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Effect of Fibre Direction on Repairing Tensile Failure of Glass Fibre / Polyester Composite

Verawaty Ismail[1], Mohd Hilmi Ariffin[1], Mohammad Syahadan Maksom[1,*]

[1] Department of Mechanical Engineering, Polytechnic Mukah, Sarawak, Malaysia

ABSTRACT

Orientations of the fibres play important roles to improve the strength and stiffness of a composite. This study is focused on the effect of fibre directions of a composite at 0º, 90º and 45º on repairing tensile failure of glass fibre/polyester composite. This experiment, carried out to investigate said effects using on fabricated unidirectional glass fibre that drawn from a woven glass fibre with polyester resin used as the binding materials. Unidirectional test specimens had been successfully fabricated, fractured and then repaired with varying fibre directions. Tensile tests on the repaired composite specimen were prepared according to the ASTM D3039/D3039M. The repairs with 0º, 45º and 90º fibre direction provided the highest tensile strength at 119.234 MPa, 53.270 MPa and 31.943 MPa respectively. The average Young Modulus results on all three series of specimens mended with 0º, 90º and 45º fibre directions are at 10217.505 MPa, 7239.747 MPa and 12103.192 MPa respectively. Physical compositions for the fabricated specimens were determined with burnout test. The fibre weight and volume ratio of 0º and 90º fibre directions show some consistency at 0.47 and 0.344 respectively. The fibre weight and volume of the 45º fibre direction is the highest at 0.506 and 0.354 due to its fibre repair directions.

Keywords:
Fibreglass; repaired fiberglass; fibre direction; tensile test; burnout test

1. Introduction

A composite is when two or more natural or artificial materials are combined together to create a superior and unique material and having a recognizable interface between them. Most composites consist of fibres of one material tightly bound into another material called a matrix. The matrix binds the fibres together somewhat like an adhesive and makes them more resistant to external damage, whereas the fibres make the matrix stronger and stiffer and help resist cracks and fractures. Composites are seen as a practical application nowadays as an alternative to metallic materials due to its lightweight and superior properties, mainly utilized in aerospace structures, high-speed boats and trains where weight is major considerations for the applications.

Glass fibre/Polyester composite is a composite material consists of glass fibre as reinforcement and polyester as binding matrix material. Fibreglass offers high tensile strength, heat and fire resistance, durable and many other properties as reinforcement of composite, but most importantly, glass fibre offers high strength to weight ratio for many applications. As for polyester resins, regardless of its lower performance to that of epoxy resins is easier to handle and cost lower than

* *Corresponding author.*
E-mail address: syahadan@pmu.edu.my

epoxies making it widely used for most marine structures. The mechanical properties of fibreglass composite mainly depend on the volume ratio of the fibre and matrix along with the individual properties of the fibre and composite themselves.

Fibre directions or orientations of a composite may refers to 0°, in which forces are applied in the same direction of the fibres, 90° for when the fibre direction is perpendicular to applied force and the 45° when the fibre direction is at 45° diagonally to the applied force. The orientations of the fibres apparently plays important roles to improve the strength and stiffness of a composite. To date, many research had been performed to investigate the effect of fibre orientations in the mechanical properties of composite materials and proven to have major roles in increasing some properties of the materials. Bakir and Hashem [1] reported that the tensile strength is the highest in specimen with 0° fibre orientation and lowest in the specimen with 90° fibre direction. Wang *et al.,* [2] analytical results indicate highest Young's Modulus of the 0° fibre orientation and lowest at about 45° fibre direction.

However, there was limited studies done on the effect of fibre directions on repairing tensile failure of fibreglass composite. Tensile failure in unidirectional reinforced fibreglass composite occurs when tensile loading is subjected parallel to the fibre direction; usually indicate how a material react to forces being applied in tension. Because of the nature of the fibreglass composite, usually tensile failure can be repaired by mechanically cleaning and patching the affected area. This experiment aims to investigate said effects using a unidirectional glass fibre that drawn from a woven glass fibre with polyester resin used as the binding materials. A series of specimens are prepared and fractured intentionally to allow for repairing process. Initial calculation of weight ratio of the fibre:resin used to fabricate the specimen is 50:50 and will be later confirmed after burnt out procedures.

2. Experimental

2.1 Materials

Continuous glass fibre drawn from woven E-glass fibre fabric was used as the reinforcing material. Polyester was opted as the matrix material with corresponding hardener as it was easier to handle, cost lower and the most common resin for fibreglass boats construction compared to epoxy resin.

2.2 Preparation of Test Specimens

A series of unidirectional, continuous fibreglass-reinforced polyester test specimens as in Figure 1A manually using hand lay-up process and cured overnight at room temperature. Test specimens were prepared according to ASTM D3039/D3039M-14 [9] for unidirectional fibre composite testing. Initial test specimens had a length of 250 mm, 15 mm width and a thickness of 1 mm for 0° with tabs from the same material of 1.5 mm thickness were fixed to both end of the specimens (Figure 1B) to prevent gripping damage on specimens during tensile test. The weight fibre-weight fractions in composite were pre-determined at 50 % and the fibre was not conditioned before fabricating the composite.

The specimens in Figure 1 were prepared for preliminary testing until failure. After tensile failure the specimens will be repaired to serve the purpose of the study. Preliminary tensile tests on the samples were carried out to find out the initial tensile strength and the pattern of the tensile fracture of the fabricated samples. Test result showed that original sample can withstand up to 10 kN of applied force, making its tensile strength at about 701 MPa before breaking. However, from preliminary tensile test, it turned out the reinforcing fibres are being pulled from end to end (refer Figure 2A*)* making the sample coupons were in total damage and impossible to repair.

Fig. 1. (A) Fabricated unidirectional specimen and (B) Specimens with tabs

Fig. 2. (A) Fractured test specimen from preliminary tensile test and (B) Fractured test specimen after an incision was introduced

To prevent total damage, a notch was introduced right in the middle of test strips as the initiation point of fracture. A small notch or incision using cutter was initiated on each sample before pulling the sample to ensure uniform fracture along in the middle of the initial sample as shown in Figure 2B. Fractured samples were then repaired using same fibre glass and matrix with different fibre directions. Repairing was done by modifying the repairing method proposed by Zimmerman *et al.,* [3] in US Patent No.5,601,676 for Composite Joining and Repair referring to Figure 3.

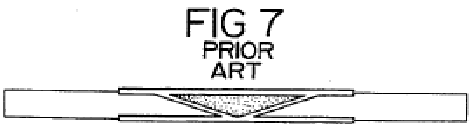

Fig. 3. Repairing composite method [3]

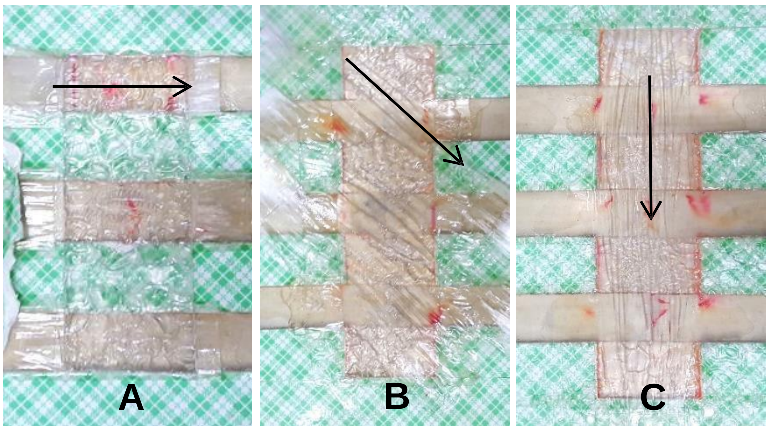

Fig. 4. Repairing specimens at (A) 0°, (B) 45° and (C) 90° fibre directions

The fractured samples were mechanically prepared by abrading the affected area at a radius about 12 times the thickness of the samples. The abraded area was then cleaned using acetone to ensure the area to be repaired was contaminant free. Then, fibreglass patches in three layers applied to the prepared area according to desired fibre directions. The repaired specimen was then pressed with steel and brick weight to squeeze excess resins away from repaired area and to initiate uniform pressure at the patch interface. The specimens were removed once they were fully cured in room temperature. The test specimens were lightly sanded and cleaned to restore them to their original appearance before being put to tests. Test strips were repaired using fibre orientation of 0°, 45° and 90° to investigate the effects of fibre directions on the repaired fibreglass composite as shown in Figure 5.

2.3 Characterization

Tensile tests on the repaired composite specimen were conducted according to the ASTM D3039/D3039M–14 Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials. The testing was performed on Shimadzu Universal Testing Machine AG-20KNX with test speed of 1 mm/min.

Fig. 5. Tensile test on universal testing machine

To calculate the tensile strength, the following equation is used:

$$\sigma = P_{max}/A \tag{1}$$

where; σ = tensile strength, MPa
P_{max} = maximum load prior to failure, N
A = average cross-sectional area, m^2

The fibre volume ratio plays an important role to achieve appropriate structural performance for a composite material. Engineering designer often uses the fibre volume ratio to derive lamina properties and structural properties. The best way to confirm the fibre weight ratio is with a burnout test. The tests were carried out by placing specimens in ceramic crucible in electric furnace at about 700°C - 900°C as in Figure 6. After the resin was burnt out, the sample was cooled and weighted. By comparing sample weights before and after the burn, the fibre weight ratio can be calculated.

Fig. 6. (A) Specimen sample in ceramic cubicle placed in the crucible furnace and (B) Remains of fibre after burnout test

The resin weight is the difference between the composite and fibre weights:

$$W_{resin} = W_{composite} - W_{fibre} \quad (2)$$

The vendor data on the density of both the fibre and the resins have to be acquired to calculate the fibre volume ratio. The fibre/resin volume ratio is calculated using;

$$\frac{V_{fibre}}{V_{resin}} = \left(\frac{W_{fibre}}{W_{resin}}\right)\left(\frac{\rho_{resin}}{\rho_{fibre}}\right) \quad (3)$$

Therefore, the matrix volume ratio is given by;

$$V_m = \frac{1}{\left(1 + \frac{V_{fibre}}{V_{resin}}\right)} \quad (4)$$

Finally, the fibre volume ratio is given by;

$$V_f = 1 - V_m - V_{voids} \quad (5)$$

3. Results and Discussion

3.1 Repaired Specimens Tensile Strength

Test specimens were tested as per standard in ASTM D3039/D3039M to evaluate their tensile strength. The results of tests on all three series of specimens mended with 0°, 90° and 45° fibre direction was tabulated in Table 1.

Table 1
Results of tensile test on unidirectional repaired specimens with 0°C, 45°C and 90°C fibre directions

Sample	Max. Force (N)	Tensile strength (MPa)	Young's modulus (MPa)
0°	1788.51	119.234	10217.505
90°	479.15	31.943	7239.747
45°	799.04	53.270	12103.192

Observations of tensile properties for unidirectional specimens repaired with 0° fibre direction show that the specimen can withstand up to 1788.51 N applied force. The specimens repaired with 90° fibre direction only been able to hold up to 479.15 N, while the 45° patched batch of specimens can stand a maximum load of 799.04 N. The unidirectional specimens mended with 0° fibre direction also has the highest tensile strength of 119.234 MPa average amongst all fibre directions used in this research. Lowest tensile strength was exhibited by specimens using 90° fibre orientations at 31.943 MPa, while the 45° fibre direction has a tensile strength of 53.72 MPa average.

Overall, the tensile strengths of specimens repaired with varied fibre direction can be compared in Figure 7 with 0° fibre direction repairs exhibit tensile strength doubled the strength of the specimens with 90° and 45° fibre direction.

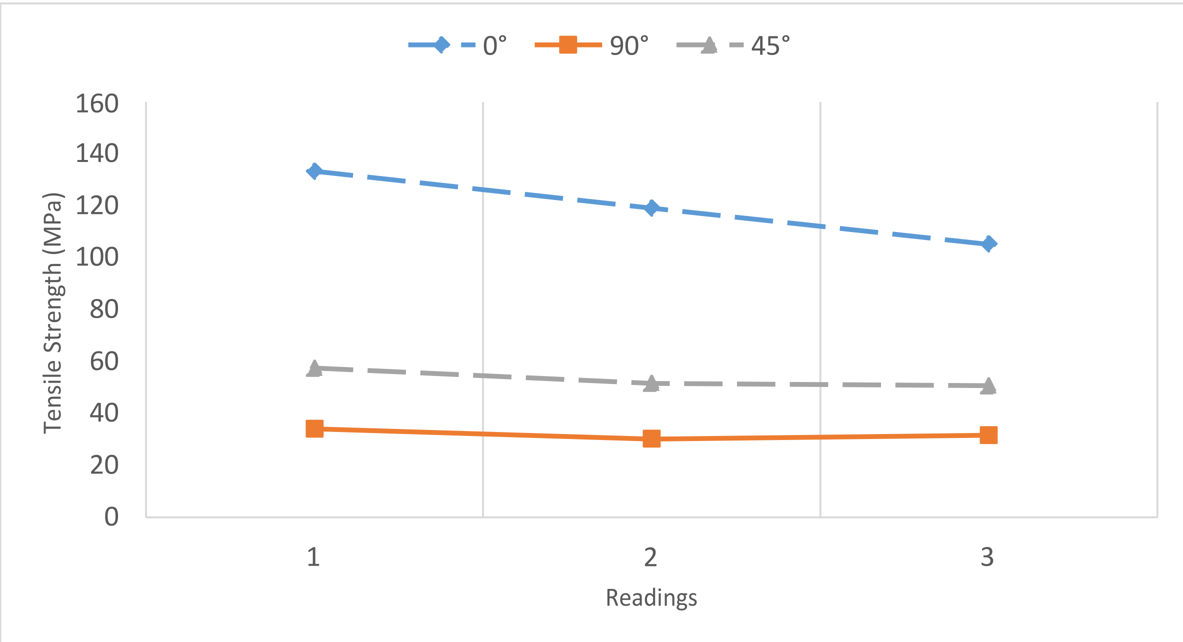

Fig. 7. Tensile test results of specimens repaired with varied fibre direction

The results basically the same of the tensile strength exhibited in precious works on the fibre directions effect on the composites. The 0° unidirectional repairs proven to be most effective in the repairing tensile fracture in this study. This is due to the direction of fibre repairs and the formerly fabricated specimens is the same providing the grips between previous and newly repaired fibres in the specimens. This fact clearly suggested that repairing tensile fracture in the same direction of the former specimens and applied load is preferable to maintain as much tensile properties as possible in repairing fibre process.

However, the tensile strength of the composite had greatly reduced greatly by about 83 % from the former 0° unidirectional specimen. This is most probably due to: (1) the uneven fibre alignment between the repaired and prior fibre; (2) discontinuation of the fibre along the specimen, (3) strength of the adhesive bonds or; (4) ineffective repairing technique being carried out in this study. The techniques provided by Zimmerman *et al.,* [3] are actually 3D bonding with interlocking fractured pieces in U, V, W and S-shaped configuration at the fracture area for composite panel with a minimum of 3 mm thickness and much wider panels. But, in this study the techniques were unable to be fully adopted due to lack of thickness and width of the specimens, making the repairs only able to be performed on the top of the fracture line instead of both top and bottom side of the specimen. The stress-strain curves of the tensile tests are also able to exhibit the ability of the material to resist deformations under load, also known as the Young's Modulus. The greater in the modulus of elasticity, the stiffer the material, or the smaller the elastic strain that results from the application of a given stress [8]. The Young's Modulus of the specimens generally can be presented by the stress-strain slope in Figure 8 which shows the 45° fibre direction has the highest modulus at about 12103.192 MPa and lowest on the 90° fibre direction with 7239.747 MPa.

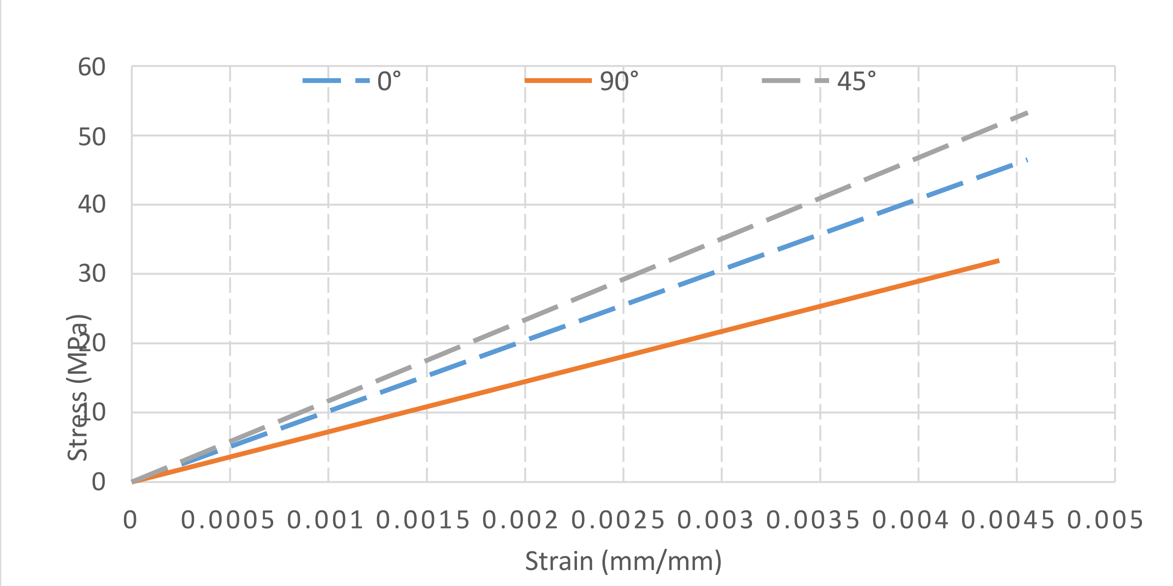

Fig. 8. Stress-Strain comparison for specimens with varied fibre direction

Based on the value of Young's Modulus from the experiment, it can be inferred as the 45° fibre direction repaired specimens were the stiffest and only elongate slightly before break, while the 90° fibre direction showed the lowest stiffness. This result can be confirmed visually from the fracture pattern in Figure 9A and 9C. This however contrasting to a study by Wang *et al.,* [2], Young's Modulus of the 45° specimens is the lowest and the highest on the 0° fibre direction specimens, analytically and experimentally. From this experiment, the value of the Young's Modulus of 0° fibre direction repairs still fairly high as suggested. The fracture pattern in Figure 9B shows small elastic strain from the repaired part of the specimens and most of repairing fibre pulled out from the specimen. As in the 45° fibre direction repairs may be able to exhibit higher Young's Modulus due to the change in fibre direction in the repair area. The change of direction provides grasps from prior specimen (at 0° unidirectional) and repaired fibre and making its stiffer and unable to elongate well in the direction of applied tensile load. Specimen in Figure 9C shows not only a part of the repairing fibre pulled out from the specimen, it also manages to fracture a portion of the prior specimen body due to the grasp from repairing fibre.

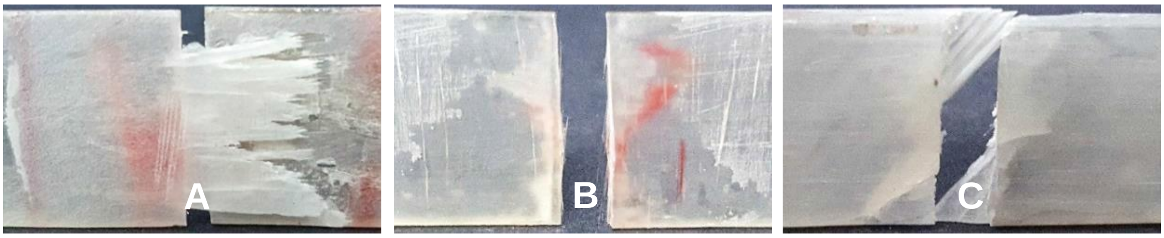

Fig. 9. Fracture patterns of the (A) 0°C, (B) 90°C and (C) 45°C repair fibre directions

3.2 Composite Fibre Volume Ratio

Burnout test was carried out to investigate a critical property of the fabricated fibreglass-polyester composite specimens in this experiment, which is the fibre volume ratio. Burnout test was performed by sampling a specimen from each series of the fibre directions.

Table 2
Fibre weight and volume ratio of specimens for 0°, 90° and 45° fibre repair directions

Sample	Fibre weight ratio	Fibre volume ratio
0°	0.472	0.344
90°	0.473	0.344
45°	0.506	0.354

Although initially, the calculation of fibre weight usage is aimed for 50:50 ratio of fibre to resin, the final weight ratios are as indicated in Table 2. There was slight shortage in fibre weight probably because of more resin added during repair procedure. Overall, the fibre weight and volume ratio of 0° and 90° fibre directions show some consistency at 0.47 and 0.34 respectively. The fibre weight and volume of the 45° fibre direction is the highest at 0.506 and 0.354 due to its fibre repair directions. More fibre is added to cover up the repair area diagonally.

4. Conclusions

The experimental on tensile strength for three different fibre direction on repairing tensile failure of fibre glass/polyester composite have been carried out to investigate the effect of the fibre directions on the repaired composite. Unidirectional test specimens had been successfully fabricated, fractured and then repaired with varying fibre directions of 0°, 90° and 45°. It can be concluded that from the test results, the 0° fibre direction provided the highest tensile strength and most ideal fibre direction for repairing tensile fracture of former 0° unidirectional specimens. The 0° test specimens also have fairly high Young's Modulus which suggests this direction of repaired fibre makes the repaired specimen stiff and inferred that there are still grasps between the prior and repairing fibre. This study is performed on fibre weight and volume ratio of average 0.483 and 0.347 respectively.

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