Experimental optimization of flexural behaviour through inter-ply fibre hybridization in FRP composite

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Abstract

Inter-ply fibre hybridization is one of the promising techniques to improve the mechanical properties of a laminated FRP composite, but the mechanical response of these hybrid composites under a flexural kind of complex loading is not fully explored experimentally. Present investigation is focused to improve the flexural properties of a glass/epoxy (GE) composite by replacing some of the GE plies by equal No. of carbon/ epoxy (CE) plies at different locations. In the 7 layered composite, replacing 2 GE plies at each ends of a GE composite resulted in a hybrid composite (C2G3C2) having 93% modulus and 96% strength as that of a C7 composite. Presence of CE plies at the tensile side leads to enhanced strength and modulus but at the same time makes the hybrid more prone to catastrophic failure. Whereas, placing the entire CE plies at the compressive side yielded progressive failure behaviour similar to that observed in the GE composite. To understand the failure mechanisms of GE and CE plies in different composite systems their fractured surfaces were studied by SEM.

Keywords: Hybrid composite; stacking sequence; flexural behaviour; fractography

1 Introduction

The excellent mechanical performance of the fibre reinforced polymer (FRP) composite in combination with its low density and corrosion resistance has made it a revolutionary material in the current structural world. The flexibility in terms of selecting the constituent materials and the ease of the fibre/polymer interfacial tailorability by physical, chemical and physico-chemical interactions has widened its potential area of application. The decisive mechanical parameters to certify a material for an engineering application include its (i) resistance to deformation (stiffness), (ii) maximum load carrying capacity (strength), (iii) damage tolerance (toughness) and (iv) cost. All the mechanical properties of these materials are again governed by the environmental moisture content [1], temperature [2–4] and loading rate [5,6]. Over the years there is a search for materials exhibiting high stiffness, strength and toughness with another special character, i.e. low density. Carbon fibre reinforced polymer (CFRP) composite exhibits very lightweight with an exceptionally high strength and stiffness but a very poor ductility resulting in catastrophic failure. Another factor which limits the application of CFRP is its high cost. Hence many attempts have been taken to replace some volume fraction of the carbon fibre in CFRP by other reinforcement fibre with an objective to reduce the overall cost of the material simulataneously enhancing the toughness but with a little or no sacrifice on the density, stiffness and strength of CFRP composite. Metal fibre possesses optimum stiffness, strength and toughness, but its high density limits its use in FRP composites. The extra-ordinary toughness of the polymer fibre with low density makes it a good engineering material, but it suffers from poor stiffness, strength and high temperature resistance. Glass fibre remains an important engineering material due to its low cost, intermediate strength and stiffness with relatively higher toughness than that of carbon fibre. The motivation behind using two types of reinforcements in a single polymer composite is to avail the advantages of both fibres and mitigating some typical disadvantages associated when the fibres are used separately [7–9]. Combining two different reinforcement fibres may be done at different configurations, i.e. (i) combining both fibre filaments into fibre bundle (intrayarn), (ii) combining different fibre bundles during sieving to make fibre layers/sheets (intralayer), and (iii) using different fibre sheets during their stacking to fabricate the final laminate (interlayer) [10].

The state of stress during tensile and compressive loading is relatively simple and stress distribution throughout the thickness of the specimen is mostly uniform, whereas in case of impact and bending load, the state of stress is complex and the nature of stress distribution varies throughout the thickness of the specimen. Hence the stacking sequence plays an important role on the mechanical response of hybrid composites under these loadings [11,12]. Over the years, significant attention has been paid on deriving the tensile behaviour of hybrid composites and in tensile loading [10,13–16], some of the special properties like pseudo-ductility has been proven to be improved by the hybridization technique. But in real time application, bending is a very commonly encountered loading condition in various mobile and immobile structural components. In a 3-point bend test, the two extreme outer layers are subjected to different tensile and compressive stresses, whereas the central layer may experience a shear stress. In addition, other artefacts of the testing such as deformation just below the roller influence the test results. Davies et al. [17–19] have reported a couple of articles on experimental analysis and mathematical modelling of flexural performance of hybrid composites. They have reported 40% and 9% improvement in flexural strength in a glass/carbon hybrid composite than pure carbon and glass composites respectively. But in that case, the tensile strength of the carbon fibre used was lower than the glass fibre.

GFRP composites have been used from a significant long time period as a structural material like rebar, due to its moderate toughness in combination with low cost, but still this material suffers from limited strength and stiffness [20,21]. On the contrary, CFRP exhibits superior strength and stiffness but with a low toughness and high cost. Hence, this current investigation is focused on optimizing the flexural properties of GFRP by replacing some glass fibres with carbon fibres of proper volume fraction and architecture. Theoretical estimation of the strength and modulus of laminated composites in tensile and compressive loading is quite simple and well established. Still due to complex state of stress during flexural loading, prediction of the mechanical properties becomes quite tedious and requires lots of material properties. A recent review has suggested that there is a dearth in the literature for understanding the flexural performance of laminated hybrid composites [22]. In this article focus has been given on the flexural performance of glass/carbon hybrid epoxy composites with various volume fractions of both fibres and their stacking sequence.

2 Experimental Section

2.1 Materials

In the present study the glass fibre (GF) used was a 3K plain weave type containing filaments of 15 μm diameter manufactured by Owens Corning. The carbon fibre (CF) was also 3K plain weave type with a filament diameter of 7 μm manufactured by Soller Composites. The epoxy used was diglycidyl ether of Bisphenol A (DGEBA) and the hardener was Triethylene tetra amine (TETA), both were manufactured by Atul Industries, India under the trade name of Lapox L-12 and K-6 respectively. Some basic properties of the fibres and epoxy are mentioned in table-1.

Table-1: Specifications of the materials used

Property	Glass Fibre	Carbon Fibre	Epoxy
Tensile strength (GPa)	3.1	4	0.11
Tensile Modulus (GPa)	76	240	4.1
Strain to failure (%)	4.5	1.5	4.6

Density (g/cc)	2.52	1.8	1.16
Areal weight of fabric (g/m^2)	360	200	-
Thickness of the fabric layer (mm)	0.2	0.2	

2.2 Fabrication of laminates

The polymer used for fabricating the current FRP composites was epoxy. The reinforcement fibres used were GF and/or CF. The glass fibre/epoxy (GE), carbon fibre/epoxy (CE) and glass carbon hybrid epoxy (GCHE) composite laminates in the current study were fabricated by hand lay-up method followed by hot press compression to maintain thickness uniformity and reduce the void content in the final laminate. The fibres were first cut into 250 mm × 250 mm sheets and then the volume fraction of glass and carbon were controlled by varying the number of layers of CF, i.e. 0, 1, 2, 3, 4 and 7 in the laminate. But in all the cases the total number of fibre layers (both CF and GF) was 7. The stacking sequence of the laminates was altered by putting CFs in various locations in the laminate as shown in figure 1.

After fabrication of the laminates by hand lay-up method all the laminates were pressed at 10 kg/cm^2 pressure and 60 °C temperature for 20 minutes. This ensures reduction of the void content, thickness uniformity in the final laminate and also is required for curing of the FRP laminates suitable for further handling. At this stage, all the laminates were having a thickness 1.8±0.1 mm. Then samples of required dimensions for flexural testing were cut from the laminates as per ASTM D7264 standard using a diamond tipped wheel cutter. All the samples were then post cured at 140 °C temperature for 6 hours [23] in an oven.

2.3 Flexural Testing

Flexural testing of all the specimens was carried out using the 3-point loading fixture of universal testing machine (Instron 5967) as shown in figure 2, at a loading rate of 1 mm/min.

As mentioned earlier, during flexural testing the nature of stress and stress distribution is different in upper and lower surfaces. Hence, samples which are not symmetric about their central plane, are tested in both ways, e.g. For 6G+1C sample with the carbon layer at one end, flexural test was performed once with CF layer as the top/loading surface (CG_6 configuration) and again with CF layer as the bottom surface (G_6C configuration). All the configurations of stacking in GCHE composites during testing are mentioned in table-2.

Table-2: Stacking sequence during flexural testing of composite samples with various no. of CF layers.

No. of CF layers (n_c)	Designation of the composite system	Stacking sequence during testing (top to bottom)
0	7G	G_7
1	6G+1C	CG_6, G_6C, G_3CG_3
2	5G+2C	C_2G_5, G_5C_2, CG_5C
3	4G+3C	C_3G_4, G_4C_3, C_2G_4C, CG_4C_2, $(GC)_3G$
4	3G+4C	C_4G_3, G_3C_4, $C_2G_3C_2$, C_3G_3C, CG_3C_3
7	7C	C_7

[G and C represent GF and CF respectively and subscripts denote its corresponding no. of layers placed together.]

2.4 Fractography analysis

To observe the possible initiation of the failure in the samples, in some cases, the flexural testing was stopped when a significant drop in stress value was noticed in the stress-strain plot. The front faces (during testing) of these samples were then observed in a scanning electron microscope (SEM).

3 Results and Discussions

3.1 Density and void content

As CF exhibits a low density (1.8 g/cc) in comparison to GF (2.52 g/cc), replacing GE plies in GE composite by CE plies inherently makes the composite specimen lighter. This again adds an advantage to CE composite which results in superior specific properties in the material. The theoretical volume fraction of carbon (v_c) in each specimen was determined by using the following formula

$$v_c = \frac{V_c}{V} = \frac{\frac{n_c \times w_A \times A}{\rho_c}}{A \times t} = \frac{n_c \times w_A}{\rho_c \times t} \quad \dots (1)$$

Where,

V_c= vol. of carbon fibre in the specimen

V = vol. of the specimen

n_c= No. of carbon fibre layers

w_A= Areal weight of carbon fibre (200 g/m^2)

A= Area of the specimen ($length \times width$)

ρ_c= Density of carbon fibre (1.8 g/cc)

t = thickness of the specimen

Similarly, the theoretical volume fraction of glass (v_g) was also determined for all specimens.The remaining volume fraction in the specimens was considered to be the volume fraction of epoxy (v_e). The theoretical volume fractions of all the constituents are reported in table-3.

The volume of CF in the overall GCHE laminate with respect to the total volume of reinforcement is taken as hybrid ratio (r_h) and is defined by the following expression [18].

$$r_h = \frac{v_c}{v_c + v_g} \quad ... (2)$$

The theoretical density (ρ_t) of all the samples was calculated by rule of mixture and the actual density (ρ_a) was measured by Archimedes principle. The difference in theoretical and actual density of the samples may be regarded as the void content (v_v) in the sample and was determined from equation 3 and are given in table-3.

$$v_v = 1 - \frac{\rho_a}{\rho_t} \quad ... (3)$$

The density and void fraction in all the composite systems are shown in figure 3. It is evident from figure that as the volume fraction of carbon increases, the laminate becomes lighter. The void fraction in all the laminates was within the range of 2.8-4.5%.

Table-3: Theoretical volume fraction of the constituents, hybrid ratio, theoretical and actual density and void fraction of each laminate

Composite system	Stacking	v_c	v_g	v_e	r_h	ρ_t(g/cc)	ρ_a(g/cc)	v_v

7G	G7	0.00	55.56	44.44	0.00	1.92	1.86	3.13
6G+1C	G6C or CG6	6.17	47.62	46.21	0.11	1.86	1.79	3.86
	G3CG3	6.17	47.62	46.21	0.11	1.86	1.81	2.84
5G+2C	C2G5 or G5C2	12.35	39.68	47.97	0.24	1.79	1.72	4.04
	CG5C	12.35	39.68	47.97	0.24	1.79	1.71	4.23
4G+3C	C3G4 or G4C3	18.52	31.75	49.74	0.37	1.72	1.64	4.49
	C2G4C or CG4C2	18.52	31.75	49.74	0.37	1.72	1.65	4.07
	(GC)3G	18.52	31.75	49.74	0.37	1.72	1.64	4.39
3G+4C	C4G3 or G3C4	24.69	23.81	51.50	0.51	1.64	1.59	3.05
	C3G3C or CG3C3	24.69	23.81	51.50	0.51	1.64	1.59	3.05
	C2G3C2	24.69	23.81	51.50	0.51	1.64	1.59	3.05
7C	C7	45.75	0.00	54.25	1.00	1.44	1.39	3.47

3.2 Flexural Testing

The flexural properties of a hybrid FRP composite are not only dependent on the volume fraction of each constituent, but also on the stacking sequence of the fibres. To have the understanding on these two aspects, specimens were tested with different volume fraction of carbon with different stacking sequence. First, the effect of stacking sequence was evaluated with 1 layer of carbon fibre and then n_c was varied.

3.2.1 GCHE composite with $\boldsymbol{n_c = 1}$

As the state of stress is complex during flexural loading, there exist different zones across the thickness of the sample experiencing different types of stress (tensile, compressive and shear) with different magnitude. The central plane of the sample is known as neutral plane which doesn’t experience any tensile or compressive load, whereas this only experiences a shear stress with low span to depth ratio [24]. From the central plane there exists a gradient of stress in either ways (top or bottom) through the thickness of the sample. The top plane experiences the maximum compressive stress, whereas the bottom plane experiences the maximum tensile stress.

Hence, it may be anticipated that the performance of the GE composite may be effectively altered when the GF layer at the top, centre or bottom is replaced by the CF. This concept motivated for carrying out the flexural performance of GCHE composite with 1 layer CF with 3 possible stacking sequences, i.e. CG_6 (CF at top), G_3CG_3 (CF at centre) and G_6C (CF at bottom). The flexural stress-strain plot of all these GCHE composites with pure GE composite (G_7) and pure CE composite (C_7) is shown in figure 5.

It is evident from figure 5 that there is a huge difference between the flexural behavior of G_7 and C_7 composites. The strength and modulus of C_7 composite is 92% and 128% higher than G_7 composite respectively. At the same time, the strain at peak load for C_7 is 20% lower than G_7 composite. Another important observation is that the failure of C_7 composite is catastrophic, whereas the failure is progressive in case of G_7 composite. The higher strength and modulus in C_7 than G_7 may be attributed to, (i) the inherent higher strength and modulus of CF than GF (as can be seen from table-1) and (ii) the better fibre/polymer interfacial bonding in case of CF/epoxy composite [25] . When the CF in the 6G+1C composite laminate was placed at the central plane (i.e.G_3CG_3), the flexural strength and modulus were increased by 10% and 17% respectively compared to G_7, and there is almost no change in the strain at peak of both specimens. In contrast to G_3CG_3, G_6C and CG_6 exhibit 26% and 20% higher strength and 39% and 42% higher modulus than G_7 respectively. Although the strain at peak of G_6C is higher than CG_6, but its failure is catastrophic due to presence of CF at the bottom (brittle tensile failure of CF) which is undesirable for any structural application. As the strength and modulus of both G_6C and CG_6 are equivalent, CG_6 may be treated as the better candidate due to its progressive failure behavior or better damage tolerance capacity. Hence amongst all the 3 6G+1C composite specimens, CG_6 can be treated as the best configuration with better strength and modulus with a progressive failure behavior.

3.2.2 *GCHE composite with* $\boldsymbol{n_c = 2}$

As placing the CF at any of the ends of the GCHE laminate yields better flexural performance than placing the CF at the central plane (as observed from section 3.2.1), in all the configurations now onwards, the CFs were kept on putting at the ends of the laminates. Hence the possible stacking sequences with 5G+2C composite system are, (i) both CFs at tensile end (G_5C_2), (ii) both CFs at the compressive end (C_2G_5) and (iii) One CF each at tensile and compressive end (CG_5C). The flexural properties thus obtained are shown in fig. 6.

The strength of C_2G_5 and G_5C_2 were found to be increased by 44% and 24%, whereas the modulus increment were found to be 38% and 43% respectively compared to G_7. Placing 1 layer of CF at each ends of the specimen (i.e. CG_5C), a drastic increment in modulus was noted (85% compared to G_7) and the strength was also increased by 50% making CG_5C to be the most strong and stiff candidate between all the configurations of 5G+2C composite system. Although there exists a sudden stress drop in the stress-strain behaviour of CG_5C composite, still the strain at failure (where there is a sudden load drop and the sample is not capable of further deformation and ultimately breaks) is 16% higher than its strain at peak. This difference in failure strain and strain at peak gives an indication to the engineers for its successful replacement before its catastrophic failure unlike C_7 where the failure strain coincides with the strain at peak. Hence, among all the configurations of 5G+2C composite system studied, CG_5C was found to be more suitable.

3.2.3 *GCHE composite with* $\boldsymbol{n_c = 3}$

Positioning CF at the top and/or bottom layer of the GCHE composite, better mechanical performance was obtained. In this sequence further the volume fraction of carbon in GCHE composite was increased by increasing the no. of CF layer to 3 and the effect of lay-up sequence was also studied. Similar to earlier configurations, here also all possible combinations of putting 3 CFs at the top and/or bottom layer (C_3G_4, G_4C_3, C_2G_4C, CG_4C_2) were studied with an extra configuration of alternate GF and CF ($(GC)_3G$ or GCGCGCG). The flexural properties of these GCHE composites are compared with GE and CE composites as shown in fig. 7.

Placing all the 3 CFs on the either side of the GCHE composite resulted in a similar modulus improvement of around 37% compared to G_7. But, the strength and strain at peak of C_3G_4 was 13% and 21% higher than G_4C_3. In the $(GC)_3G$ configuration, although the strain at peak is almost similar to G_7, but the modulus obtained was not as significantly higher compared to other configurations of 4G+3C composite system. One important point here to observe is that the trend of deformation behavior of C_3G_4 and $(GC)_3G$ specimens resemble with that of G_7 (progressive failure). As putting CFs on both sides of the GCHE composite exhibited improved properties than placing them together at either side (as observed from section 3.2.2), here also better modulus was obtained in case of C_2G_4C and CG_4C_2 (both around 77% higher compared to G_7). The strength and strain at peak of C_2G_4C are 32% and 42% higher than CG_4C_2 respectively. Hence, C_2G_4C exhibits maximum strength and modulus in comparison to other configurations of 4G+3C composite system. Other interesting point here is to note that in case of C_2G_4C, there exists a sudden drop in stress value at a strain of 1.64%, but still the sample is capable of bearing further strain, with a stress value more than that of the G_7 composite. If we compare from the C_7 point of view, the strength and modulus achieved by C_2G_4C specimen were 86% and 77% of the C_7 composite respectively.

3.2.4 *GCHE composite with* $\boldsymbol{n_c = 4}$

As reported earlier, here also it was noted that placing CFs at both ends ($C_2G_3C_2$, C_3G_3C, CG_3C_3) yields a higher modulus than placing all the CFs at either end (C_4G_3, G_3C_4). Out of all the configurations of 3G+4C composite system, $C_2G_3C_2$ (where the hybrid ratio is only 0.51) was found to be having phenomenal high strength and modulus, which are *96%* and *93%* that of C_7 composite respectively. Like CG_5C, although there is a sudden stress drop in the stress-strain plot of $C_2G_3C_2$, but this failure strain is 11% higher than the corresponding strain at peak. Hence this gives a prior indication before catastrophic failure unlike C_7 composite. Another key observation in this 3G+4C composite system is that, the C_4G_3 composite exhibits a gradual failure behavior like G_7, which is desirable for applications where ductility remains the prime concern over strength and stiffness. Like C_2G_4C in section 3.2.3, here also a configuration C_3G_3C was noticed having a sudden stress drop at a strain value of 1.75%, but still the specimen is capable of straining further with a higher required stress at each point of strain than G_7 composite.

3.2.5 Comparison of flexural properties of all the GCHE composites studied

Based on the above results some interesting observations are drawn. One important point to note that unlike strength and strain at peak, the modulus of an asymmetric (about the central ply) laminate is independent of the loading side, e.g. C_2G_5 exhibits the same modulus as that of G_5C_2, whereas their strength and strain at peak are different. The effectiveness of the strength and stiffness enhancement in GCHE composite is better when the CFs are located at the top and/or bottom end(s) due to higher strength of CE ply than GE ply. This is because of the higher strength of CF than GF and better interfacial strength of CF/epoxy than GF/epoxy. But, if there is a CE ply located at the bottom most (tensile) side of the specimen (call it as CE_{1b}), there exists a sudden load drop in the stress-strain plot when this CE_{1b} fails (in the close vicinity of the peak stress) due to the relative brittle nature of CE ply. After failure of this CE_{1b} ply the subsequent ply (2nd ply from the bottom) experiences the maximum tensile stress. Now, further deformation/failure behaviour of the composite depends on the nature of this ply. The possible conditions are;

(i) If this 2nd bottom ply is a GE ply, probably the stress exhibited on the ply exceeds its tensile strength and hence this also fails immediately which leads to a huge drop in load carrying capacity of the composite as observed in G_6C, CG_5C, C_2G_4C and C_3G_3C lay-ups as shown in figure 9(a) containing only one large load drop segment.

(ii) If there exists another CE ply (call it as CE_{2b}) just above the failed CE_{1b}, then the CE_{2b} experiences a huge stress concentration immediately after the failure of CE_{1b} but due to the superior strength of CE ply, the CE_{2b} may be able to carry the load to some extent and hence the magnitude of the load drop is not that huge. As we go on deforming the specimen further, the stress on CE_{2b} ply increases and ultimately it fails when the stress reaches its tensile strength. Here again a sharp drop in the load can be observed in the stress-strain plot. Now, as the thickness of the sample gets reduced significantly, catastrophic failure occurs irrespective of the type of 3rd bottom ply. In this way the stress-strain plot of GCHE composites with 2 or more no. of CE plies at the bottom with no CE ply at the top contain 2 segments of load drop unlike G_6C (only 1 CF at bottom) composite, which contains only 1 load drop segment as can be observed from figure 9 (b) and (b′).

Another important observation is that placing CFs only at the compressive side of the GCHE composite (no CF at the tensile side), no sudden load drop was noticed, and the failure behaviour is progressive in nature as can be noticed from figure 9(c). This is due to the relative ductile nature of GE ply failing during tensile loading, located at the bottom plane.

From strength and stiffness point of view, for each of the $\boldsymbol{r_h}$ studied, the GCHE composite configuration with maximum strength and stiffness are taken and reported in table-4. When there is not much difference in strength and/or modulus of two configurations of a composite system, the failure behaviour is the next criteria to select the material.

Table-4: Stacking sequence for the maximum strength and modulus for each composite system.

Composite system	Stacking sequence during testing (top to bottom)
7G	G_7

6G+1C	CG_6
5G+2C	CG_5C
4G+3C	C_2G_4C
3G+4C	$C_2G_3C_2$
7C	C_7

The flexural strength and modulus of these composite specimens are compared in figure 10. Hence, for getting better strength and modulus CFs must be put at both sides of the GCHE composites. An outstanding strength and modulus could be obtained from $C_2G_3C_2$ having a hybrid ratio of only 0.51, which are 96% and 93% that of C_7 composite respectively. This configuration is fair enough having almost similar strength and modulus as that of C_7 with a reduced cost and better strain to failure. Here also an indication (difference between strain at peak and failure strain) of failure can be obtained before catastrophic failure unlike C_7. Nevertheless, one thing which must be kept in mind before using these GCHE composites is that a sudden catastrophic failure may be resulted when there is some CFs at the bottom of the laminate.

One interesting inference could also be derived from the strength and modulus vs. hybrid ratio plots (figure 10(b)) that both strength (σ_f) and modulus (E) are related with the hybrid ratio (r_h) by parabolic relationships as per the below mentioned expressions.

$$\sigma_f(MPa) = 355.2 + 887.7r_h - 543.1r_h^2 \quad \dots(4)$$

$$E(GPa) = 25.8 + 71.6r_h - 42.5r_h^2 \quad \dots(5)$$

3.3 Fractography

For getting the possible mode of damage initiation in the composites, some tests were intentionally stopped when a significant drop in the stress-strain curve was noticed (just after obtaining the peak stress). The front sides of those samples were then visualized under SEM. Figure 11 depicts the failure morphology of a G_7 composite. One can observe various failure modes such as ply splitting, kink band formation and fibre fracture in this G_7 composite. Ply splitting is a common phenomenon in laminated composite, which results due to delamination between the adjacent plies. Delamination results in loss in load carrying capacity of the composite. Due to ply splitting the adjacent ply is unable to resist the applied load and hence in that local vicinity a group of fibres experience micro-buckling. This micro-buckling ultimately transforms into kink bands. Kink bands were only observed in the compressive side of the G_7 composite at different locations as shown in figure 11(c). One can also visualize extensive damage between the top and central plies of the G_7 composite. Nevertheless, fibre fracture could also be noticed only at the extreme bottom of the G_7 composite (figure 11 (b)), which is a typical signature of tensile failure.

Fracture morphology of C_7 composite has been shown in figure 12. Some fibre fracture and transverse crack on both tensile and compressive sides, and its further propagation through thickness transformed into the ultimate failure of the C_7 composite. The extent of delamination and ply splitting are significantly less in C_7 composite as compared to G_7 composite which can be attributed to strong fibre/matrix interface between CF and epoxy matrix.

It has been seen that the crushing marks due to the stress concentration beneath the loading roller is more prominent in case of G_7 than C_7 composite which was also noticed in SEM. In G_7 composite, the damage signatures were abundant between the upper and central plane of the specimen whereas in C_7 composite the damage width was narrow but continuous throughout the thickness as can be observed in figure 12 (a) indicating the relative brittle nature of this system. No micro-buckling and kink bands were observed in the compressive side of C_7 composite as shown in figure 12 (c).

Figure 13 represents the fracture micrograph of $C_2G_3C_2$ composite. A bulk transverse crack can be noticed at the tensile end (figure 13 (b)) which might be due to the breakage of all the CFs in that zone. This crack seems to be arrested when it reached the GE ply and terminated as a delaminated surface at GF/epoxy interface. Similarly in the compressive side (figure 13 (c)) damage was only noticed in the very upper zone only. Both in tensile and compressive sides, damage seems to be restricted by the CE plies only, or in other words the GE plies experience a lower stress as most of the energy/stress was carried out by the CE plies. As the flexural strength of these composites is mostly derived from the end plies, the strength of $C_2G_3C_2$ reaches 96% of the strength of C_7 composite.

3.4 Damage constitutive model

Due to presence of different phases (fibre, polymer and fibre/polymer interface) in FRP composite, the nature of deformation and failure in FRP composites is very complex. It can be reasonably considered that the deformation behaviour of FRP is the combination of the responses of its constituting phases. Various deformation mechanisms such as fibre deformation, river-line formation, shear cusps, micro-buckling and so on act independently or sequentially to result the ultimate failure by delamination, fibre fracture, matrix failure etc. The response of these kinds of materials upon application of any stress/strain can suitably be predicted by Weibull distribution function [26,27].

$$\sigma = E\varepsilon \exp\left[-\left(\frac{E\varepsilon}{\sigma_o}\right)^{\beta}\right] \quad \dots (6)$$

where E represents the flexural modulus of the material. The constants σ_o and β are the design parameters, known as Weibull scale parameter and shape parameter respectively. σ_o is an indicative of nominal strength of the FRP composite and β corresponds to the scatterness in the strength (higher the value of β, lower is the strength scatter). For determining these design parameters, the following expression may be used derived from equation 6.

$$\ln\left[\ln\left(\frac{E\varepsilon}{\sigma}\right)\right] = \beta \ \ln(E\varepsilon) - \beta \ln(\sigma_o) \quad \dots (7)$$

Hence, a linear relationship exists between $\ln(E\varepsilon)$ and $\ln\left[\ln\left(\frac{E\varepsilon}{\sigma}\right)\right]$. The slope of this straight line corresponds to β. From the value of this slope (β) and intercept ($\beta \ln(\sigma_o)$), the value of σ_o can be determined. The design parameters were determined for the composite configurations listed in table-4. The linear fitting for eq. (7) for various composites are shown in figure 14(a). Thus the values of σ_o and β obtained were plotted against their corresponding hybrid ratio as shown in figure 14(b). The scale parameter vs. hybrid ratio has a similar trend as that of the experimental strength vs. hybrid ratio. Another interesting observation is that for GCHE composites, the shape parameter is relatively higher than both pure GE and pure CE composites. Hence the $C_2G_3C_2$ has a similar strength as that of C_7 with a less strength scatter which indicates $C_2G_3C_2$ to be a more reliable material in real applications. A comparison between the experimental and simulated stress-strain plots has been shown in figure 14(c). This shows that the simulated curves are in good agreement with the experimental data.

4 Conclusion

A systematic study was carried out to comprehend the flexural performance of FRP composite with inter-ply fibre hybridization. A series of glass and/or carbon epoxy composites have been tested with different stacking sequences. Effects of number of CE ply (hybrid ratio) and their position on the flexural performance of hybrid composites are presented and following conclusions can be drawn from the present study:

1. The flexural performance of an inter-ply fibre hybrid laminated composite is strongly dependent on the stacking sequence of the different fibre plies in the composite. It is better to replace the end GE plies of a GE composite by CE plies than replacing the central GE ply for better flexural strength and modulus.
2. Replacing only one layer (out of total 7 layers) of GE ply by CE ply in the compressive end of the GE laminate increases its strength and stiffness by 20% and 42% respectively.
3. For a GCHE composite which is asymmetric about its central plane, changing the loading side significantly alters the flexural stress-strain curve, strength and strain at peak but the modulus remains unaffected. (e.g. C_2G_5 and G_5C_2 both exhibit almost same flexural modulus, whereas their flexural strength and strain at peak are significantly different).
4. If the aim is to optimize the strength and/or stiffness and cost, then the inter-ply hybridization is more effective when CE plies are simultaneously provided in both (tensile as well as compressive) ends than placing all the CE plies at one end.
5. Replacing 2 GE plies at each ends (compressive and tensile) of a 7 layered GE composite, by CE plies ($C_2G_3C_2$ composite) yielded 96% strength and 93% modulus as that of C_7 composite with nearly same strain at peak but better failure strain. In this configuration, the volume fraction of CF was 51% of total reinforcement.
6. If the aim is to design a hybrid composite whose failure should not be catastrophic, then present study suggests that placing all the CE plies in the compressive end can yield the best solution with progressive failure behaviour. Although the enhancement in strength and modulus would not be as significant as compared to other configurations but their deformation behaviour is nearly similar to a G_7 composite.
7. Modelling with Weibull distribution function has a shown that the shape parameter (β) is higher for hybrid composites than pure GE and CE composites indicating the

strength scatter is relatively less in hybrid composites than both pure GE and CE composites.

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