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ORIGINAL ARTICLE

Characterisation of Hybrid Carbon Glass Fibre Reinforced Polymer (C/GFRP) of Balanced Cross Ply and Quasi Isotropic under Tensile and Flexural Loading

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ABSTRACT – This study is performed to characterize composite material of hybrid carbon glass reinforced polymer (C/GFRP) of two (2) types; namely balanced cross ply and quasi isotropic subjected to tensile and flexural loading. The mechanical testing performed on the hybrid composite as per ASTM standard and aimed to extract the mechanical properties related to tensile and flexural. The failure modes associated with the rupture of the composites/hybrid composites samples under tensile and three-point bending were assessed via JEOL 6010 Plus Scanning Electron Microscopy (SEM) instrument. The combination of GFRP lay-up at 0° at tensile side, GFRP lay-up 90° at compression side and ±45° lay-up of CFRP at shear/compression region enable the hybrid composite cross ply 8 to record the highest flexural strength. The substitution of 0° GFRP with 0° layup CFRP together with layup of 90° GFRP in hybrid composite cross ply 4, matrix/resin dominated layup acts as stress reliever in compression region during flexural loading taking place. This has induced to the increase of flexural strength, which observed to improve its original constituent of cross ply 2 (balanced cross ply GFRP). The factor of layup GFRP at transverse direction has enabled hybrid composite to possess a higher tensile modulus and to record considerably high tensile strength. The role of GFRP layup in enhancing the strain to failure in tensile and its role as a reliever in improving flexural strength during flexural loading has been tested and justified in this experiment.

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HYBRID CARBON GLASS FIBRE REINFORCED POLYMER (C/GFRP)

Carbon fibres(CF), having a low elongation at break (approximately 2%) leads to the brittle fracture of its composites. In the hybridisation coming from the use of two or more types of fibres reinforced the same resin, the disadvantages of one type fibres can be balanced by the advantages of the others[1]. It also provides recommendations for experimental measurements of the hybrid effect, which is a synergetic increase of the failure strain of low elongation fibres when hybridised with higher elongation fibres. This implies that the carbon fibres (CF) has a very low strain to failure and is regarded as a disadvantage for the use of carbon fibre reinforced polymers (CFRP) when utilised as structural members that will be subjected to tensile, compressive, shear and or/flexural loading. On the other hand, glass fibres (GF) which have much lower strength than carbon fibres but are tougher due to higher strain-to-failure. It has been proved that incorporation of GF into CF is possible to improve the failure strain of CFRP, turning the materials to a combination system called hybrids [2][3]. Apart from the toughness issue, CF are also very expensive which is regarded as the main drawback why CFRP are only popular in aero industries and automotive sector where weight saving is considered to be the primary concern [3]. GF are cheaper than CF and the glass fibre reinforced polymers (GFRP) have been increasingly used to replace steel in automotive industry. The use of CFRP could yield a 40-60% weight reduction; but its adoption rate still remains low. The hybridisation of GF into CF selectively could be an effective way to reduce vehicle weight without excessive cost [4].

Tensile and Flexural Behaviour of Hybrid Composite Material

Fibre-hybrid composites are attracting an ever-increasing interest from academia and industry. It is therefore vital to develop a solid understanding of their basic mechanical properties. Measuring and predicting the tensile failure of hybrid composites however remains a challenging task. Several scholars provide recommendations for experimental measurements of the hybrid effect, which is a synergetic increase of the failure strain of low elongation fibres when hybridised with higher elongation fibres. The hybridisation may also result in the improvement of composites mechanical properties characterised by the increase of ultimate tensile strain compared with those of low elongation non-hybrid fibre reinforced composites [2][5][6][5]. Like most materials, fibre reinforced polymers (FRP) face the strength versus toughness dilemma. For example, in the case of carbon fibre (CF) being well known for having superior strength and stiffness; but these high strength and stiffness come at the expense of its low toughness. Relative glass/carbon ratios significantly influence the flexural properties, and laminate geometry further optimises them. Utilisation of hybridisation can improve the flexural strength. In the aim to improve flexural strength, the fibre volume fraction of glass/epoxy plies needs to be higher than that of carbon/epoxy plies[6]. Furthermore, glass fibres (GF) which have much lower strength than carbon fibres but are much tougher due to having a higher strain-to-failure[7]. Significant findings have been found on the mechanical characterisation of woven, cross-ply and quasi-isotropic made of one constituent of composite material [8–10] [11]. Therefore, this research paper aims to contribute an understanding on the effect of cross-ply and quasi-isotropic hybrid composite carbon fibre reinforced polymer (CFRP) and glass fibre reinforced polymer (GFRP) under tensile and flexural loading(via three-point bending).

MATERIALS

The material under study is composite, which comes in the form of prepreg mode supplied by Rockwest Composite. The GFRP and CFRP prepreg with a dimension of approximately 1.2 m width and 0.1625 mm thickness (GFRP) and 0.4 mm thickness (CFRP) were in the form of prepreg roll before being cut into plates shape and undergone curing process. The types of hybrid composite C/GFRP arrangement/layup under study are the balance cross-ply and quasi-isotropic, as the authors intend to contribute to the gap exist in the composite community literature on those type of hybrid composite C/GFRP specifically under tensile and flexural loading.

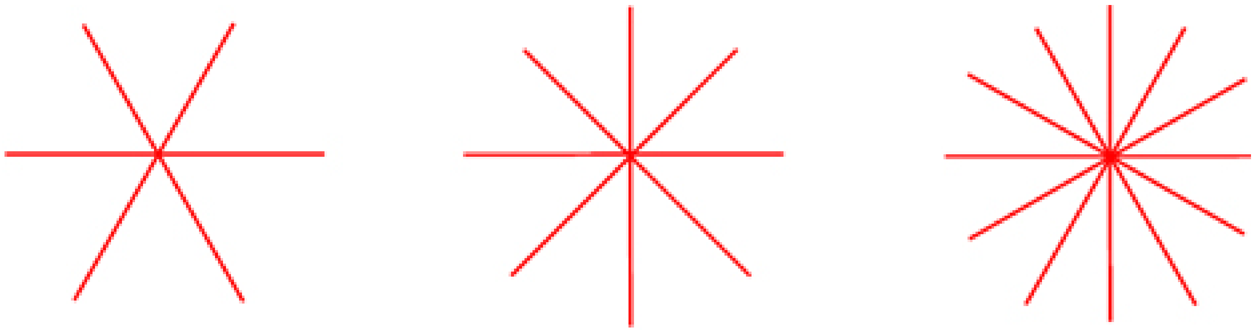
Hybrid C/GFRP Balance Cross-Ply

A laminate is called cross-ply laminate if all the plies used to fabricate the laminate are only 0° and 90°. Moreover, 0/90° orientations demonstrated better strength performance compare to 45/-45° [12] For a cross-ply laminate the terms $A_{16} = A_{26} = B_{16} = B_{26} = D_{16} = D_{26} = 0$. This is because these terms involve the terms $\bar{Q}_{16}$ and $\bar{Q}_{26}$ which have the products of *mn* terms. This product is zero for any cross-ply. Thus, the terms $\bar{Q}_{16}$ and $\bar{Q}_{26}$are identically zero for each ply. Cross-ply laminates are usually based on a stack of unidirectional plies arranged at 0° and 90° to a chosen reference direction. A cross-ply laminate is a special case of the angle-ply laminate with laminae at 0° (usually taken as the reference x-direction) and 90° [13].

Hybrid C/GFRP Quasi Isotropic

A laminate is called quasi-isotropic when its extensional stiffness matrix behaves like an anisotropic material. This requires that; $A_{11} = A_{22}\,, A_{16} = A_{26} = 0$, and $A_{66} = (A_{11} - A_{12})/2$. Further, this extensional stiffness matrix is independent of orientation of layers in laminate. This requires a laminate with $N \geq 3$ equal thickness layers and *N* equal angles between adjacent fibre orientations. The *N* equal angles, Δθ between the fibre orientations, in this case, can be given as Eq. (1) [13]. The quasi-isotropic laminate with this construction for *N*=3, 4 and 6 have fibre orientations as shown in Figure 1.

$$\Delta\theta = \frac{\pi}{N} \tag{1}$$



(a) $N = 3(\Delta\theta = 60^o)$, (b) $N = 4(\Delta\theta = 45^o)$ and (c) $N = 6(\Delta\theta = 30^o)$

Figure 1. Fibre orientations in typical quasi-isotropic laminates.

It should be noted that the isotropy in these laminates is in-plane only [14]. The matrices *B* and *D* may not behave like an isotropic material. Hence, such laminates are quasi-isotropic in nature. Some examples of quasi-isotropic laminate are $[0/\pm60]$s, $[0/\pm45/90]s$.

Hybrid Balanced Cross Ply and Quasi Isotropic C/GFRP Layup Under Study

The Hybrid Composite C/GFRP under study which undergone tensile and flexural testing via three-point bending were arranged as shown in Table 1 and Table 2. Each testing for tensile loading and three-point bending consist of a minimum of five samples which cut in accordance with ASTM standard.

METHODOLOGY

Composite is prepared via hot press machine as shown in Figure 2 with recommended pressure of 6 bar with 1 bar from vacuum suction as shown in Figure 3, and set at 120 °C temperature for approximately 1-hour duration. Figure 4 depicts the uniaxial tensile test set up and three-point bending flexural test used in the study.

Table 1. Cross-ply hybrid CFRP/GFRP

No	Hybrid composite name	Arrangement/layup
1	#Cross Ply 1	$[90^o_{2C}/0^o_{2C}/90^o_{2C}]_S$
2	#Cross Ply 2	$[90^o_{2G}/0^o_{2G}/90^o_{2G}]_S$
3	#Cross Ply 3	$[90^o_{2C}/0^o_{2G}/90^o_{2C}]_S$
4	#Cross Ply 4	$[90^o_{2G}/0^o_{2C}/90^o_{2G}]_S$

Table 2. Quasi-isotropic hybrid CFRP/GFRP

No	Hybrid composite name	Arrangement/layup
1	#Cross Ply 5	$[0^o_{C}/90^o_{C}/\pm45^o_{C}]_S$
2	#Cross Ply 6	$[0^o_{2G}/90^o_{2G}/\pm45^o_{2G}]_S$
3	#Cross Ply 7	$[0^o_{C}/90^o_{C}/\pm45^o_{2G}]_S$
4	#Cross Ply 8	$[0^o_{2G}/90^o_{2G}/\pm45^o_{C}]_S$

Figure 2. Hotpress machine used in preparing the composite and hybrid composite panel.

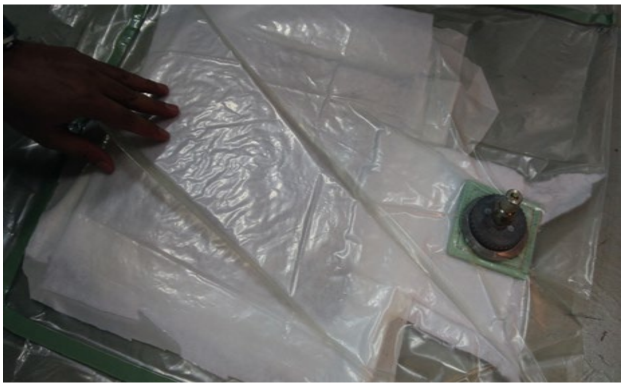


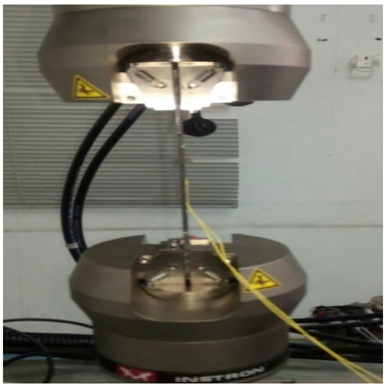
Figure 3. Composite prepreg underwent 1 bar equivalent pressure under vacuum.

Uniaxial Tensile Test (ASTM D3039)

The tensile specimen was placed in a testing machine aligning the longitudinal axis of the specimen and pulled at a crosshead speed of 2 mm/min. The specimens were loaded step by step till they fail under uniaxial loading. The load was recorded using the digital data acquisition system. The stress-strain behaviour is obtained to be linear, and the final failure occurs catastrophically. The values of Young's Modulus, E_1, poisson ratio, ν_{12} and axial strength, X_t are obtained as follows:

$$\sigma_1 = \frac{P}{A} \quad \nu_{12} = -\frac{\varepsilon_1}{\varepsilon_2} \quad E_1 = \frac{\sigma_1}{\varepsilon_1} \quad X_t = \frac{P_{ult}}{A} \tag{2}$$

where σ_1 is the stress computed in 1 (longitudinal direction similar to loading direction) and P_{ult} is the maximum load recorded by the load cell upon failure/rupture of the specimen under tensile loading[15].



(a)

(b)

Figure 4. Type of loading for composite material under study: (a) uniaxial tensile test with a strain gauge attached and (b) three-point bending test (flexural).

Flexural Three-Point Bending Test (ASTM D790-07)

Three-point bending test has been performed in accordance with ASTM D790-07 to determine the flexural stiffness and strength properties of polymer matrix composites as shown in Figure 4. Finished laminates were then cut into specimens of 12.7×130 mm for testing. The specimen depth ranged from 1.28 mm to 1.85 mm, depending on stacking configuration. The flexural stress, σ_f, and flexural strain, ε_f, from bending deformation of hybrid composite is given by the relation in Eq. (3).

$$\sigma_f = \frac{3PL}{2bh^2} \quad , \quad \varepsilon_f = \frac{6Dh}{L^2} \tag{3}$$

where P is the load applied computed from the load cell, L, b and h are the span width and depth of the specimen while D is the deflection computed from the deflection occurred correspond to load applied. Scanning electron microscopy (SEM) using JEOL 6010 Plus was utilised to investigate the damage morphology of hybrid composite. High-resolution Zeiss Axioskop 2 Plus microscope was also used to capture image showing failure mode of samples. The comprehensive results pertaining to mechanical properties related to tensile and flexural obtained from experimental performed as accordance with ASTM described before are tabulated and plotted.

RESULTS AND DISCUSSION

Tensile Behaviour of Hybrid Composite Balanced Cross-Ply and Quasi-Isotropic C/GFRP

The tensile modulus and tensile strength of the sample of CFRP, GFRP, and hybrid composite C/GFRP with balanced cross-ply layup and quasi-isotropic layup was determined for six samples each, and the average value of strength has been taken. The observed tensile stress against tensile strain are plotted in Figure 5 and Figure 6 for the cases of hybrid composite cross-ply and quasi-isotropic respectively. Tensile strength for the samples are tabulated in Table 3 and Table 4 for the cases of hybrid composite cross-ply and quasi-isotropic respectively. From Figure 6, it is observed that the tensile modulus and tensile strength of the hybrid composite lie between the quasi-isotropic CFRP and quasi-isotropic GFRP. This is in agreement with outcomes by [16, 17] Meanwhile Figure 5 suggests correlation between the layup sequence and the resultant tensile modulus. For example, the balanced cross-ply CFRP, GFRP and hybrid C/GFRP, replacement of 90° layup of CFRP with 90° layup of GFRP show a slight increase on the resultant Tensile modulus but attaining approximately similar tensile strength. On the other hand, replacing the 90° layup of GFRP in cross-ply GFRP with 90° layup of CFRP has contributed to the lower modulus of elasticity and almost similar record on tensile strength. From this study, it is concluded that the inclusion of carbon fibre layup at 0° parallel with longitudinal loading, in the glass fibre reinforced polymeric composite significantly enhanced the tensile strength of the hybrid composite but not the case with CFRP layup at 90° i.e. transverse direction with respect to loading [8],[17].

Figure 7 shows the tensile modulus and tensile strength plot of the balanced cross-ply of hybrid C/GFRP. Close record on tensile strength for both Cross Ply 1 and Cross Ply 4, with a decrease of tensile strength for the latter due to delamination on interlaminar 90° GFRP and 0° CFRP. This led to minimal delamination observed, matrix cracking of 90°/transverse GFRP layup followed by CFRP 0° longitudinal direction fibre ruptured. This is also parallel with findings from [11, 18] with regards to transverse behaviour composite under tensile loading. On the other hand, Cross Ply 1 and Cross Ply 4 recorded tensile modulus which is consistent with the theoretical rule of mixture. The same phenomena apply to Cross-Ply 3 and Cross Ply 2, where both depicted quite close value of tensile strength and their tensile modulus also observed to follow the rule of mixture [19].

Table 3. Hybrid C/GFRP balanced cross-ply under tensile loading.

Hybrid layup	Hybrid ratio	Density (g/cm^3)	Tensile modulus (GPa)	Tensile strength (MPa)	Strain to failure (%)	Major mode of failure
#Cross Ply 1	0	1.73	46.47	687.74	0.0157	Delamination between 90°/transverse and 0^o longitudinal direction CFRP layup. Matrix cracking on transverse layup CFRP.
#Cross Ply 2	1	1.78	23.87	276.23	0.0175	Matrix cracking of 90°/transverse GFRP layup. Fibre ruptured of GFRP 0^o longitudinal direction after delamination.
#Cross Ply 3	0.1688	2.09	15.432	262.513	0.0223	Matrix cracking of 90°/transverse CFRP layup followed by GFRP 0° longitudinal direction fibre ruptured.
#Cross Ply 4	0.4483	1.93	58.724	663.73	0.0124	Minimal delamination observed, Matrix cracking of 90^o/transverse GFRP layup followed by CFRP 0° longitudinal direction fibre ruptured.

Table 4. Hybrid C/GFRP quasi-isotropic under tensile loading.

Hybrid layup	Hybrid ratio	Density (g/cm^3)	Tensile modulus (GPa)	Tensile strength (MPa)	Strain to failure (%)	Major mode of failure
#Cross Ply 5	0	1.09	51.092	583.56	0.0115	Off axis shear stress induced heavy delamination effect at the ±45° CFRP layups in the middle section. Failure starts at the middle section and off axis shear effect also seen at the outer CFRP layup failure plane.
#Cross Ply 6	1	2.32	21.91	256.56	0.0126	Off axis shear stress brought to delamination effect at the ±45° GFRP layups in the middle section but moderate effect. Combination of fibre kinking and bridging at the outer layer/1st layup seen during damage process.
#Cross Ply 7	0.4483	2.44	29.49	497.86	0.0204	Off axis shear stress brought to delamination effect at the ±45° GFRP layups in the middle section on significant effect. Fibre breakage at 0° first/external layup.
#Cross Ply 8	0.4483	2.36	42.5	425.63	0.012	Delamination between $0^o/90^o$GFRP outer layups. Fibre bridging and kinking of GFRP at outer layup.±45° layup of CFRP in the middle section seen undamaged for most of samples.

Figure 8 shows tensile modulus and tensile strength plot of quasi-isotropic of Hybrid C/GFRP. Cross Ply 5, which comprises of quasi-isotropic CFRP layup observed to attain highest tensile strength meanwhile Cross Ply 6 which is GFRP quasi-isotropic layup, recorded the lowest tensile strength. Hybrid composite Cross Ply 8 found to have lower tensile strength but having higher tensile modulus than Cross Ply 7. In Cross Ply 8, it was observed that delamination occurs between 0/90° GFRP outer/external layups. Fibre bridging and kinking of GFRP seen at outer layup 0°.

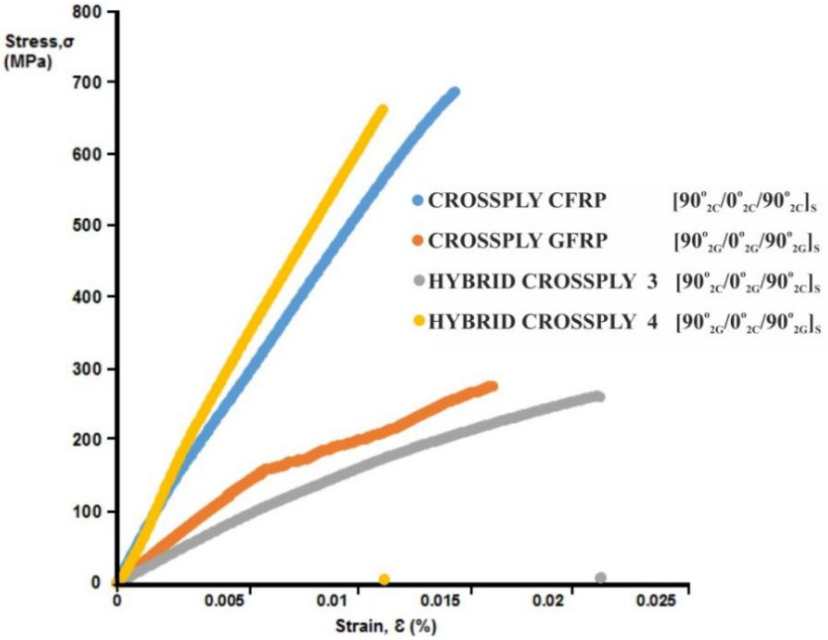


Figure 5. Tensile stress against tensile strain for cross-ply CFRP, GFRP, hybrid Cross Ply 3 and hybrid Cross Ply 4.

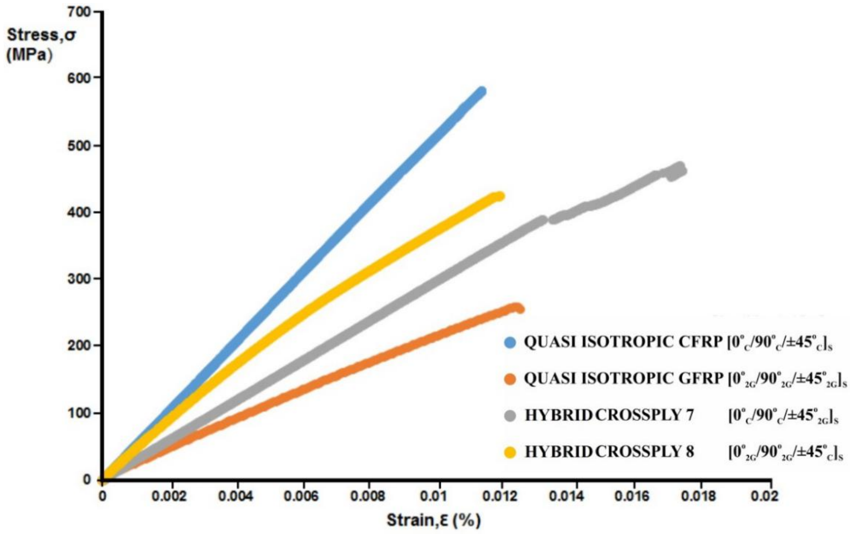


Figure 6. Tensile stress against tensile strain for quasi-isotropic CFRP, GFRP and hybrid Cross Ply 7/8.

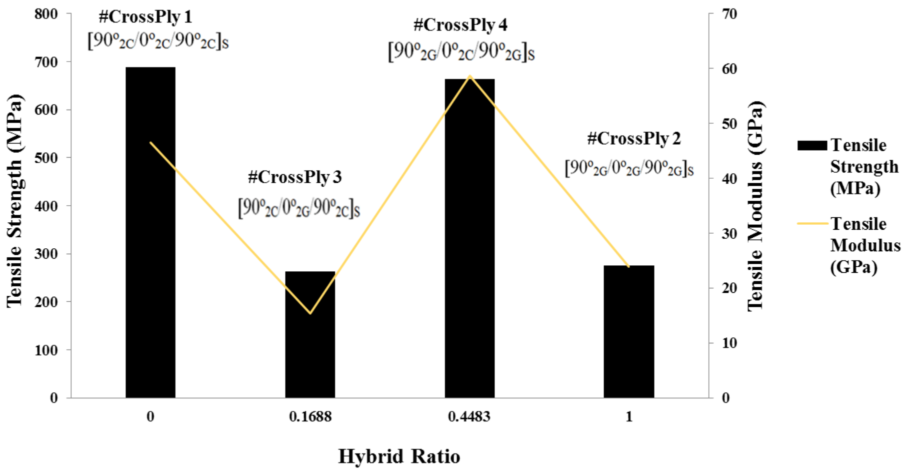


Figure 7. Histogram plot of balanced cross-ply of hybrid C/GFRP on tensile modulus and tensile strength.

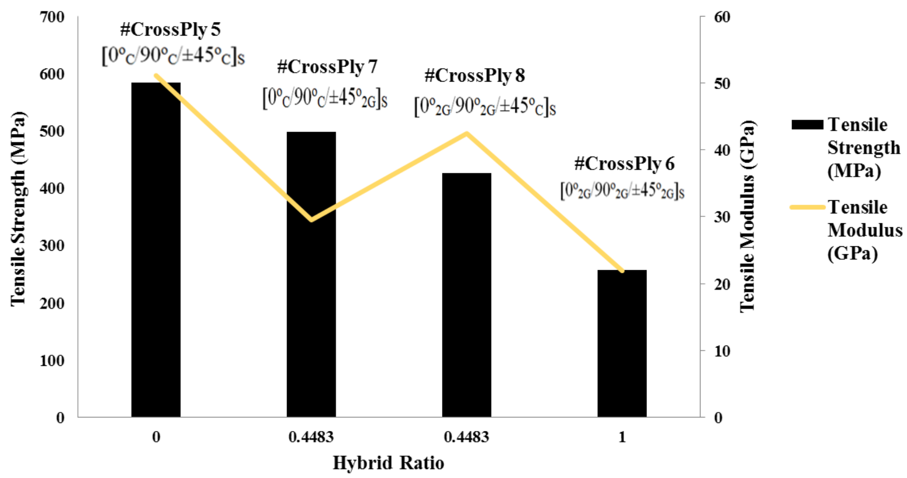


Figure 8. Histogram plot of quasi-isotropic hybrid composite C/GFRP on tensile modulus and tensile strength.

Flexural Behaviour of Hybrid Composite Balanced Cross-Ply and Quasi-Isotropic C/GFRP

The load vs deflection plots for a minimum of five samples for each composite layup has been converted into flexural stress against flexural strain using the equation described earlier. Table 5 and Table 6 shows crossplay hybrid C/GFRP and quasi-isotropic hybrid C/GFRP flexural properties under flexural loading (3-point bending test), respectively. Both tables include major failure modes associated with the flexural loading test performed. The average plot for each composite and hybrid composite (minimum of five samples for each layup) is taken and combined in Figure 9 for balanced cross-ply case and Figure 10 for quasi-isotropic case. From Figure 9, cross-ply specimen, which is fully constructed from CFRP layup shows the highest flexural modulus and flexural strength. Meanwhile, Cross Ply 3, depicts the lowest flexural strength. Cross Ply 2 and Cross Ply 3 exhibits quite similar trend of plot with Cross Ply 2 account for slightly higher flexural strength than the former. All the plots exhibit a linear curve up until the point of failure.

Figure 10 shows the flexural stress against flexural strain for quasi-isotropic category of the composite layup. In general, all four plots show a linear relationship up to the failure initiation and experiencing a nonlinear trend before experiencing complete rupture of the specimen under testing. This occurs due to the existence of ±45° layup, which provides in-plane shear stress field during flexural loading [20, 21]. Hybrid Cross Ply 8 shows the highest flexural strength surpassing quasi isotropic CFRP although recorded lower flexural modulus than the latter. Hybrid Cross Ply 7 depicts a quite high flexural modulus and strain to failure, due to combination of 0° layup CFRP at the external (compression and tensile region) as well as ±45° GFRP layup in the middle section to accommodate the flexural strain extension.

Table 5. Cross-ply hybrid CFRP/GFRP under 3-point bending test.

Hybrid layup	Hybrid ratio	Density (g/cm^3)	Flexural modulus (GPa)	Flexural strength (MPa)	Strain to failure (flexural) (%)	Major mode of failure
#Cross Ply 1/Cross Ply CFRP	0	1.73	22.695	689.25	0.0347	Matrix micro cracks at the 90° CFRP layup compressive side. Interlayer delamination between 0/90° CFRP at the tensile side.
#Cross Ply 2/Cross Ply GFRP	1	1.78	10.639	485.25	0.0489	Interlayer delamination between 0/90° GFRP layup at the tensile side.
#Cross Ply 3	0.1688	2.09	11.174	413.17	0.0459	Interlayer delamination between CFRP/GFRP and matrix cracking on CFRP layup, crack propagated through thickness brought to matrix damage. Fibre-matrix interface cracking and fibre rupture
#Cross Ply 4	0.4483	1.93	21.039	569.81	0.0285	Matrix cracking and damage for most of the GFRP layups at the through-thickness section for the tensile and compressive side of the hybrid specimen. CFRP fibre bridging and breakage in the centre section in line with the direction of bending applied.

Table 6. Quasi Isotropic Hybrid CFRP/GFRP under 3-Point Bending Test.

Hybrid arrangement/ layup	Hybrid ratio	Density (g/cm^3)	Flexural modulus (GPa)	Flexural strength (MPa)	Strain to failure (flexural) (%)	Major mode of failure
#Cross Ply 5/Quasi Isotropic CFRP	0	1.09	54.788	733.61	0.0181	Interlayer delamination between 0/90° GFRP layup at the tensile side. Matrix ruptured and fibre bridging at $\pm 45^o$ layup of CFRP in the middle section of sample and at the compressive side. Fibre buckling of CFRP at compressive side induced to matrix breakage.
#Cross Ply 6/Quasi Isotropic GFRP	1	2.32	20.611	619.21	0.0314	Minimal intralayer delamination of GFRP layups at both compressive and tensile side. Minimal matrix cracking and damage at $\pm 45^o$ layup of GFRP seen at compressive side.
#Cross Ply 7	0.4483	2.44	39.223	709.82	0.0162	CFRP layup on compressive side experiencing fibre buckling, minimal damage on $\pm 45^o$GFRP layup side. Minimal interlayer delamination of CFRP/GFRP observed.
#Cross Ply 8	0.4483	2.36	22.675	797.77	0.0347	Fibre ruptured of GFRP at tensile side, Fibre damage and matrix cracking propagating through the thickness of GFRP at the compressive side. Intralayer delamination $\pm 45^o$CFRP layup occurred

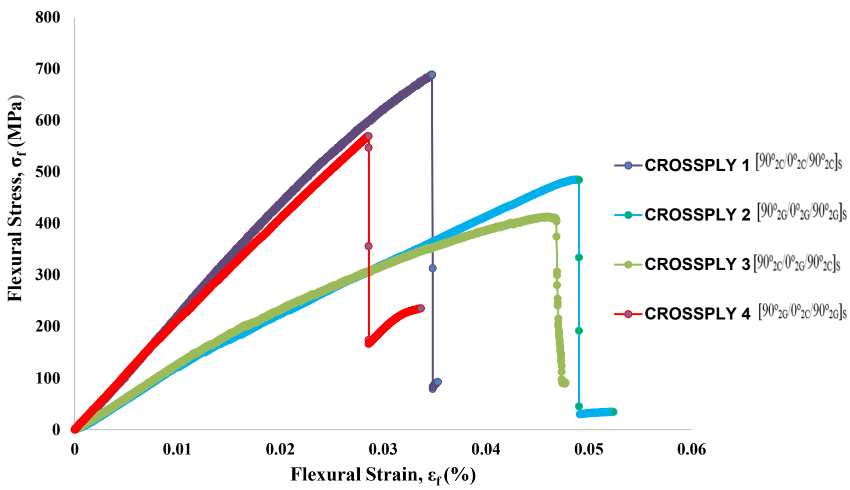


Figure 9. Flexural stress against flexural strain for balanced Cross Ply 1, Cross Ply 2, Cross Ply 3 and Cross Ply 4.

Figure 11 shows a histogram of flexural modulus and flexural strength for balanced cross-ply composite and hybrid composite C/GFRP. Cross Ply 1 depicts the highest flexural strength as well as flexural modulus while hybrid Cross Ply 3 shows the lowest flexural strength as well possessing low flexural modulus, which is 11.174 GPa. Having resin dominated GFRP layup (4 layers) oriented at 90° in the compression region during flexural loading has dampen and induced less stress concentration and distribution due to its low modulus of elasticity, has enabled hybrid Cross Ply 4 recorded high flexural strength.

Figure 12 illustrates the plot of flexural modulus and flexural strength for composite and hybrid composite C/GFRP quasi-isotropic under study. Hybrid Cross Ply 8 depicted the highest flexural strength but possess quite low flexural modulus. This is consistent with findings from [21, 22] which prove that layup ±45° CFRP than ±45° GFRP produces higher shear stress field distribution which accommodates the flexural loading implied. For Cross Ply 6, intralayer delamination of GFRP layups at both compressive and tensile side and matrix cracking and damage at ±45° layup of GFRP seen at the compressive side which brought into failure initiation and lowest flexural strength recorded.

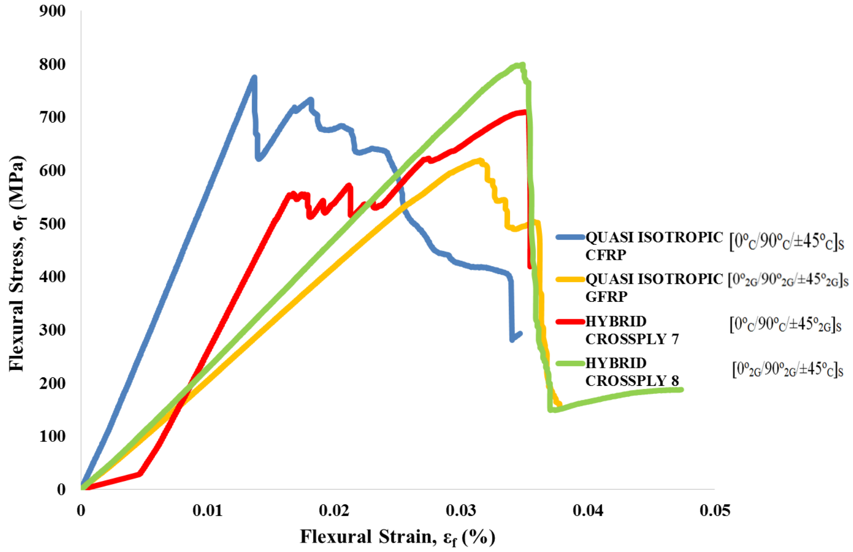


Figure 10. Flexural stress against flexural strain for quasi-isotropic CFRP, GFRP, hybrid Cross Ply 7, hybrid Cross Ply 8.

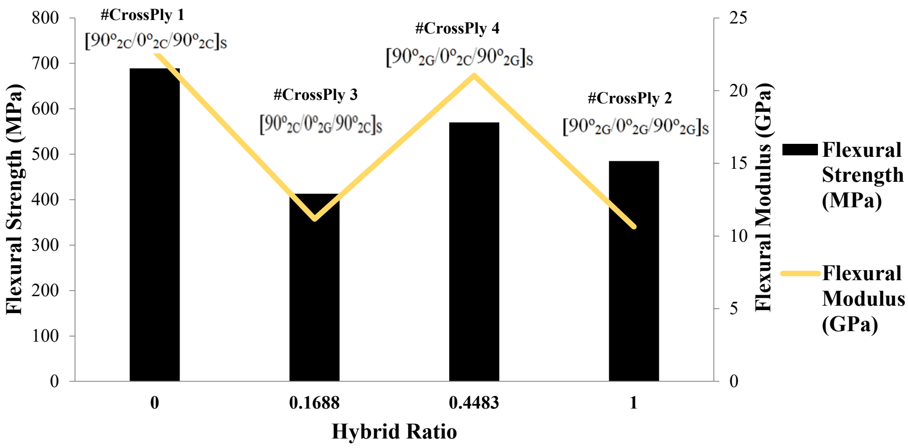


Figure 11. Histogram plot of balanced cross ply of hybrid C/GFRP on flexural modulus and flexural strength.

Figure 13(a) illustrates the systematic positioning of balanced cross-ply and quasi-isotropic hybrid composite C/GFRP with respect to their tensile and flexural modulus. Cross Ply 5 which constructed from quasi-isotropic CFRP depicts the highest flexural modulus and considerably high tensile modulus which came second after Hybrid Cross Ply 4 on the highest magnitude of tensile modulus among all the composites. On the other hand, the hybrid Cross Ply 3 represented the lowest magnitude of both tensile modulus and flexural modulus.

Figure 13(b) displays the positioning of balanced cross-ply and quasi-isotropic hybrid composite C/GFRP on tensile and flexural strength. Cross Ply 1, which is made of all CFRP balanced cross-ply layup exhibits the highest tensile strength and a quite high flexural strength. Hybrid Cross Ply 3 recorded the lowest tensile strength as well as flexural strength. Instead, hybrid CrossPly 8 demonstrated the highest flexural strength with an average magnitude of tensile strength among all the composite/hybrid composite studied.

Figure 14 represents the positioning of balanced cross-ply and quasi-isotropic hybrid composite C/GFRP with respect of strain to failure (tensile) and strain to failure (flexural). Quite significant, Cross Ply 2, which is balanced cross-ply full GFRP demonstrates the highest strain to failure (flexural) with considerably high strain to failure (tensile). Hybrid composite CrossPly 3 depicts the highest strain to failure (tensile) and substantially high strain to failure (flexural). Meanwhile, the other hybrid composite shows proximity with each other in terms of position in regards to strain to failure in tensile and strain to failure in flexural.

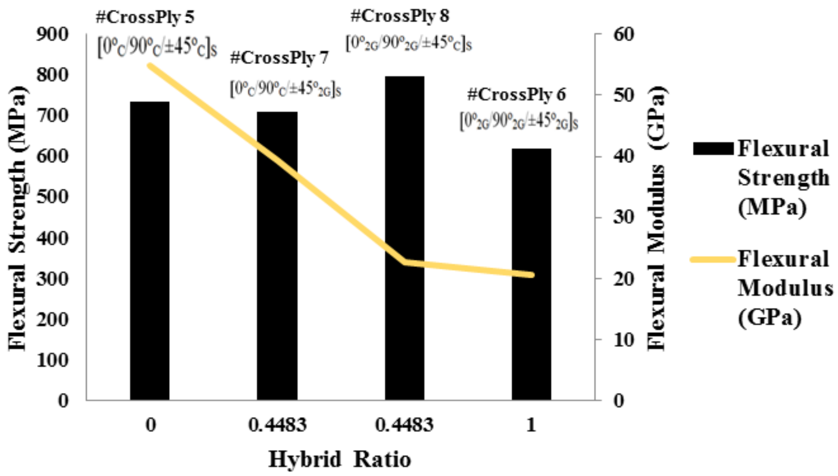
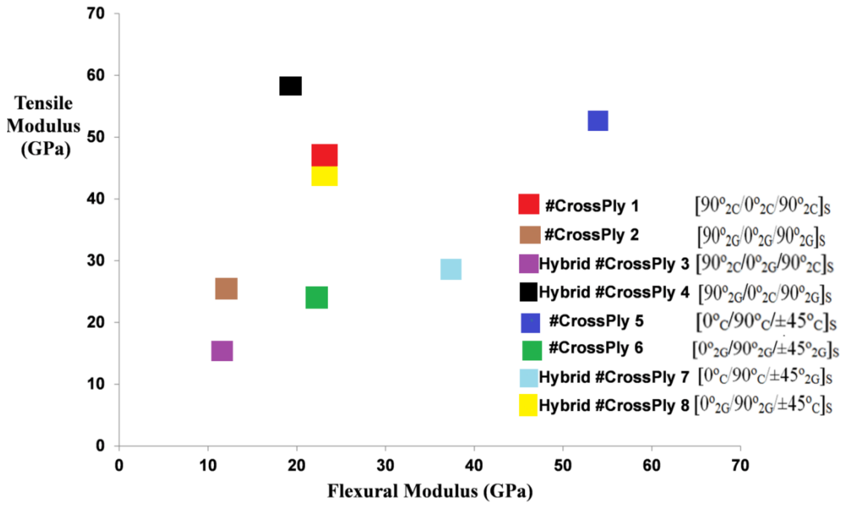
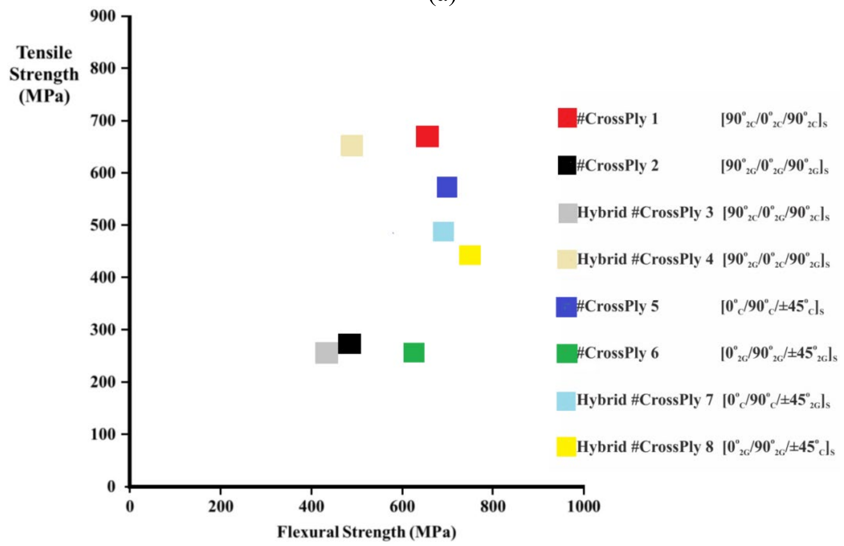


Figure 12. Histogram plot of quasi-isotropic hybrid composite C/GFRP on flexural modulus and flexural strength.



(a)



(b)

Figure 13. The positioning of balanced cross-ply and quasi-isotropic hybrid composite C/GFRP on (a) tensile and flexural modulus and (b) tensile and flexural strength.

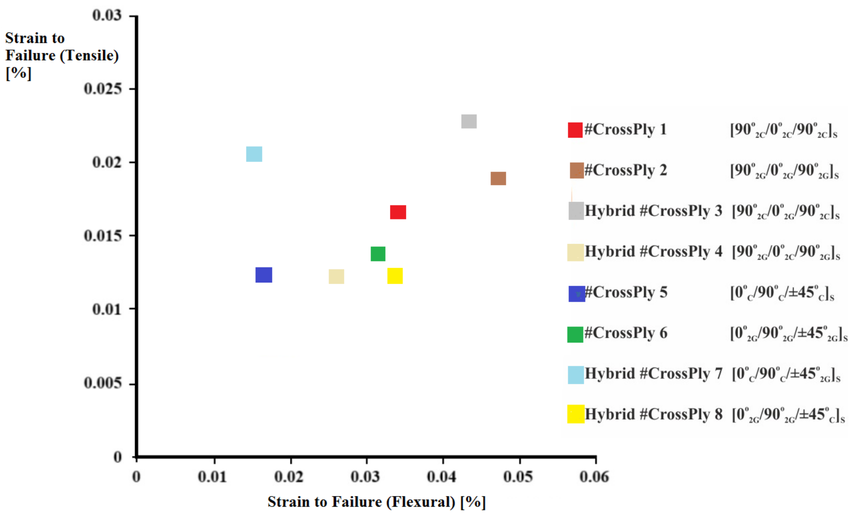
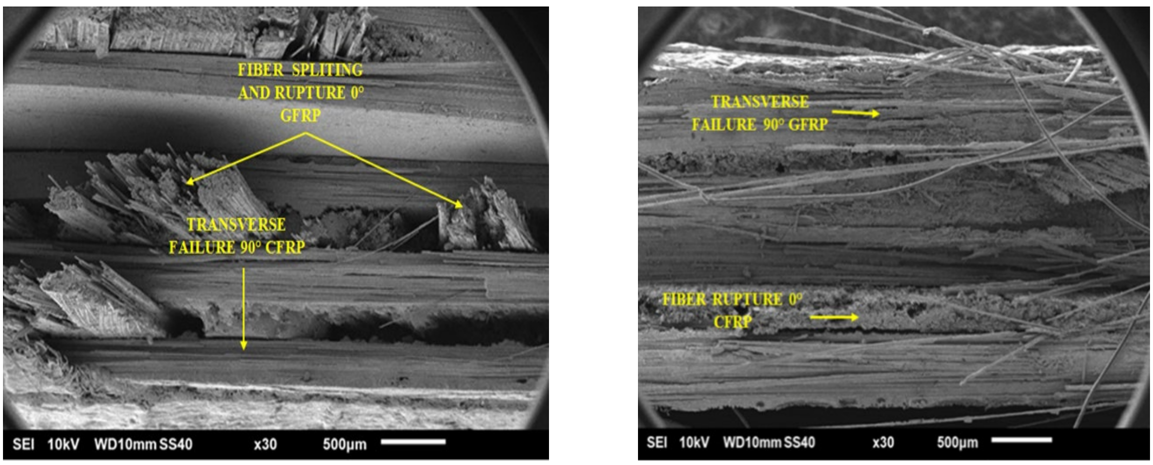


Figure 14. The positioning of balanced cross-ply and quasi-isotropic hybrid composite C/GFRP on strain to failure (tensile) and strain to failure(flexural).

Failure Mode of Hybrid Composite C/GFRP under Tensile and Flexural Loading

Composites exhibited a relatively brittle behaviour and poor damage resistance when they were subjected to tensile, compressive, flexural or mixed-mode loading conditions, which induced critical issues for their usage[23]. Fractography has proved to be a valuable composite research tool. It can provide the following information such as micromechanics of damage growth and failure; fractography underpins the understanding of failure processes within composites and consequently, the development of physically-based failure criteria[24]. Fractography has proven to be a vital tool for interpreting samples failures to support the development of failure mode assessment. For samples of three-point bending, some fracture faces, such as those generated under compression, tend not to separate. However, for tensile samples and interlaminar fractures tend to separate during failure, and are thus susceptible to post-failure damage. For instance, Figure 15(a) depicts an SEM view of hybrid composite C/GFRP Cross Ply 3 post ruptured of tensile loading. It can be observed that it involves interlaminar delamination between neighbouring plies together with transverse matrix cracking.

Figure 15(b) illustrates an SEM image of hybrid composite C/GFRP Cross Ply post damage under tensile loading. Minimal delamination observed, matrix cracking of 90°/transverse GFRP layup followed by CFRP 0° longitudinal direction fibre ruptured. This phenomenon was also discovered by other scholars [25, 26]. Figure 15(c) depicts the SEM image of hybrid composite C/GFRP Cross Ply 7 after ruptured from tensile loading. It can be observed that off-axis shear stress brought to delamination effect at the ±45° GFRP layups in the middle section on significant effect. Fibre breakage was also seen at 0° first/external layup. Figure 15(d) displays an SEM image of hybrid composite C/GFRP Cross Ply 8 after ruptured from flexural loading. It is observed that fibre ruptured of GFRP at tensile side, fibre damage and matrix cracking propagating through thickness of GFRP at compressive side. Intralayer delamination also occurred at ±45° CFRP layup. Figure 15(e) represents an SEM image of hybrid composite C/GFRP Cross Ply 4 after ruptured from flexural loading. Matrix cracking and damage for most of the GFRP layups were observed at the through thickness section for tensile and compressive side of hybrid specimen. CFRP fibre bridging and breakage in the center section in line with direction of bending applied. Figure 15(f) displays an SEM image of hybrid composite C/GFRP Cross Ply 7 post damage from flexural loading. It was assessed that CFRP layup on compressive side experiencing fibre buckling, minimal damage on ±45° GFRP layup side and minimal interlayer delamination of CFRP/GFRP observed.



(a) (b)

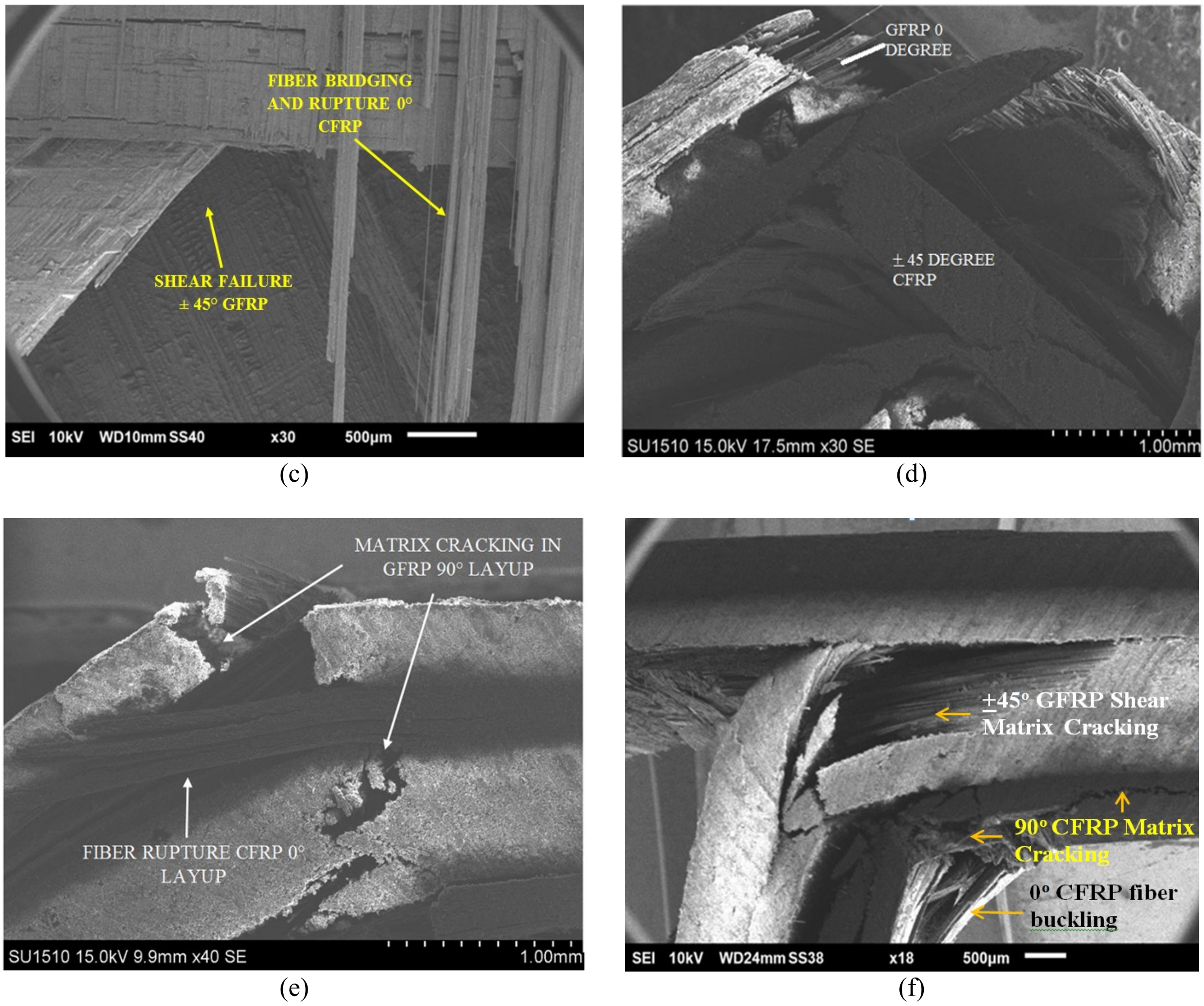


Figure 15. SEM image of hybrid composite C/GFRP (a) Cross Ply 3 (b) Cross Ply 4 and, (c) Cross Ply 7 after ruptured from tensile loading, and (d) Cross Ply 8, (e) Cross Ply 4 and (f) Cross Ply 7 after ruptured from flexural loading.

CONCLUSION

Experiments on balanced cross-ply and quasi-isotropic hybrid composite C/GFRP have been performed in regards to their characterisations towards tensile and flexural loading as per ASTM standard. For tensile mode; the factor of layup GFRP at 90°/transverse has made hybrid composite Cross Ply 4 possessed higher tensile modulus and recorded considerably high tensile Strength. The substitution of ±45° layup of GFRP into quasi-isotropic composite CFRP has induced slight non-linearity at the peak of stress-strain relationship before failure. The shear strain experienced in the ±45° layup of GFRP introduced a higher overall strain to failure for quasi-isotropic hybrid composite Cross Ply 7. From flexural behaviour perspective, the combination of GFRP layup at 0° at the tensile side, GFRP layup 90° at the compression side and ±45° layup of CFRP at shear/compression region enable the hybrid composite Cross Ply 8 to attain the highest flexural strength. The role of GFRP layup in enhancing the strain to failure in tensile and acts as dampening and reliever in improving flexural strength during flexural loading has been quantified and tested from this experiment.

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