AN EXPERIMENTAL STUDY OF THE INFLUENCE OF FIBER ARCHITECTURE ON THE STRENGTH OF POLYMER COMPOSITE MATERIAL

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ABSTRACT

The study focuses on the influence of fiber architecture (sequence and orientation) on flexural strength of glass fiber reinforced composite material. Composite materials are used increasingly in various fields such as space and aviation industries, architectural structures, shipbuilding materials, sporting goods, and interior and structural materials of automobiles due to the excellence of mechanical characteristics as well as light weight, heat resistance, and control characteristics. The main purpose of this study is to obtain the effects of fiber sequence and orientation to the flexural properties of laminated polymer composite material. Glass fiber reinforced polymer laminates are produced with each laminate consists of four layers of lamina. The matrix used is thermoset polyester with woven roving and chopped strand mat E-glass fiber as reinforcement materials. Each sample is different from another in terms of stacking sequence and orientation angles. Hand lay-up process is used to produce composite laminates and a tungsten carbide jigsaw cutter is used to cut the samples to required dimensions. The experimental work is carried out in accordance to three-point flexure test of ASTM-D790. It is noted from this work that the existence of chopped strand mat had significantly improved the flexural properties of the composite laminates.

KEYWORDS*: Glass Fiber Reinforced Polymer, Laminate, Woven Roving, Chopped Strand Mat, Flexural Strength.*

1.0 INTRODUCTION

The word composite in term of composite material signifies that two or more materials are combined on a macroscopic scale to form a useful third material (Jones, 2008). The advantage of composite materials is that, if well designed, the newly produced materials usually possess properties that are superior to the properties of those elements on their own. Some of the properties that could be improved include strength, stiffness, weight, corrosion and wear resistance, and etc. There are three main groups of most common man-made composites; fiber reinforced polymer (FRP), metal matrix composites (MMC) and ceramic matrix composites (CMC). The study focuses on the influence of fiber architecture to the flexural properties of FRP. FRP are composite materials composed of heat-hardening or room temperature curing resins as matrix together with reinforcement materials. The study uses E-glass fiber as the reinforcement material and polyester as the matrix material.

The scope of this study is to find the effect of glass fiber orientation and sequence to the flexural properties of the glass fiber reinforced polyester laminates. Generally, the bending properties of composite materials can be characterized using supported beams under concentrated loads method. However, such tests are commonly based on homogeneous beam equations. For laminated materials, however, these formulas must be modified to account for the stacking sequence of the individual plies (Sideridis and Papadopouls, 2004) and (Sideridis and Papadopouls, 2004) had also succesfully determined the shear strength of unidirectional glass fiber reinforced epoxy resin composites of different fiber directions using the short beam three-point bending test.

In another study, (V.Cecen *et.al.*, 2007) had used tensile and three-point flexural test to investigate the anisotropic behavior of different glass fabric reinforced polyester composites. Two commonly used types of traditional glass fabrics, woven roving fabric and chopped strand mat, have been used. It is observed from the investigation that the strong correlation between the changes in the interlaminar shear strength values and fiber orientation angle in the case of woven fabric laminates.

2.0 LITERATURE REVIEW

Lamina is a flat arrangement of unidirectional fibers or woven fabrics in a matrix (Jones, 2008). Laminated composite materials consist of layers of at least two or more lamina that are bonded together as shown in FIGURE 1. Stacking plates of composite materials have the properties of uneven quality and anisotropic nature unlike general metallurgical materials as they are stacking plates of composite materials in the combination of different types of materials (Lee *et.al.*, 2004). The best mechanical properties are in direction of the fiber placement (Miller, 1998). Therefore, lamination enables the process of tailoring the directional dependence of strength and stiffness of a composite material to match the design needs.

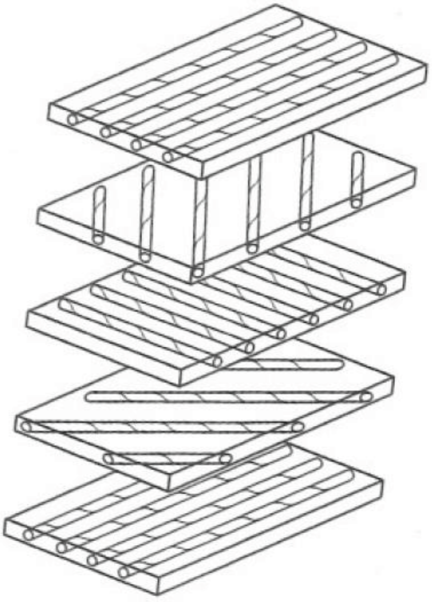

FIGURE 1 Unbonded view of laminate (Source: Jones, 1999)

There are two types of glass fibres used in this study. The first is E-glass fiber in the form of plain weave woven roving 600 gm/m^2 (XD-600). Second is chopped strand mat 450 gm/m^2 (KCM 450A) E-glass fiber. Although E-glass fiber has lower properties than S-glass fiber, it is the most widely used fibers in composite manufacturing. One of the reasons is due to its relatively lower price compare to S-glass fiber. The matrix is unsaturated polyester resin (BIP 2700-ATN) with 1-2% methyl ethyl ketone peroxide (MEKP) as catalyst. Both fiber and resin are supplied by Wee Tee Tong Chemicals (Singapore) Pte. Ltd.

3.0 METHODOLOGY

3.1 Fabrication Process

The four-ply composite plates were fabricated using hand lay-up process. Hand lay-up is especially suited for very large components, but for lower production quantities. There are several advantages in low volume production, such as flexibility in mould design, use of cheaper mould materials, almost unlimited mould size, lower cost of other equipment, etc. It is also easy to repair damaged parts or rejects during the early periods of the production process. Due to the possibility of economical design changes, hand lay-up is also suitable for complex works (Akovali, 2001).

Chopped strand mats (KCM 450A) and woven roving (XD-600) of E-glass fiber were impregnated with unsaturated polyester resin (BIP 2700-ATN) with 1-2% methyl ethyl ketone peroxide (MEKP) as catalyst. The ratio of resin:fiber is fixed at approximately 2:1 as suggested by Mariatti and Chum (2005). The fiber and resin were laminated according to designated configurations. Then, two plates of glass were used to sandwich the laminate to give a nice decorative surface. Prior to the process, Mirror Glaze® mold release wax was applied onto the glass surface to prevent the unwanted bonding between the materials and the glass surface. The laminated composites were cured at room temperature for 24 hours. Finally, the laminates were cut according to specimen size using a tungsten carbide jigsaw cutter (T130RF). The chosen specimen size is 3.2 mm x 12.7 mm x 125 mm. TABLE 1 and FIGURE 2 shows the laminate sequence and orientation angle of the four-ply composite laminates.

TABLE 1 Stacking sequence and orientation angle

Specimens Type	Stacking Sequence Orientation	Ply	Material
A1 - A5	[0/90/0/90]2S	4	GF/POLYESTER
B1 - B5	[0/90]2S[0/45]2S	4	GF/POLYESTER
C1 - C5	[0/45/0/45]2S	4	GF/POLYESTER
D1 - D5	[CSM/CSM]2S	4	GF/POLYESTER
E1 - E5	[CSM]2S[0/90]2S	4	GF/POLYESTER
F1 - F5	[CSM]2S[0/45]2S	4	GF/POLYESTER

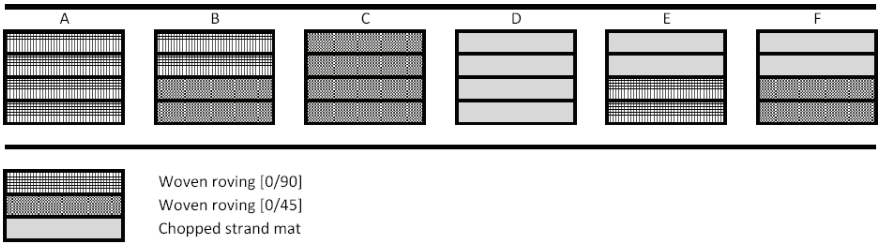

FIGURE 2 Laminate configurations

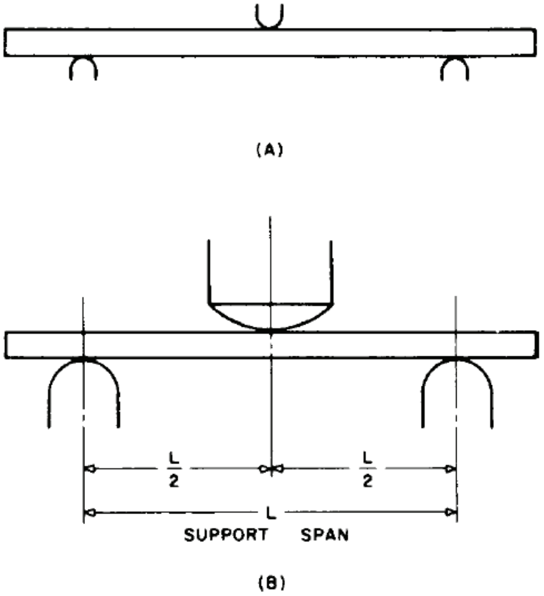

FIGURE 3 Allowable Range of Loading Nose and Support Radii (a) Minimum radius = 3.2 mm [1⁄8 in.]. (b) Maximum radius supports 1.6 times specimen depth; maximum radius loading nose = 4 times specimen depth. (Source: ASTM D790-03)

The machine used for the three-point flexure test is the Instron® 5585 Universal Testing Machine (UTM) integrated with Bluehill® Materials Testing Software. A three-point fixture is mounted on the UTM machine to hold the specimen at a certain ratio of support span to depth. FIGURE 4 shows the three-point fixture and the UTM machine used in this study. The standard recommends support span to depth ratio of 16:1, 20:1, 32:1, 40:1 and 60:1 (Adams *et.al.*, 2003). In this study the support span to depth ratio is set at 32:1 with strain rate at 3 mm/min. Each specimen type was tested at least five times to get an average data.

(a) (b)

FIGURE 4 Machine and fixture (a) Instron® 5585 Universal Testing Machine, (b) Three-point fixture

4.0 RESULTS AND DISCUSSION

It is known that the mechanical properties of FRP composite materials are not only influenced by the type of fiber and resin used but also the process of producing the material. This includes manufacturing method, fiber orientation, stacking sequence, curing process and etc. In this study, the relation between flexural properties of GFRP and the stacking sequence and orientation were studied based on the ASTM's three-point flexural test.

Specimens used in this study are as shown in TABLE 1. The specimens stacking sequence and orientation are using either woven roving fiber glass with [0/90] orientation or chopped strand mat bind together with BIP 2700-ATN cured polyester. The three-point flexural test results are summarized in TABLE 2. Detail results for each sample are shown in FIGURE 5 to FIGURE 10.

TABLE 2 Three-point flexure test results

Specimens	Maximum Load (kN)	Maximum Stress (Gpa)	Flex Modulus	Flexure Stress at Maximun Flexure Load (Mpa)	Flexure Strain at Maximun Flexure Load (mm/mm)
A1	0.0473	0.0600	3786.5600	55.8500	0.0282
A2	0.0535	0.0600	5334.1600	63.1400	0.0204
A3	0.0443	0.0500	3400.2500	52.2700	0.0238
A4	0.0521	0.0600	4675.6600	61.5900	0.0161
A5	0.0546	0.0600	4248.4100	64.4900	0.0285
Average	0.0504	0.0580	4289.0080	59.4680	0.0234
B1	0.0281	0.0300	1703.2700	33.2400	0.0237
B2	0.0266	0.0300	1677.1400	31.4200	0.0389
B3	0.0324	0.0400	1589.5500	38.3100	0.0405
B4	0.0287	0.0300	1794.7800	33.9000	0.0221
B5	0.0267	0.0300	1672.5100	31.5100	0.0319

Average	0.0285	0.0320	1687.4500	33.6760	0.0314
C1	0.0295	0.0300	1305.2400	34.8200	0.0422
C2	0.0313	0.0400	1446.1200	37.0100	0.0333
C3	0.0348	0.0400	1384.2200	41.0700	0.0461
C4	0.0285	0.0300	1330.2500	33.7000	0.0393
C5	0.0331	0.0400	1412.6300	39.1100	0.0448
Average	0.0314	0.0360	1375.6920	37.1420	0.0411
D1	0.2413	0.2900	16627.9300	285.0400	0.0196
D2	0.3168	0.3700	21469.0800	374.2200	0.0197
D3	0.2453	0.2900	17200.8000	289.6800	0.0188
D4	0.2830	0.3300	22947.6400	334.2600	0.0171
D5	0.2700	0.3200	18786.9800	318.8600	0.0201
Average	0.2713	0.3200	19406.4860	320.4120	0.0191
E1	0.2636	0.3100	26640.3400	311.3100	0.0138
E2	0.2413	0.2900	19991.8000	285.0100	0.0178
E3	0.2514	0.3000	20780.1400	296.8900	0.0170
E4	0.2640	0.3100	21669.4600	311.7900	0.0172
E5	0.1859	0.2200	19292.5100	219.5400	0.0130
Average	0.2412	0.2860	21674.8500	284.9080	0.0158
F1	0.3700	0.4400	27667.7000	437.0100	0.0200
F2	0.2431	0.2900	20264.3500	287.1600	0.0188
F3	0.4007	0.4700	31162.2800	473.2800	0.0178
F4	0.3938	0.4700	28016.7300	465.0900	0.0200
F5	0.4915	0.5800	34419.0000	580.5300	0.0202
Average	0.3798	0.4500	28306.0120	448.6140	0.0194

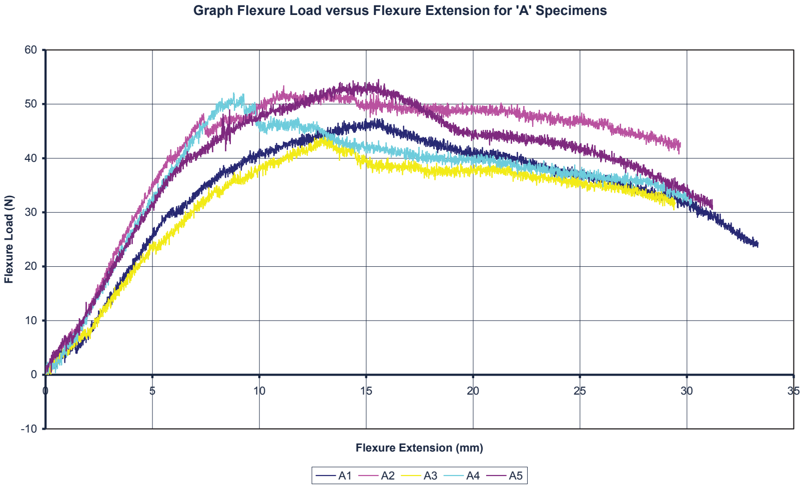

FIGURE 5 Specimens A1-A5: Flexure Load vs. Flexure Extension

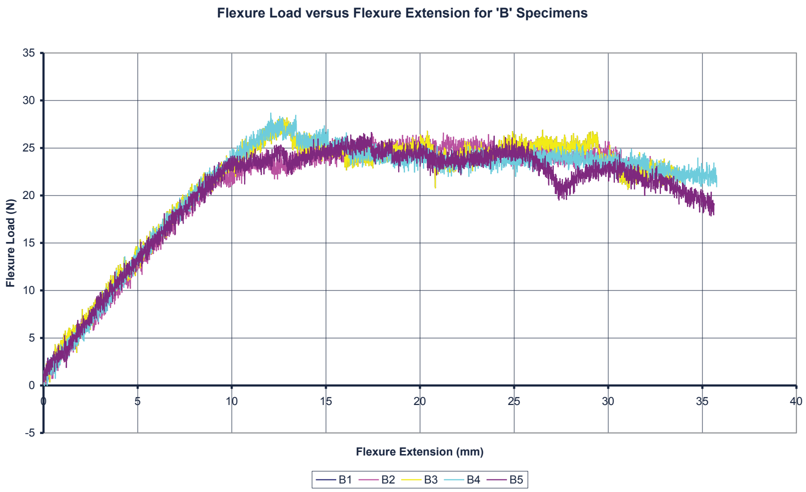

FIGURE 6 Specimens B1-B5: Flexure Load vs. Flexure Extension

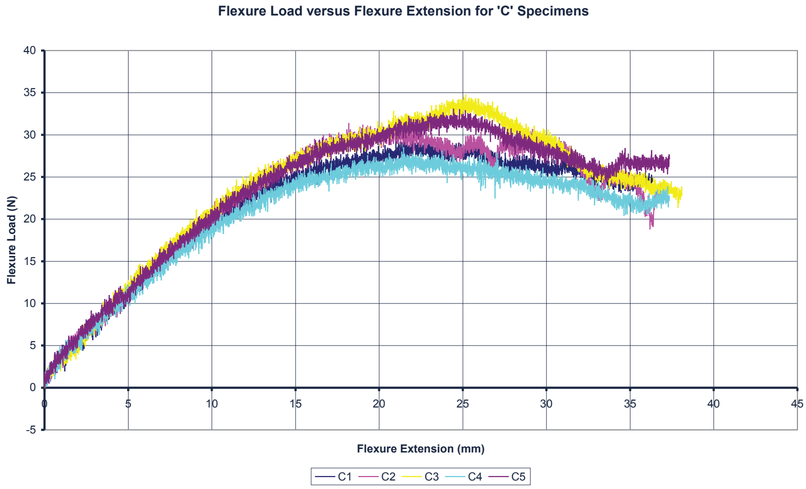

FIGURE 7 Specimens C1-C5: Flexure Load vs. Flexure Extension

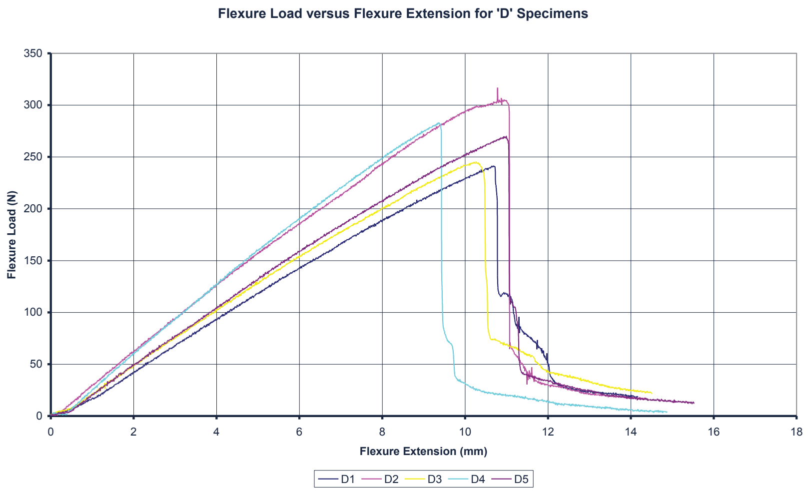

FIGURE 8 Specimens D1-D5: Flexure Load vs. Flexure Extension

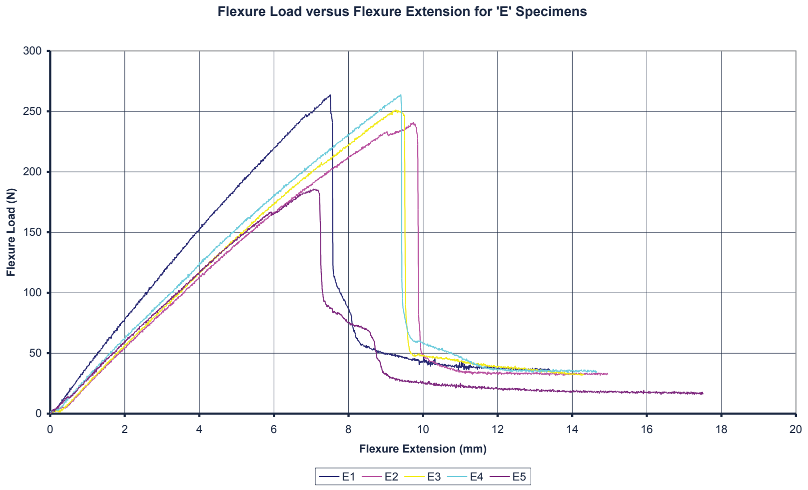

FIGURE 9 Specimens E1-E5: Flexure Load vs. Flexure Extension

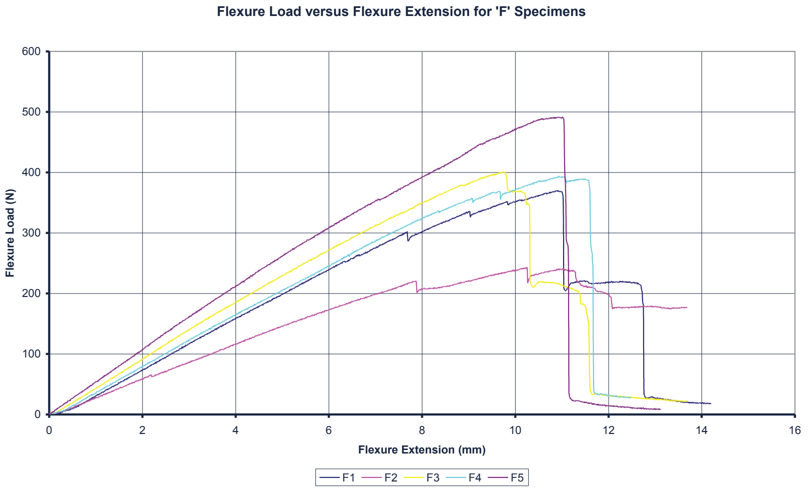

FIGURE 10 Specimens F1-F5: Flexure Load vs. Flexure Extension

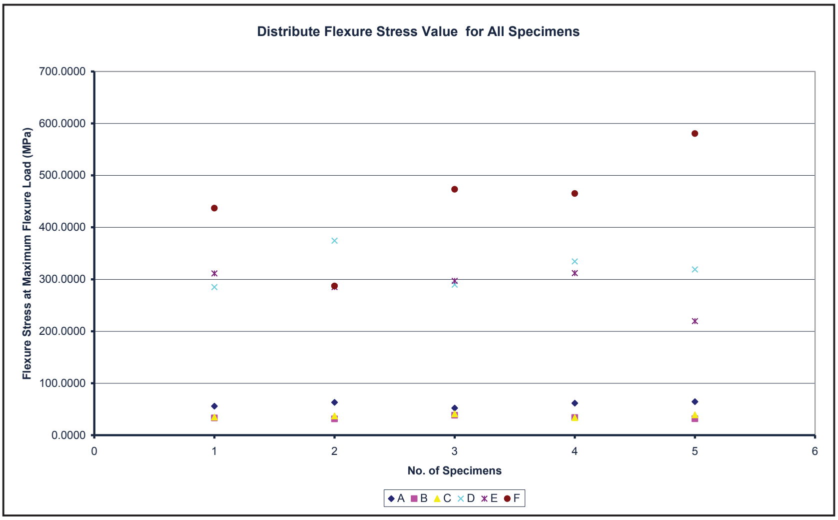

FIGURE 11 Flexure strength of different laminate configurations

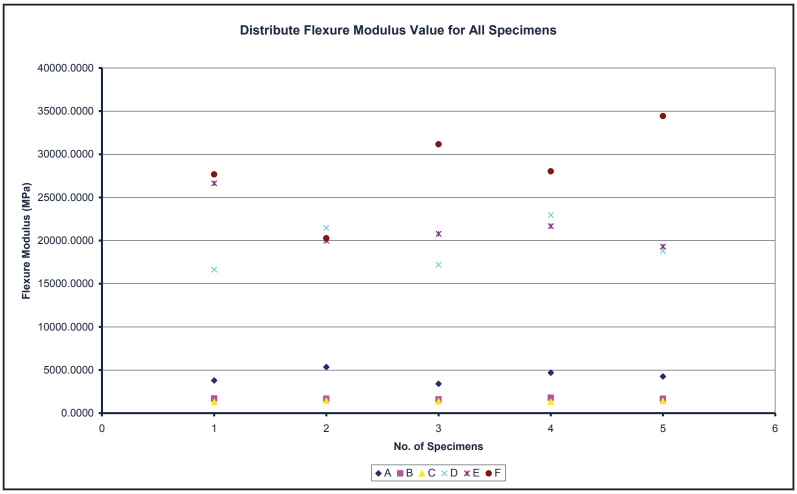

FIGURE 12 Flexure modulus of different laminate configurations

FIGURE 5 to FIGURE 10 show the graphs of Flexure Load vs. Flexure Extension of each specimen of different laminate configurations. The graphs show that the collected data between each specimen are quite consistent especially for specimen B and C. Whilst FIGURE 11 and FIGURE 12 show the flexure strength and flexure modulus of different laminate configurations. It is obvious from these two graphs that specimen D, E and F are superior in term of flexure properties compare to specimen A, B and C. The most superior combination is specimen F with flexure strength average of 448.6 MPa.

The main difference between specimen A, B, C and D, E, F is the existence of chopped strand mat layers. Specimens A, B, C are consist of only woven roving glass fiber oriented either in [0/90] or [0/45], or combination of both orientations as in specimen B. On the other hand, specimens D, E, F are consist of chopped strand mat laminas with E and F use the combination of woven roving and chopped strand mat lamina. It is interestingly noted that the existence of chopped strand mat lamina had significantly improved the flexure properties of the composite laminates.

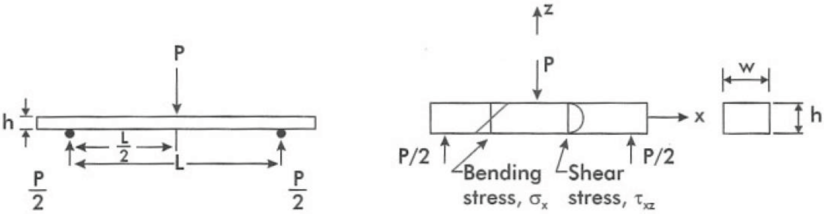

FIGURE 13 Stresses in three-point flexure test
(Source: Adams *et.al.*, 2003)

Analysis of a macroscopically homogenous beam of linearly elastic material (Timoshenko, 1984) indicates that an applied bending moment is balanced by a linear distribution of normal stress, σ_x as shown in FIGURE 13. During three-point flexure test, the top surface of the beam is in compression while the bottom surface is in tension. The shear stress is constant along the length of the beam and directly proportional to the applied force P. However, the flexural stresses, in addition to being directly proportional to P, vary linearly with position along the length of the beam, and are zero at the each end support and maximum at the center (Adams *et.a*l., 2003).

It is known that during three-point flexure test, composite materials are typically stronger in tension than compression. This means under normal condition a composite beam is more likely to fail at the middle of the top surface where applied force P is maximum. This is confirmed with observation made during the experimental work. For example as shown in FIGURE 14, the top surface of the beam (specimen A) failed under compression but there was no obvious crack found on the opposite surface.

FIGURE 14 Compressive failure at mid-top surface

Another interesting observation during experimental work was the failure mode of chopped strand mat laminates. The use of chopped strand mat laminates is undoubtedly resulting in improved flexure properties. The randomly distributed fiber in chopped strand mat has the ability to distribute the load almost evenly as in isotropic materials. This will increase the strength of the composite material as demonstrated by specimens D, E and F. However, chopped strand laminate are more brittle than woven roving laminates. Rupture failure was found on chopped strand mat laminates when it is subjected to its load limit. FIGURE 15 shows the rupture mode of specimen D at the tension side of composite beam.

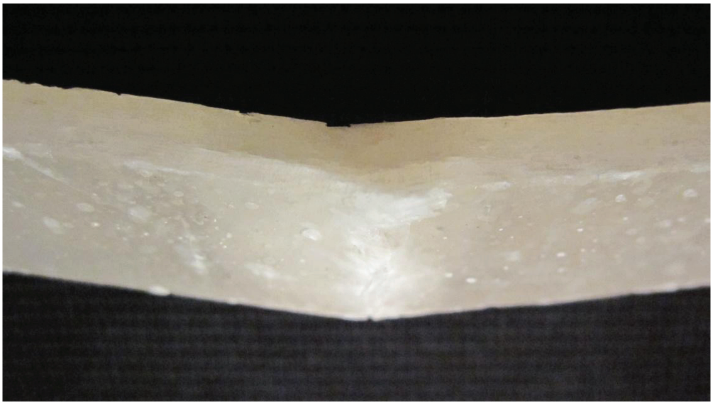

FIGURE 15 Rupture failure at mid-bottom surface (tensile)

Although specimen E and F are using the same combination of laminates, specimen E has the lower flexure strength compare to specimen F. In term of stacking sequence, specimen E and F are similar with both have two layers of chopped strand laminates at compression side and two layers of woven roving laminates at tensile side. The difference between these two is the orientation angle of its woven roving fiber. Specimen E uses [0/90] while specimen F uses [0/45] orientation. Due to the [0/90] orientation of woven roving, specimen E has parallel oriented fibers interlaced with perpendicular oriented fibers. This perpendicular oriented fibers are weaker in tensile mode. As the result, specimen E failed at mid-bottom surface earlier than specimen F during flexure test. FIGURE 16 shows the tensile failure of specimen E.

On the other hand, the [0/45] orientation of woven roving of specimen F replaces perpendicular oriented fibers with 45 degree oriented fibers. As the theory suggests, the orientation angle could improves the flexural properties of the material. And as proven by the experimental results, the change in woven roving orientation angle has significantly improved the flexure strength of specimen F with the highest flexure strength average of 448.6 MPa.

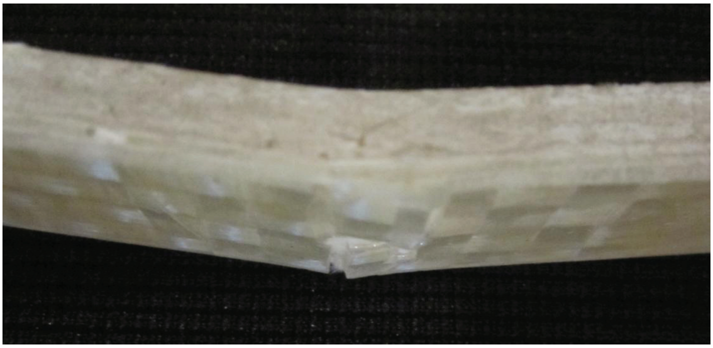

FIGURE 16 Tensile failure at mid-bottom surface

5.0 CONCLUSION

It is noted that the existence of chopped strand mat lamina had significantly improved the flexure properties of the composite laminates. From the experiment results, specimens with chopped strand mat layer are superior in term of flexure properties compare to laminates with no chopped strand layer. The most superior combination is specimen F with flexure strength average of 448.6 MPa. Specimen D which consists of all chopped strand layers, failed at tension surface due to rupture failure as it is more brittle than woven roving layer. Orientation angle of woven fiber has an influence factor to the flexural properties of the composite material. It is believed that the difference in flexural properties between specimen E and F is due to different orientation angle of woven fiber.

6.0 ACKNOWLEDGEMENT

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