The Effect of Hybridisation on Carbon and Glass Fibres Reinforced Composites under Quasi-Static Loading

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ABSTRACT

Fibre hybridisation in composite structures is a promising strategy to control the stiffness and energy absorption characteristics. The hybrid structure could offer a better balance of appropriate mechanical properties tailored to specific application. Carbon fibre is extremely strong compared to glass fibre, and to overcome the challenges of replacing conventional materials in respect of the appropriate mechanical properties, hybridisation seems to be a good approach. In this study interlaminar hybrid composites were produced with carbon and glass fibres as reinforcement and non-hybrid samples of carbon fibre reinforcement. All the composite plates were tested under quasi-static loading and the results obtained were plotted as load – displacement graphs for loading and un-loading; the slope of the loading curve taken as estimate for the bending stiffness. The results of the laminate bending stiffnesses were 312 kN/m, 407 kN/m, 224 kN/m and 223 kN/m for the configurations $[90_C/0_C/\pm45_C]_S$, $[90_C/0_C]_{2S}$, $[90_C/0_G/\pm45_{CG}]_S$ *and* $[90_C/0_G]_{2S}$ *respectively; which showed reduction with the introduction of glass fibres. Hence, the process of hybridisation could be used to modify a couple of the characteristics of composite structures including the natural frequencies and damping properties. Micro-photograph of the damaged section revealed matrix crack and ply debonding.*

Keywords: *fibre composites, hybrid, bending stiffness, quasi-static, autoclave.*

Introduction

Fibre reinforced composites have now come of age and due to the exceptional properties of the materials, they are now being accepted in various industrial applications particularly in the aviation industries [1]. A primary advantage is that the characteristics of the composite structure can be tailored a specific design requirement; for instance, carbon fibre is known for its high performance and weight saving material of choice for the aviation industries. Also, some aluminium parts of bicycles are now made of fibre reinforced composites because of the strength, reduced weight, rigidity and resistance to stretching of these modern-day advance materials.

Bhutta et al [2] conducted dynamic and static loading test on composites reinforced with macro steel fibres and polypropylene fibres in fly-ash and metakaolin based alkali to investigate the effect of inclination angle and reported that both the inclination angle and loading rate to failure are affected by the inclination angle, but the failure modes were similar for both static and dynamic tests. Bulut and Erklig [3] used quasi static indentation test results on hybrid composite samples to explore the energy absorption behaviour under low energy impact and concluded that the failure mechanism depends on the type of fibre reinforcement and the stacking configuration. Attard et al [4], manufacture carbon-fibre reinforced composite with hybrid matrix composition to control the damping properties as against the conventional carbon-fibre reinforced epoxy composite.

Spronk et al [5] compared static test results and the low velocity impact characteristics of carbon/epoxy and glass/polyamide-6 composite laminates. The response was compared in terms of the displacement and energy absorbed; and significant differences were noted and hence concluded that test methods are not interchangeable. Liang et al [6] subjected flax and E-glass fibres reinforced epoxy matrix composites of 43% fibre volume fraction to tension, compression and shear loadings and reported that the strength of glass/epoxy composite was higher by 76% compared to flax/epoxy composite. David and Johnson [7] modelled the crush characteristics of composite crashworthy structures under dynamic loading, using a quasi-static crush model to replicate the dynamic crush characteristics. To improve the properties of glass fibre reinforced composite, AI Selmy and Hegazy [8] developed the hybrid combination of polyamide and glass fibres as reinforcement but noted that stacking sequence has effect on the properties. The use of glass fibres for the surface and polyamide fibres in the core, enhanced the tensile and flexure strength.

Fotouhi et al [9] performed static indentation tests on S-glass / epoxy and carbon / epoxy composite laminates to assess the mechanical performance. The results from S-glass / epoxy composite revealed more deflection and energy absorbed before failure and Sun et al [10] tested tube structures made of aluminium, net carbon fibre reinforced plastic and the hybrid under transverse bending loads and observed that the energy absorbed by the hybrid structure was the higher. Bergmann et al [11] performed a few ±45° off-axis tensile tests on woven fabric composites at low and high strain rates and observed the energy absorption performance. They concluded that high strain rates affect the stiffness, strength and the energy absorbed.

Al-Mosawe et al [12] investigated about the bonding properties between carbon fibre reinforced polymer (CFRP) composites and steel using the quasi-static experimental test approach. CFRP composites of three categories were considered, classified as low modulus, normal modulus and ultra-high modulus; and concluded that ultra-high modulus CFRP composites has significant effect on the bond properties. Zhuang et al [13] examined the critical fracture plane of unidirectional fibre reinforced composite, considering a broken fibre as the nucleation point and strength support of the surrounding fibres.

Kumar et al [14] used acoustic emission to monitor the damage in quasi-isotropic glass/epoxy, glass/basalt/epoxy and glass/carbon/epoxy composites under static indentation loads and reported that the combination of carbon and glass fibres improves the interlaminar shear strength. Zuo et al [15] presented a model describing ply cracking and joint debonding of a wind turbine blade under static and cyclic loading; geometrical transition regions were reported to display crack damage when blade was under static load and sub-critical damage growth when under cyclic loading. Poyyathappan et al [16] reported that the exposure to cyclic loading for limited duration of synthetic fibre polymeric composites (hybrid or non-hybrid) improves the flexural strength; which was attributed to the strain toughening of the fibres

Sreenivas Rao et al [17] produced sisal/coir, sisal/hemp and sisal/flax fibres reinforced epoxy hybrid composites and tested for their mechanical properties. Tensile and flexure strength was higher for sisal/hemp fibres reinforced hybrid composite compared to the other two, while sisal/coir fibres reinforced hybrid composite performed better for compression strength and hardness. Echeverria et al [18], tested various hybrid composites reinforced with natural and synthetic fibres for sound absorption using the impedance tube method and revealed the indication of low absorption coefficient in the frequency range of 500 Hz to 2.5 kHz. Harizi et al [19] adopted the mechanical-acoustic experimental coupling method to investigate the behaviour of carbon fibre reinforced sandwich composites under three point bending with video-microscope to monitor the damages.

Ramaswamy et al [20] tested composite to metal joints of the types of Single-lap, interlocking adhesive and baseline adhesive subjected to static and dynamic load and reported that the interlocking adhesive joints showed between 75–120% increase in the work to failure. In another study, Zhou et al [21] reported about the effect of temperature on the three point bending properties of composite structure with Y-frame core and carbon fibre reinforced skin and observed the drop in the bending load–displacement curves with the increase in temperature. Anbazhagan et al [22] tested sandwich composite structures with skin materials of aluminium, glass fibre-reinforced plastic and metal-composite hybrid with honeycomb core, till perforation by quasi-static loading and was able to predict the experimental force-displacement response by numerical method.

Jung et al [23] tested open-cell aluminium foams and new Ni/Al composite foams under static and impact loads and reported the Ni/Al hybrid structure as a better energy absorber. Low energy impact of 25 – 50 J and quasi-static indentation test were conducted on particle-toughened composite by Bull et al [24] and identified that particle toughened composites can delay the onset of fracture. Taghizadeh et al [25] tested composite plates made of Dyneema / Glass woven fibres and aluminium face sheets with cylindrical indenters of different nose shapes and reported that the presence of Dyneema improved the load carrying capacity. Ikbal et al [26] concluded that hybrid composites made of intralaminar layer of carbon and E-glass fabrics in epoxy matrix gives higher tensile and compressive strengths.

The use of composites in the industries is on the increase and different researchers and scientists have discussed the characteristics under various loading conditions. Hence, it is important to continue the discussion about the behaviour of hybrid and non-hybrid composites under loading. Therefore, in this investigation the behaviour of composites laminate of the following configurations, $[90_C/0_C/\pm45_C]_S$, $[90_C/0_G/\pm45_{CG}]_S$, $[90_C/0_C]_{2S}$ and $[90_C/0_G]_{2S}$ under quasi-static loading were evaluated. Considering the same thickness of the samples they were all gradually loaded to 2.5 kN at the rate of 10 mm/min and then unloaded to zero using the instrumented universal testing machine. The four laminates considered in this study are all the same thickness, two of them have ±45° plies which helps in the absorption of shear loads in structural applications. The laminates consist of the hybrid, non-hybrid, cross-ply and quasi-isotropic characteristics and the results obtained showed the differences in the behaviour.

Material properties

Carbon and glass fibre unidirectional epoxy matrix materials of 60% fibre volume fraction were used for this study. The hybrid laminates manufactured comprised of equal composition of the two types of reinforcements, that is 30% glass fibre and 30% carbon fibre. The carbon fibre reinforced–epoxy tape was obtained from Easy Composites Ltd, while the glass fibre reinforced prepreg was supplied by Cytec Industrial Materials Ltd. Fibre reinforced composite structures usually give combination of properties such as modulus, rigidity, strength etc. which are preferred compared to traditional materials. The samples used for this investigation were produced with glass fibre and carbon fibre reinforced composite materials and their mechanical properties are shown in Tables 1 and 2 respectively.

Table 1: Mechanical properties of glass fibre reinforce lamina.

PROPERTY	**VALUE**
Longitudinal modulus, E_1 (GPa)	69.7
Transverse modulus, E_2 (GPa)	7.5
Transverse modulus, E_3 (GPa)	7.5
In-plane shear modulus, G_{12} (GPa)	3.58
Major Poisson's ratio, v_{12}	0.32

Table 2: Mechanical properties of carbon fibre reinforce epoxy lamina

PROPERTY	**VALUE**
Longitudinal modulus, E_1 (*GPa*)	234
Transverse modulus, E_2 (*GPa*)	10
Transverse modulus, E_2 *(GPa)*	10
In-plane shear modulus, G_{12} (*GPa*)	6
Major Poisson's ratio, v_{12}	0.3

As indicated in Table 2, the value of the elastic modulus E_1**,** of carbon fibre is stronger compared to fibre glass and the decision to adopt carbon and/or glass reinforcement in composites will depend on many considerations in a design process. Carbon fibre reinforcement will be suitable if a small amount of flexibility is required compared to fibre glass.

Manufacture of test samples

The test samples were produced from rolls of pre-pregs of fibre reinforced lamina. Using a 45° squares and sharp blade, appropriate sizes (240mm x 210mm) of laminae were obtained from the roll and stacked according to the configuration shown in Table 3 to form the laminates. After stacking all the plies of the laminates, a roller was used to further press them together, purpose of which is to reduce any possible air gaps. They were then placed on a steel plate and then covered with release film, breather cloth, vacuum bag and sealed round its perimeter with a tape as shown in figure 1 and then the whole assembly was placed under as vacuum pressure for about 2 hours before curing in the autoclave. The schematic of the bagging of the composite laminate under vacuum is shown in figure 2. The vacuum process helps to eliminate residual air trapped within the laminate.

Figure 1: Composite laminate under vacuum pressure.

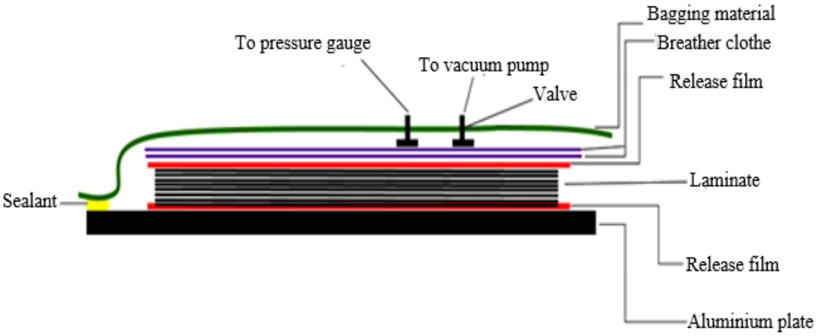

Figure 2: Vacuum bagging of composite laminate.

Table 3: Laminate stacking configuration

NON HYBRID	HYBRID
$[90_C/0_C/\pm45_C]_S$	$[90_C/0_G/\pm45_{CG}]_S$ (represent – $[90_C/0_G/45_C/-45_G]_S$)
$[90_C/0_C]_{2S}$	$[90_C/0_G]_{2S}$

C – Carbon fibre ; **G –** Glass fibre ; **S** – Symmetric laminate

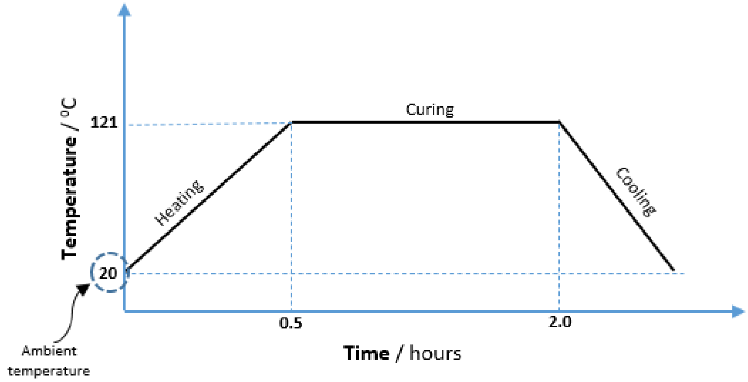

Figure 3: Composite manufacturing cure cycle.

After the vacuum pressure is released, the assembly was immediately transferred to the autoclave for curing and the cure cycle is as illustrated in figure 3. The laminates were gradually heated to a temperature of 121°C and maintained at this temperature for a period of 90 minutes, after which the door of the autoclave was slightly opened for a gradual cooling to ambient condition. After completion of curing process in the autoclave, the assembly was carefully taken out the unit; the sealant and bagging material removed, followed by the breather cloth and release film before taking out the samples. The edges of the manufactured test samples were trimmed using an abrasive cutting tool.

Experimental Procedure

The flexural strength of composite gives a knowledge about the ability to resist deformation under bending load and this depends on the boundary conditions. In these series of experiments carbon fibre/epoxy composites and glass/carbon fibre/epoxy hybrid composites were supported on a rectangular hollow steel base on the instrumented Tinius Olsen universal testing 25ST machine and clamped at two opposite sides as shown in figure 4 and all efforts were taken to ensure that the clamps were tightened properly for every test. The test samples were manufactured to the dimensions of 240(mm) x 210 (mm) because of the features of available support fixture shown in figure 5. The test machine has a maximum loading capacity of 25 kN and the samples were loaded at a cross-head speed of 10 mm/min. The load – displacement data were obtained for loading and unloading of the test samples for analysis. The tested samples were examined through visual inspection and micro-photographs of the fracture zones.

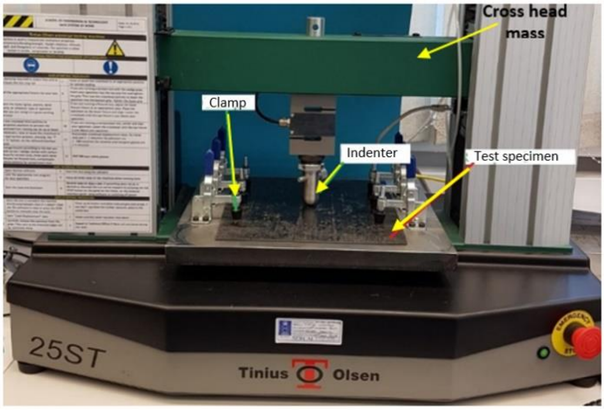

Figure 4: Experimental setup

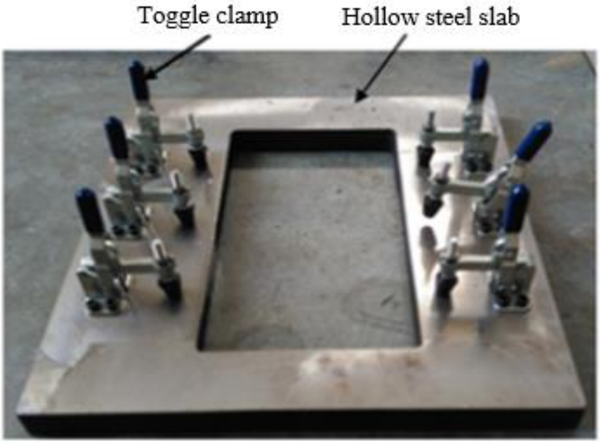

Figure 5: Photograph of the test sample support fixture.

a b

Figure 6: top (a) and back (b) surface photographs of tested laminate.

Presentation of the front and rear surfaces of a sample after the test are shown in figure 6. The experiments were conducted to investigate about the energy absorption characteristics of fibre reinforced composites and the effect of hybridization. Physical surface examination of the tested composite laminate showed the mark of indentation of the on the top surface as seen in figure 6a. The tested sample was cut across through the point it was loaded by the indenter using an abrasive cutter and micro-structural photograph of the damaged surface was taken with a ‘Motic’ metallurgical microscope at x 50 magnification.

Experimental Results

The results of composite plates clamped to a support and loaded at the centre under quasi-static condition using Tinus Olisen universal test machine are presented here. The experimental results for all the composites tested are displayed in figures 7 and 8 as load – displacement graphs. All the samples were loaded using the universal test machine to a load of 2.5 kN and then unloaded. This value was chosen as it was enough to create internal damages in the laminates considering their thickness. The loading sections for the results obtained from test conducted on the non-hybrid composite samples show a couple of very small sharp drop of the loading, these are likely due to the crack of the matrix material (i.e. epoxy) by the indenter as revealed by the cross-sectional photograph of figure 9. The test results for the hybrid samples consisting of both the carbon and glass fibres as reinforcement show some wrinkling around the peak zones for both the loading and unloading curves, this is thought to be because of the combined effects of fibre properties mis-match and matrix crack; this is in agreement with the study conducted by Liu 27]. A major cause of delamination or crack in composite laminate is the shear stresses or mismatching of bending stiffnesses due to the stacking configuration and differences in the elastic properties, this was highlighted by Liu [27] and Jacob et al [28]. Also, Ahmed & Vijayarangan [29] emphasised on the importance of good interfacial adhesion between the fibre and the matrix, of which effect is particularly significant for thick composites, close to supports or in composites with weak interfaces.

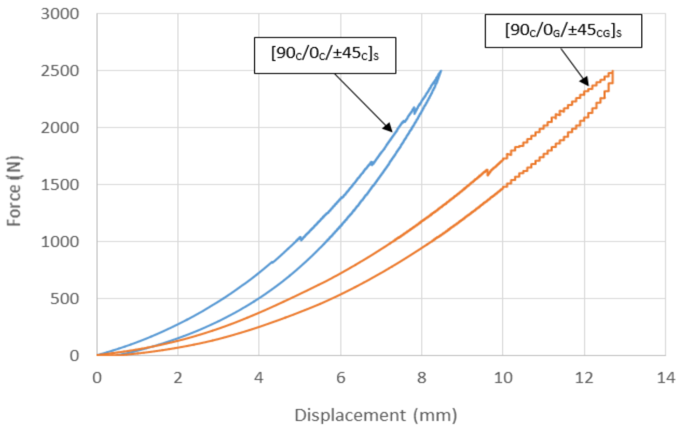

Figure 7: Superimposed force – displacement plot for laminate $[90_C/0_C/\pm45_C]_S$, and $[90_C/0_G/\pm45_{CG}]_S$

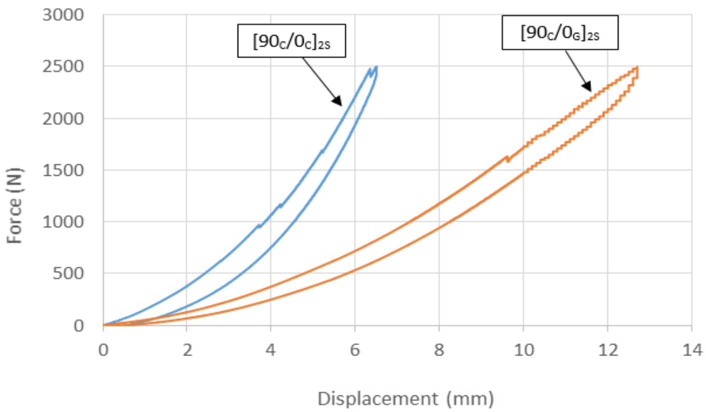

Figure 8: Superimposed force – displacement plot for laminate $[90_C/0_C]_{2S}$, and $[90_C/0_G]_{2S}$

The superimposed graphs in figures 7 and 8 showed that the laminate stacking configuration are the same, but one is made carbon fibre as reinforcement and the other combination of carbon and glass fibres. All the composite plates were loaded to a maximum of about 2.5 kN, but the displacements are different. The maximum displacements are 8.46 mm, 6.5 mm, 12.7 mm and 12.7 mm for the laminate $[90_C/0_C/\pm45_C]_S$, $[90_C/0_C]_{2S}$, $[90_C/0_G/\pm45_{CG}]_S$ and $[90_C/0_G]_{2S}$ respectively. Hence, for the same loading regime the displacement of the hybrid composites was more; that is the non-hybrid composites were stiffer. This is expected as the modulus of carbon fibre is higher than that of glass fibre. This will generally imply that shock absorption could be controlled by the use hybrid composites made of fibre reinforcements of different moduli.

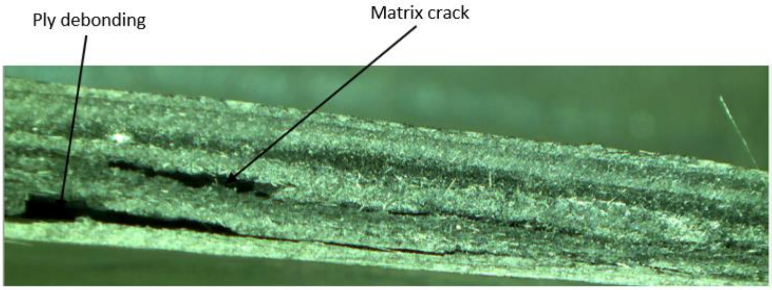

Figure 9: Cross section microphotograph of tested laminate.

The image revealed the complex failure mechanisms of the composite (figure 9). The results extracted from the graphs plotted in figures 7 and 8, and microscope image depict that both stacking sequence and hybridisation play critical role in the overall deformation and energy absorption characteristics of the composite plates. As shown in figure 9 the predominant modes of failure (energy dissipation) were matrix crack, delamination and fibre/matrix interfacial debonding.

Analysis of test results characteristics

The bending stiffness has been known to be an important property in assessing the damage resistance of a composite in particular delamination, this highlighted by Liu [27]. It changes with the stacking configuration of the plies in the composite. It is an important property of a composite plate as it gives knowledge about the response under loading. To estimate the bending stiffness of the composite plates used for this study a section of the loading curve was plotted and the average of the slope estimated as a straight line with R^2 value of approximately 1, as shown in figure 10. The data from the origin to about 100 N were neglected as this region was taken for the bedding in of the hemispherical indenter into the composite laminate. The R-squared value gives measure about the scatter of the data points about the straight line and results between 0.9 and 0.99 are usually classed as very good.

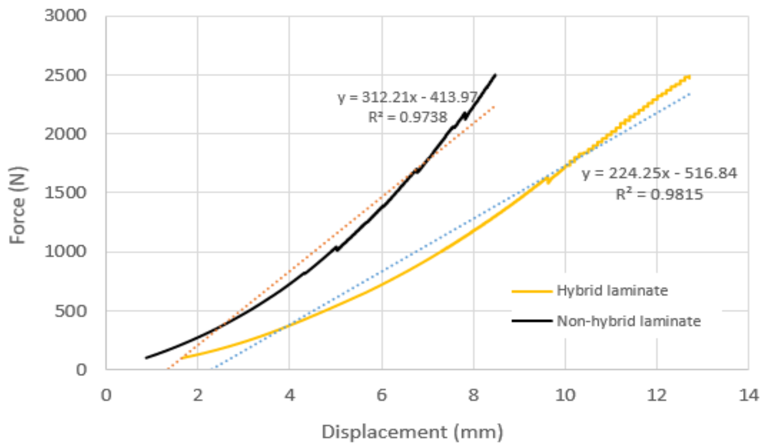

Figure 10: Representative plot for CFRP laminate to determine the stiffness

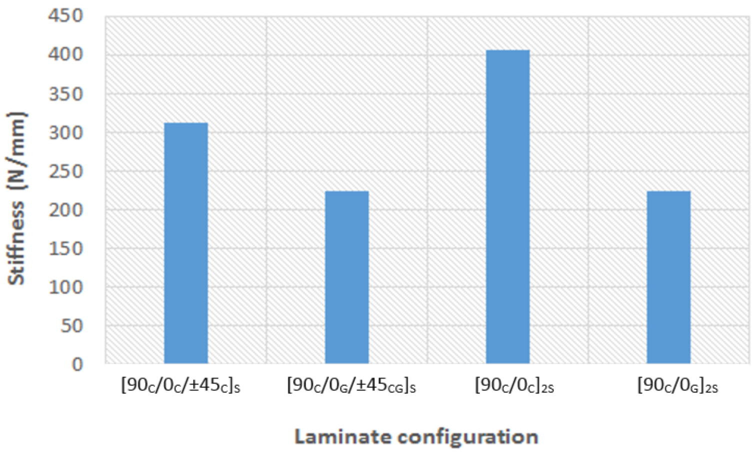

Figure 11: Comparison of laminate bending stiffness.

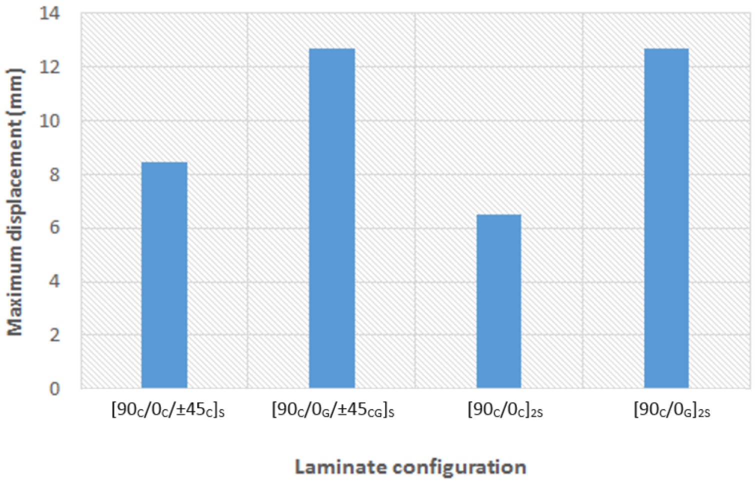

Figure 12: Maximum displacement plot of the laminates.

Figure 11 compares the bending stiffnesses of the non-hybrid and hybrid composite plates. The bending stiffnesses were estimated by taking the slope of a straight line through the mean data of the load – displacement graphs and the results are 312 kN/m, 407 kN/m, 224 kN/m and 223 kN/m for the laminates $[90_C/0_C/\pm45_C]_S$, $[90_C/0_C]_{2S}$, $[90_C/0_G/\pm45_{CG}]_S$ and $[90_C/0_G]_{2S}$ respectively. Also used to assess the stiffness were the maximum displacement of the composite plates represented in figure 12; the values are 8.46 mm, 6.5 mm, 12.7 mm and 12.7 mm for the laminates $[90_C/0_C/\pm45_C]_S$, $[90_C/0_C]_{2S}$, $[90_C/0_G/\pm45_{CG}]_S$ and $[90_C/0_G]_{2S}$ respectively. The deflection of the hybrid composites was more and hence expected to absorb more energy in the case a load strike, which agrees with the findings of Fotouhi et al [9], Jesthi & Nayak [30] and Hung et al [31]. Also reported that the use of hybridised composites of carbon and glass fibre could minimised the cost and controllably achieved the desired properties.

Concluding remarks

Hybrid composite structures have extensive engineering applications in present day advance technology; in cases where stiffness is less important natural fibres could be included as a reinforcement. In this investigation carbon fibre - epoxy matrix composites and glass/carbon fibre-epoxy based hybrid composites were tested under quasi-static condition to analysis their characteristics. The following conclusions were drawn from the results:

- The non-hybrid composite laminates manufactured with carbon fibre-epoxy plies were stiffer under bending compared to their hybrid counterpart of similar stacking configuration;
- The maximum displacement of the hybrid composite plates was higher for the same maximum load and cross-head loading speed;
- Hybridisation affects composite laminate characteristics and can be used to control the overall behaviour, which mean that the use of two or more types of fibres of different elastic properties as inter or intra laminar reinforcement in composites will assist for tailoring the mechanical properties of the structure.

Acknowledgement

The author is grateful to the University of Hertfordshire for the support given to this study.

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