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On Improvement of Mechanical Properties of Hybrid FRP Composites Via VARTM and Rule of Mixture

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Abstract: Evaluation on the performance of hybrid Fiber Reinforced Polymer (FRP) composites is inevitable prior to their final usage in various engineering structures. Hence, this study presents an experimental investigation of the interplay hybrid laminates effect of plain woven carbon and E-glass fibers with the epoxy matrix on the tensile and flexural behaviors. The carbon-glass FRP hybrid composites were fabricated using Vacuum-Assisted Resin Transfer Molding process (VARTM) which is capable of producing high volume fractions panels. The full carbon and full glass FRP composites were also fabricated using the same technique as a reference parameter. Mechanical properties and performance of the carbon-glass FRP hybrid composites were evaluated against the full carbon or full glass fiber reinforced polymer composites according to the ASTM standards. The mechanical properties (in term of strength and strain, respectively) of single fibers composite were enhanced by hybridization of carbon and glass fiber composites. In addition, theoretical analysis through the rule of mixture reveals that the carbon-glass FRP hybrid composite has exhibited a positive hybrid effect in term of tensile and flexural behaviors.

Key words: Hybrid composite, carbon fiber, glass fiber, vacuum-assisted resin transfer molding, mechanical properties, rule of mixture

INTRODUCTION

Over some decades, composite materials have been aggressively engineered and rapidly applied in various sectors and industries. In fact, interests in the usage of composite materials have been growing worldwide following the high performance and weight requirements in their manufactured products. Lightweight and high-performance Fiber Reinforced Polymer (FRP) composites have been well introduced and established extensively in several applications. This includes in an automobile (body components), marine parts (e.g., petrol boats, landing gears), aerospace components (e.g., wing, rotor blades, fuselages, transmission shafts) and sporting goods (e.g., golf shafts, tennis and squash racket). One clear example is from Boeing Industry, in which majority parts of Boeing 787, 767 and 777 are made of glass and carbon fiber composites. The main reason of using FRP composites is obviously to reduce the body weight and optimize the fuel consumption (Soutis, 2005).

FRP composites are known to have distinct mechanical and structural properties over conventional composites such as metal alloys, wood and minerals. The constituent materials in FRP composites usually insoluble to each other, but the final properties are expected to be better than their constituent material and suitable for various design requirements (Mazumdar, 2001). There is a variety of fibers and resin systems available in the market nowadays such as glass/epoxy, aramid/polyester and carbon/epoxy. Since, glass fibers have high damage tolerance, acceptable and balanced properties apart from low cost, they have been widely implemented in many commercial applications. On the other hand, carbon fibers are often high in strength and stiffness, but brittle and most expensive among synthetic fibers (Hwang and Mao, 2001). Hence, this becomes the primary reason for incomprehensive application of carbon fibers in consumer products throughout the global market.

In the current competitive market, product and material designers have faced difficulties in satisfying strict requirements of ideal FRP composites in a single-fiber composite. This includes low cost, stiffness, strength, high damage tolerance, impact and fatigue properties, corrosion resistance and low density. Therefore, some researchers suggest that hybridization of two or more different fibers in the composite materials can combine the individual advantages of different fiber features as well as reducing the weight of composites and ultimately their cost (Hwang and Mao, 2001; Pandya *et al.*, 2011; Zhang *et al.*, 2012; Bunsell and

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Harris, 1974). According to American Society for Testing and Materials (ASTM) standard, the definition of hybrid composites is to include at least two distinct physical or mechanical properties reinforcements and matrix material. To enhance the mechanical performance of hybrid composite, high modulus and stiffness fibers are incorporated into the high elongation and low-cost fibers (Pandya *et al*., 2011). Carbon and glass fibers are the most utilized fibers in the hybrid FRP composites due to their ability to attain special or unique properties of the composites material. Based on previous studies, carbon fibers are capable of producing high specific strength and modulus properties of the composites, but they are normally low in elongation rate. In order to alleviate this drawback, most of the researchers incorporated high damage tolerance and low-cost glass fibers to create quality hybrid composites (Pandya *et al*., 2011; Zhang *et al*., 2012; Dong *et al*., 2012; Kretsis, 1987).

A number of researchers have embarked on experimental and theoretical studies on improving hybrid FRP properties by controlling the fibre volume fraction and resin system since, 1950. Rule Of Mixture (ROM) is the simplest and accurate way to predict the mechanical properties such as modulus and strength of composite materials through fibre volume fraction (Zhang *et al*., 2012; Himani and Purnima, 2010). For instance, Bunsell and Harris (1974) studied the performance of unidirectional hybrid glass and carbon fiber composites. The composite test panels of unbonded and bonded hybrid composite were fabricated by leaky mold method. It was reported that the properties of well-bonded hybrid composite behaved comparatively strong compared to that of unbonded material. However, the results showed that positive hybrid effect was not observed for elastic modulus based on the Rule Of Mixture (ROM) method. A review by Kretsis (1987) focused on mechanical properties of unidirectional carbon-glass reinforced hybrid composites due to limited study on multidirectional laminates composites. The researcher proposed that the tensile modulus of hybrid composites could be estimated or determined through ROM method. However, the tensile, compressive and flexural strengths showed negative hybrid effect for unidirectional hybrids composite as its fall below ROM prediction.

Sadeghian *et al*. (2006) investigated the effect of opening mode (mode-I) delamination when fabricating Carbon Nanofiber (CNF) in polyester/glass composite by Vacuum assisted Resin Transfer Moulding (VARTM). The results showed that the CNF was toughened and bridged with the glass fiber laminate. Compared to that of the traditional polyester/glass, the hybrid composite via VARTM reduced the mode-I delamination and exhibited 100% improvement in critical energy release rate. Meanwhile, the impact performance of glass-carbon reinforced hybrid composite was studied by Naik *et al*. (2001) using a drop-weight impact test machine. They found that the impact strength increased with the addition of glass fiber in the carbon FRP composite. In a recent study, Dong and Davies (2014) studied the flexural and tensile properties of uni-directional S-2 glass and T700S carbon reinforced epoxy hybrid composites for different volume fractions and four spans to depth ratios. The results showed that the hybrid properties were improved by increasing the fiber volume fraction and the span to depth ratio of greater than 32. However, it is important to note that a high fiber volume fraction will increase the composite manufacturing difficulties and costs. In another study, Pandya *et al*. (2011) and Zhang *et al*. (2012) studied hybridization of woven E-glass fiber and carbon fiber in epoxy by wet hand lay-up process. The results of tensile, compressive and flexural strain in glass/ carbon FRP hybrid composites shown the positive hybrid effect as predicted by the ROM. However, the ultimate tensile and compressive strength in the hybrid composite indicated some percentage loss when to compare to that of full carbon FRP composite.

Based on the previous review, it is evident that although the applications of the woven fiber composite are extensive in various field, only a few researchers reported on the hybrid effect of woven glass-carbon FRP hybrid composite. Until recently, the only reported study was by Pandya *et al*. (2011), Zhang *et al*. (2012) and Naik *et al*. (2001) in which the hybrid composites were produced by the traditional wet hand lay-up method. It is essential to highlight that; it is often difficult to control the thickness and volume fraction composite through this process. Hence, the results may not be comprehensive if not conclusive.

In this research, VARTM was applied to fabricate hybrid composite with plain E-glass and carbon fiber in epoxy resin in order to obtain consistent and reliable experimental results. The tensile and flexural test results of carbon-glass FRP hybrid composite were compared with single fiber (glass and carbon) composites. Furthermore, the mechanical properties and effect of hybrid composite materials were predicted through the theoretical Rule Of Mixture (ROM) with several underlying assumptions.

MATERIALS AND METHODS

As mention in the introduction section, the hybrid composite is capable of enhancing damage tolerance and impact properties of carbon/epoxy composite by

Table 1: Specifications of fibre reinforcements

Fibre specification	Carbon fibre	Glass fibre
Type	T300, 3K Tow	E-glass
Areal weight (g m^{-2})	200	200
Thickness (mm)	0.25	0.25
Weave pattern	Plain	Plain

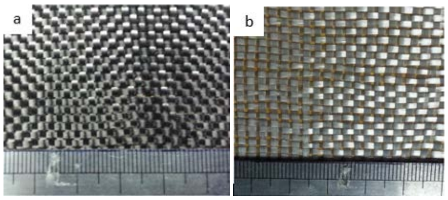

Fig. 1: a) Plain woven carbon fibre; b) Plain E-glass fibre

incorporating with low cost and high elongation glass fiber, in the epoxy matrix. The fiber reinforcements were plain-woven E-glass and carbon fiber (Fig. 1). This type of architecture has been mainly used in industries, hence was chosen in this study. The epoxy matrix was EpoxAmite 100 resin and 103 slow hardener which is suitable for resin infusion process. All materials were supplied by Makna Value Ltd (Malaysia) and Mecha Solve Engineering Ltd. Brief specifications of carbon fiber and E-glass fiber are listed in Table 1.

Preparation of hybrid composites: Hybrid FRP panels for this study were fabricated by vacuum assisted resin transfer molding which is categorized as closed-mold process and capable of producing high-quality composite parts with low tooling cost. Apart from that, VARTM also offers a safe and clean fabrication environment compared to wet hand lay-up method (Azmi, 2012). Schematic diagram of VARTM is depicted in Fig. 2.

During the fabrication, 5 layers of mould release agent (wax) were applied on flat glass mould to ease the removal of final cured panel. The woven carbon fiber and glass fiber mats were cut into a size of 320×320 mm prior to lay-up of the fiber reinforcements. Afterward, the fiber mats were alternatively piled up on the flat glass mould with orientations: {CGCG} where C and G represent carbon fiber and glass fiber respectively. Once the setup completed as depicted in Fig. 2, the air in the mould was removed by the vacuum pump. Prior to infusion of the resin, the compaction pressure on the dry fiber reinforcement was found to be <15 mbar. Subsequently, the mixture of epoxy and slow hardener at the ratio of 4:1 was infused into the mould cavity under full vacuum pressure. The infused laminated panel was cured in the room temperature for 24 h prior to mechanical testing.

Characterizations of fiber reinforced polymer hybrid composite: In order to specify the important properties of

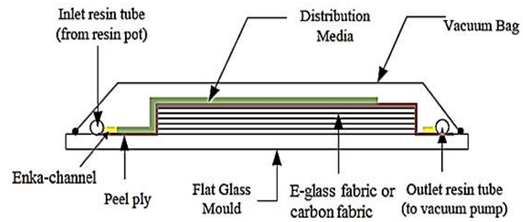

Fig. 2: Schematic diagram of VARTM

FRP composites, quantitative description of the proportions of fiber and resin content is imperative. The consistent percentage of fiber reinforcements and epoxy resin in every batch panels should be measured in order to minimize any variability during fabrication and testing. The proportion of fiber reinforcements in the FRP composite was determined by fiber volume fraction using burn-off test as stated in ASTM D3171-09. It is to note here that the ratio of volume fiber relative to the total volume of the composite is considered as fiber volume fraction and it ranges from 0-1. Five samples were randomly chosen from different batch panels and cut into the size of 625 m^2. Prior to burn-out process, the mass of specimens and crucibles were measured by Electronic balance meter (AY220, 0.1 mg) while the density of specimen was measured by Densimeter. The samples were then burned in the Nabertherm electrical furnace at 500°C for 5 h. Once all data have been collected, the volume fraction was calculated using Eq. 1:

$$v_f = \frac{M_f}{M_i} \times 100 \times \frac{\rho c}{\rho f} \quad (1)$$

Meanwhile, the tensile strength and modulus of the carbon-glass FRP hybrid composites as well as full carbon fiber composites and full glass fiber composites were determined using a Universal Testing Machine (AG-X, 250kN-300kN SHIMADZU) with loading rate 1 mm/min. This test was conducted as per the ASTM D3039/D standard. Five rectangular specimens of 250×25 mm were prepared from different batch panels and the average value were tabulated. Likewise, the flexural properties were determined using the same Universal Testing Machine. Five different batch panels specimens were prepared and tested at room temperature through three-point bending as specified in ASTM D 790. The flexural strength, strain and modulus were evaluated based on the average value from the five samples. The rate of crosshead speed was calculated using Eq. 2:

Table 2: Density and volume fraction for five different batches of FRP hybrid specimens

Composite configuration	Thickness (mm)	Density (g cm^{-3})	Fibre volume fraction (v_f)
Full Carbon (C)	4.23	1.898	0.52
Hybrid (CGCG)			
Batch 1	3.96	1.582	0.58
Batch 2	4.01	1.603	0.56
Batch 3	4.13	1.624	0.54
Batch 4	3.92	1.655	0.52
Batch 5	4.03	1.592	0.54
Average hybrid (CGCG)	4.01	1.611	0.55
Full Glass (G)	4.12	1.498	0.63

$$R = \frac{ZL^2}{6d} \quad (2)$$

Where:

R = The rate of crosshead motion
L = The span length
d = The depth of beam
Z = The rate of straining of the outer fiber

Theoretical prediction: As mention earlier, the mechanical performance of hybrid composites is often influenced by their weight fractions and fiber volume fractions. Thus, the Rule Of Mixture (ROM) and Hooke's law were used to predict the performance of hybrid composites in term of their tensile and flexural properties. The strength of hybrid composite mixture was calculated based on Eq. 3 and a few assumptions were made to predict these results (Pandya *et al*., 2011; Zhang *et al*., 2012; Naik *et al*., 2001). Some important underlying assumptions needed: fibers are arranged in hexagonal close packing throughout the matrix in the hybrid composite. The adhesive bonding is strong between fiber and matrix and free of a void in the hybrid composite. The last assumption is that the fiber, matrix and composite behaving as iso-strain during loading:

$$\sigma_h = \sigma_c v_c + \sigma_G (1 - Vc) \quad (3)$$

Where:

σ_h = Tensile strength for hybrid composite
σ_c = Tensile strength for full carbon fiber composite
σ_G = Tensile strength of full glass fiber composite
V_c = Carbon composite volume fraction

RESULTS AND DISCUSSION

Prior to design and manufacturing of a composite structural element, designer requires detail knowledge of the material properties, particularly, the basic quantity or volume fraction and quality of fibers that are reinforcing in the composite. Therefore, quantity and quality for reinforcing fibers are highly concerned for numerous researchers in improving the desirable properties (tension, compression and flexural) and widen their applications.

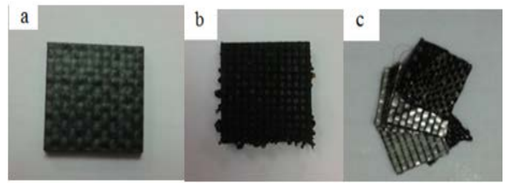

Fig. 3: Fibre volume fraction test: a) Sample before burning; b) After 2 h burning; c) Completely burning

Fiber volume fraction, density and thickness: Quantitative descriptions of fiber reinforcements in the carbon-glass FRP hybrid composites for this study are assessed through fiber volume fraction and density, in which the results are shown in Table 2. It should be noted here that the average thickness for carbon-glass FRP hybrid composite, full carbon fiber and full glass fiber were 4.01, 4.23 and 4.12 mm, respectively. As apparent, the deviation or variation of thickness for the composite laminate is statistically small. This is mainly due to the capability of VARTM to produce nearly consistent panels under a constant flow rate of polymer resin and stable vacuum condition.

Results from density measurement showed that the density for {CGCG} hybrid composite varies marginally with full carbon fiber and full glass fiber. The density for full carbon fiber {C} was 1.498 g cm^{-3}, whereas, the full glass fiber {G} was 1.898 g cm^{-3}. Based on these measurements, it is anticipated that the density of hybrid composite would be reduced through the addition of 50% low-density carbon fibers. From the Densimeter, the average density for carbon-glass FRP hybrid composite {CGCG} was measured to be 1.611 g cm^{-3} which is in good agreement with Zhang *et al* (2012). This result clearly indicated that the low-density hybrid composite could enhance the specific strength (ratio tensile strength to density) properties, reduce the weight and low in fabrication cost for the composite panel. As a result, the hybrid FRP composite would be a highly potential choice and substitute for several automotive and aerospace components.

Meanwhile, the final burning process for burn-off test is depicted in Fig. 3. It is evident after 5 h burning in the

Table 3: Tensile performance for five different composite specimens

Batch no:	Ultimate strength (MPa)	Ultimate strain (%)	Tensile modulus (Gp_a)
1	442	2.58	28.55
2	468	2.98	23.93
3	448	2.96	25.25
4	424	2.76	26.21
5	454	2.93	25.82
Average	447	2.84	25.95

oven at 500°C, the epoxy resin was completely charred and the left over in the crucible were the fibers. The fiber volume fractions were calculated based on Eq. 1 and the results are as shown in Table 2. The fiber volume fractions for {CGCG} hybrid composite were found to be fairly consistent and the average value was calculated to be 0.55 whereas for full Carbon {C} composite was 0.58 and full Glass {G} composite was 0.56, respectively. Compared to previous reported study by Pandya *et al.* (2011), the fiber volume fraction for the {CGCG} hybrid was slightly improved from 0.52-0.55. It can be inferred that the VARTM method for fabricating the hybrid composite was capable of compacting the fiber reinforcement under vacuum pressure to produce uniform thickness and low void content than the hand lay-up method. As indicated, the mechanical properties have a profound influenced by the constituent fibers. Thus, high fiber volume fraction allows more fibers to distribute the load and perform high mechanical performance in their service lifetime (Zaman and Awang, 2009; Brahim and Cheikh, 2007).

Based on Pan (1993), the ideal fiber arrangement in the hexagonal close packing is considered to produce maximum fiber volume fraction (σ_G) for a composite material, in which its optimum value is 0.785. It implies that this maximum fiber volume fraction should be a benchmark for hybrid composite in achieving the optimal mechanical performance. However, if fiber volume fraction of a composite is >0.785, the matrix is too thin, hence, the spacing between fiber and matrix is limited. As a result, the matrix is unable to support and transfer the load from fiber and, subsequently this creates micro cracking during loading. Therefore, designer and manufacturer must consider the maximum or allowable fiber volume fraction when designing and fabricating new hybrid composite.

Performance under tensile loading: Effectiveness and quality of reinforcing fibers in a composite such as elongation and stiffness properties are analyzed by tensile test in the longitudinal direction. The tensile stress and strain for different batch of {CGCG} FRP composites are presented in Table 3. The ultimate tensile stress, strain and modulus for different batch {CGCG} appear to be consistent and the average values for these properties are 447 MPa, 2.84% and 25.95 GPa, respectively.

Comparatively, the tensile strengths for full Carbon composite {C}, full Glass composite {G} as well as the

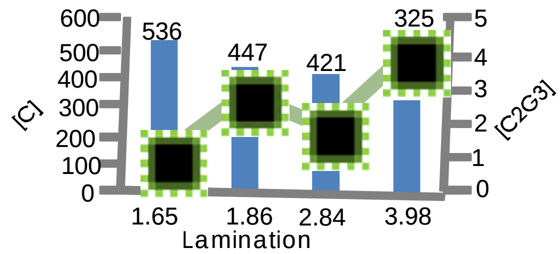

Fig. 4: Tensile performances for hybrid composites and full fibre composites

{C_2G_3} hybrid from a previous study Pandya *et al.* (2011) are depicted in Fig. 4. As expected, the full Carbon composite {C} has the highest ultimate tensile strength and lowest elongation which is 536 MPa and 1.65% respectively, owing to stiffness and brittle behaviors of the carbon fibers. On other hand, the low modulus Glass fiber {G} has the lowest ultimate strength, 325 MPa but high in strain, 3.98%.

Meanwhile, the average ultimate tensile strength of {CGCG} appears to combine the carbon fiber and glass fiber advantages/features as well as mitigating the less desirable properties. With regards to ultimate tensile strain, placing the glass fiber between carbon fiber results in a higher ultimate tensile strain. Since the glass fiber is higher elongation than carbon fiber, thus it alleviates the damage and micro-cracking of carbon fiber and allowing the carbon fiber to perform until reaching its maximum ultimate strength in the hybrid composite. Thus, in this study, it is evident that the ultimate strain increases to more than 140% for hybrid composite {CGCG} compared to that of {C} and only 40% to {G}. This is likely due to the bridging effect and strong bonding between high modulus carbon fiber and low modulus glass fiber that reduce the damage rate in tensile loading. These results are good agreement with Kretsis (1987), Bunsell and Harris (1974) as well as Pandya *et al.* (2011) and Himani and Purnima (2010) and they claimed that, the hybrid composite was the effective way to improve mechanical properties while reducing the material cost. As mentioned earlier, VARTM is an effective way to fabricate compact and quality composite panels than the hand lay-up method. It is evident that the tensile performance of VARTM {CGCG} hybrid composites in this present

Table 4: Flexural performance for five different composite specimens

Batch no:	Ultimate strength (MPa)	Ultimate strain (%)	Tensile modulus (Gp_a)
1	451	1.98	28.47
2	438	2.12	25.83
3	447	2.03	27.52
4	449	1.93	23.26
5	434	2.09	29.08
Average	443	2.03	26.83

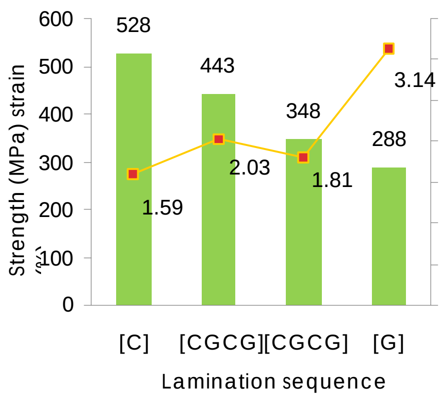

Fig. 5: Flexural performance for hybrid composites and full fibre composites

study is higher than that of the hand lay-up {C_2G_3} hybrid composites from the previous study (Pandya *et al*., 2011) as shown in Fig. 4.

These results lead to the conclusion that, alternating the stacking sequence and strong bonding between epoxy and fibers in the hybrid composites have shown significant influence towards the mechanical performance. The hybrid composite was fabricated with a high adhesive epoxy resin system, owing to the presence of polar hydroxyl and ether groups which is not observed in other thermosetting polymers such polyester. It is believed that polar hydroxyl is capable of performing strong bonding between the different layers of fibers and prevents cracking during tensile loading. Moreover, the alternating stacking sequence and constant VARTM vacuum pressure would optimize the spacing between fibers and matrix. Therefore, it allows the bridging effect in the composites and facilitate continuous load carrying of the carbon fiber after micro cracking until reaching their tensile limit (Pan, 1993).

Performance under flexural loading: Flexural strength is another mechanical property characteristic that can determine the performance of FRP composites. Flexure test typically includes tensile at the bottom panels, compressive at the top panels and shear stress between laminates layers when loading. Flexural performance for different batch of hybrid composites is shown in Table 4. Fig. 5 illustrates the comparisons of flexural strength and strain for different type composites and other researcher results. A similar trend as the tensile properties is evident for flexural properties of the hybrid composite. The experimental results showed that the highest flexural strength of 528 MPa is for the full carbon {C} composite, followed by the {CGCG} hybrid composite with 443 MPa flexural strength and the last order is a {G} composite of 288 MPa. On the other hand, this is somewhat contrary for flexural strain, in which the full glass fiber {G} has 3.14% strain, followed by the {CGCG} hybrid composite with 2.03% strain and as expected, the most brittle is full carbon fiber {C}, only 1.59 % in strain. These results clearly indicated that the hybridizing of the carbon fiber and glass fiber in the epoxy system has a remarkable effect on the flexural strength and strain which is similar to that of tensile performance. In addition, the result of this study demonstrated that the flexural strength of the {CGCG} hybrid composite accounting a loss of only 19.19% of flexural strength for {C} composites but an enhancement 53.82% of flexural strength for {G} composite. Apparently, the percentage gain in ultimate flexural strain {CGCG} is significantly higher (23.03%) than full carbon fiber {C}, thus benefited in alleviating the brittle behavior of the carbon fiber.

The superior flexural properties of carbon-glass FRP hybrid composite can restrain the damage and transverse micro-cracking prior to the ultimate strength. Based on literature review, the low elongation fibers (carbon fiber) may fail first to form cracks on the polymer matrix, but the further damage would be impeded by the surrounding high elongation glass fibers (Himani and Purnima, 2010; Naik *et al*., 2001). Therefore, it can be inferred that carbon fibers could take more strain after microcracking; hence this resulted in higher ultimate strain and stress limit of hybrid composite {CGCG}. From this result, it can be concluded that the hybrid composites provide unique properties of high strength and low cost which cannot be realized in the single type fiber composite.

Prediction of tensile and flexural strength based on rule of mixture: The linear Rule Of Mixture (ROM) was used to predict the theoretical results of tensile strength and flexural strength in the {CGCG} hybrid composite. As shown in study, Eq. 3 was employed to

Table 5: Comparison of theoretical and experimental results of carbon-glass FRP hybrid composites

Mechanical properties	Measured	Theoretical	Deviation (%)
Tensile strength	447.00	340.48	31.29
Flexural strength	443.00	369.14	20.01

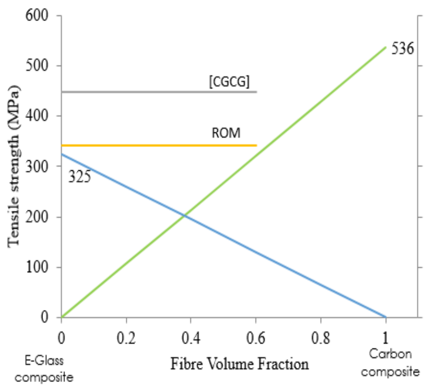

Fig. 6: Hybridisation effect on tensile strength

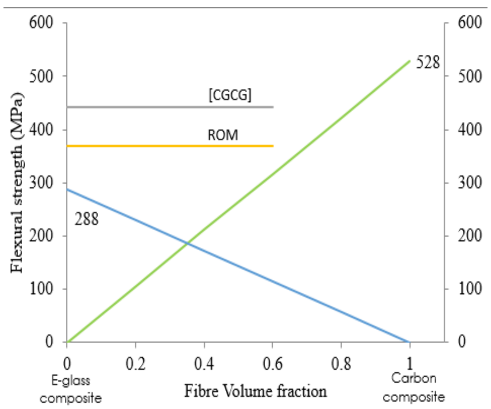

Fig. 7: Hybridisation effect on flexural strength

calculate the theoretical results following several underlying assumptions. First, the fiber reinforcements in the composite are uniform, continuous and perfect bonding exists between the fiber and matrix.

Comparison between experimental results and theoretical results are shown in Table 5. Meanwhile, the hybrid effect graphs as depicted in Fig. 6 and 7, are plotted based on the calculation results from ROM formula and fiber volume fraction. The two interaction lines represent the tensile strength of single fiber composite which are full carbon fiber and full glass fiber according to the respective volume fraction. When the value of volume fraction is zero, it represents full of glass fiber composite, in which the tensile and flexural strength are 325 and 288 MPa, respectively. On the contrary, volume fraction of one represent full carbon fiber composite and the tensile and flexural strength are 536 MPa and 528 MPa, respectively. Experimental results and theoretical results for hybrid composite are denoted by {CGCG} and ROM respectively in Fig. 6 and 7.

From Table 5, it is apparent that there is a deviation between experimental results and theoretical value for tensile and flexural strength. Specifically, the predicted tensile strength from ROM is 340.48 MPa whereas the experimental value of tensile strength for hybrid composite is 536 MPa at the 0.55 fiber volume fraction. Likewise, the same trend is also evident for flexural strength in which the predicted ROM is 369.14 MPa, whereas the experimental results for hybrid composite is 528 MPa. With regards to the comparison, the experimental tensile and flexural strengths of the hybrid composite were improved 30.19% and 20.01%, respectively against the theoretical ROM results. Such deviation is illustrated in Fig. 6 and 7 and it can be considered as the hybrid effect in the hybrid composite. It can be seen that, the hybrid effect {CGCG} in tensile and flexure strength lie slightly above the ROM value, thus this circumstances represents as positive hybrid effect. The positive effect occurs in the hybrid composite owing to the perfect bonding and bridging effect between glass and carbon fibers. The high elongation glass fibers were surrounded in the low elongation and low stiffness carbon fiber to restrain the damage and achieve their ultimate strength limit. As a result, the hybrid composite is able to withstand higher strength and strain than full single type fiber composite.

The results obtained in this present study were in good agreement with few researchers (Pan, 1993; Saka and Harding, 1990; Jawaid and Abdul Khalil, 2011). Saka and Harding (1990) carried out an in-plane mechanical testing and they used different prediction method to calculate the theoretical performances such as the simple laminate theory. They claimed that hybridizing high modulus fiber with low modulus fiber in a matrix showed positive hybrid effect in mechanical performance. However, the research of Fu (Qiu and Schwartz, 1993) was contrary to the results obtained from this study. They have reported negative hybrid effect for the tensile properties of Kevlar and S-glass fibers hybrid micro composites. The negative deviation result was due to the failure of glass fibers and Kevlar in strain.

CONCLUSION

This study has presented and discussed the manufacturing and mechanical performance of the carbon-glass hybrid composites prepared by VARTM. Consistent volume fraction and high mechanical performance of carbon-glass hybrid composite were successfully fabricated. Analysis of the results obtained from mechanical test and volume fraction leads to the conclusion that hybridization of glass and carbon fiber in epoxy is an effective method to enhance the tensile and flexural performance. The final results showed that percentage gain in the strengths for hybrid composite is significantly higher than the percentage loss in the ultimate strain. Besides that, it should be noted that the hybrid composite is also shown positive hybrid effect in tensile strength and flexural properties when compared with the theoretical rule of mixture results. The positive hybrid effect is likely due to the strong bonding and bridged effect in the optimal spacing between fiber and matrix. Based on the experimental results, hybridization can be used to improve the tensile and flexural properties of single fibers composite and satisfying strict requirements of low cost, low density and high specific strength.

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