crack occurred in both shear plane and in between shear plane failure. The failure between shear planes occurred across the unsupported quadrant at shear plates and this failure may be indicated by initial flaws in the specimen. In most cases, the shear failure ruptured along the entire of the length of the specimen even though each specimen did not possess similar ultimate load and shear stress.



(a) Failure at the shear plane

(b) Failure in between shear plane

Figure 8. Failure observed in shear test.

4. Conclusions

Understanding the mechanical properties of bamboo is necessary as the bamboo has a lot of potentials to be used in the construction field. The main purpose of this study was to present the tensile and shear strength of different species of bamboo including the failure behaviour of the bamboo specimens.

Based on the extensive experimental testing on tensile and shear strength, Dendrocalamus Asper and Bambusa Vulgaris were found to have the highest values in compressive and tensile strength followed by Gigantochloa Scortechinii, and Schizostachyum Grande. Meanwhile, in shear, Gigantochloa Scortechinii and Bambusa Vulgaris also were found to provide the highest shear followed by Dendrocalamus Asper and Schizostachyum Grande. The typical failure of bamboo were due to the fracture of internal bonding of the unidirectional bamboo fibres itself. Furthermore, the strength between each part in full bamboo culm shows small different in strength value where the top part of specimens always give higher strength value compared with the middle and bottom part of the specimen It can be conclude that three species of Malaysia bamboo to have a good potential to be used as a construction material.

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