Experimental investigation of the tensile and modal properties of epoxy based symmetric interlayer glass/carbon hybrid composites

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Abstract:
Interlayer hybrid composites can be tailored for enhanced strength and stiffness. Research on enhancing the mechanical properties of Interlayer hybrid composites is being explored by varying fiber orientations, layup sequence, different type of fiber materials. The objective of this work is to investigate the effect of stacking sequence of the high modulus carbon fibers on the tensile and modal properties of symmetric glass/carbon fiber interlayer composite. The interlayer hybrid composites were fabricated for different stacking sequence of carbon fibers using hand layup technique. Tensile strength and modulus were evaluated as per ASTM 3039 standard. Experimental modal analysis was carried out for two boundary conditions (Free-Free and Cantilever). The modal properties such as natural frequency, mode shapes and damping were studied. The results show that interlayer hybridizations by using low & high modulus fibers along with their stacking sequence about the neutral axis of the laminate have significant influence on the tensile and modal properties. Interlayer hybridization technique offers the potential to provide better mechanical and modal properties in design of high-performance composites.

1. Introduction

It is advantages for aerospace, automotive and wind turbine industries to the design and develop structures using composites which are light in weight and stronger compared to conventional materials. The light weight composite structures lead to enhanced fuel efficiency, enhanced performance and reduction in cost of the end product. The decrease in weight can make the structure more prone to vibration and noise. The vibration characteristics of a structure is related to its mass, stiffness and damping. The mass of the structure and stiffness are related to kinetic and strain energies while the damping relates to the dissipation of mechanical energy. In comparison with conventional materials composite materials possess better damping properties. The understanding of damping behaviour of the composite material is beneficial to mitigate the harsh effect of vibrations.

Hybrid composites are the emerging material and their properties are being explored and studied by researchers across the world. The main purpose of the hybridization is to develop a superior material by making use of the advantages of its constituent’s materials and overcoming any disadvantages possessed by its constituents [1]. The synergy between different constituent material is used to develop a new material having superior properties compared to conventional composite. Based on the combination of the constituent materials hybrid composites can be categorised as; (i) interlayer hybrid wherein two or more different fiber types are stacked one upon the other; (ii) intraply hybrid in which dissimilar fibers are co-woven in the single ply; (iii) intrayarn wherein two different fibres are combined randomly at the fibre level [1, 2]. The interlayer composites are the simplest form of the Hybrid composite. The design and development of an interlayer hybrid composite is complex. Interlayer hybrid composites can be tailored depending on the fiber type used, fiber material, fiber content, stacking sequence of the fibers in the laminate, fabrication process and interfacial adhesion between the
fiber/matrix in the laminate. The mechanical and dynamic properties of the interlayer composites can be influenced by the stiffness and stacking position of the low and high modulus fiber in the laminates.

In recent years research on hybrid composite using experimental and computational approach to understand the hybrid effect has been progressing rapidly [3–6].

Pegoretti et al [7] studied the effect of interply and intraply weaving pattern on the mechanical properties of hybrid composites. The studied showed improved tensile properties for symmetric interply hybrids. Pandya et al [8] studied experimentally the in-plane mechanical properties of hybrid composites. He evaluated tensile properties using ASTM 3039 and reported that by placing glass plies in the exterior and carbon plies at the centre of the laminate produced higher tensile properties than stacking carbon plies on exterior and glass plies towards the centre of the laminate. An increase of 30.7% in tensile strength was reported for the hybrid composites. Swolf et al [9] reported that highest hybrid effect of 16% was seen for glass/carbon with 50/50 ratio. They suggested that hybrids with thin ply may result in enhanced tensile properties than comingled hybrids. Wisnom et al [10] showed experimentally that the magnitude of the hybrid effect depends on the thickness of carbon ply in a carbon/glass hybrid composite. An enhancement in failure strain of up to 20% was seen for very thin carbon plies of thickness less than 29 μm. Weiili Wu [11] investigated the tensile and compressive behaviour of interlayer and intralayer composites. It was reported that tensile & compression modulus of interlayer and intralayer hybrid composites were similar for the same mixed ratio and increased linearly with increase in carbon content.

Jesthi et al [12] have investigated the mechanical properties of glass [G]s, carbon [C]s and hybrids [G3C2S], [G2C2G]S, [GGC2G]S composites for marine applications. It was seen that the tensile strength of seawater aged hybrid with [GGC2G]S stacking sequence enhanced by 14% as compared to neat GFRP laminate. Ashok et al [13] showed from the experimental work that the failure strain of interply hybrid composite is higher than intraply hybrids by 7.4%. It was mainly attributed to the lower damage evolution exhibited by the carbon fiber because of constrains provided by surrounding glass fibers. Srinvivas et al [14] have studied the influence of temperatures and loading speeds on the tensile properties of glass/carbon inter-ply composites. Stacking CE ply at the centre of the laminate (G2C1G2) imparted hybrid effect and pseudo-ductility. The tensile properties of G2C1G2 were higher than modulus of GE by 65.95% at speed of 0.1 mm min⁻¹ and 110 °C.

Along with ongoing research on the mechanical properties, researchers are working on exploring the vibration characteristics of composites [15–17].

Ying et al [18] have modelled damping using FEM method based on mode analysis theory and strain energy. The results indicated that natural frequencies of the composite laminate reduced as orientation of the fiber increased. The orientation of fiber influenced the damping loss factors. Nayak et al [19] have performed experimental studies to understand the vibration behaviour of glass and carbon fibers hybrid composites. It was seen that frequency was minimum for (G–C–G–G)s and (C–G–C–G)2 hybrid stacking. Using the impulse excitation techniques, the vibration characteristics were investigated experimentally for hybrid composite beam with glass/carbon fiber by Murugan et al [20]. The effect of stacking sequence of high and low modulus fibers on the static and vibration properties was evident. The modal properties of the hybrid composites with plain-woven-glass and intra-ply woven carbon/Kevlar fabrics were studied by Bulut et al [21]. The stacking position and percentage of the fibers used in the laminates showed significant effect on natural frequency and damping values of hybrid laminates. Tingting et al [22] showed that in hybrid composite the tensile modulus is influenced by its hybrid ratio. The study showed that damping is influenced by both hybrid ratio and sequence of ply stacking in a laminate. Rajkumar et al [23] have studied the tensile and vibration properties of a (G–C–G) hybrid composite with and without hole. The modal properties like frequency & damping ratio of the composite without tensile hole showed increased value due to undisturbed fiber strength. Vinayak et al [24] have investigated the influence of temperature and moisture variation on free vibration characteristics of skew hybrid composite laminate and sandwich plate using FEM. It was observed that for hybrid composite and sandwich plates, the non-dimensional frequency increases with increase in skew angle and aspect ratios.

In design and development of lightweight structures using interlayer hybrid methodology it is not only important to know the mechanical properties but also have an understanding of modal damping and frequency. The research works published on the interlayer hybrid composites are focused either on enhancing the mechanical performance of the composites or characterization of the vibration properties. The availability of literature on the interlayer hybrid composites with both mechanical and vibration properties are scant. Also, the previous studies have investigated hybrid composites with higher percentage of carbon fiber in the laminate. Though increase in percentage of carbon fiber makes the material stronger and lighter, the product cost is more due to higher cost of carbon fibers.

In this paper interlayer hybrid composite comprising of 20% carbon & 80% glass fibers for different symmetric stacking sequence of carbon fiber is studied for 0° fiber orientation. The scope of experimental work is to evaluate the tensile and modal properties for three different combinations of interlayer symmetric hybrid composites i.e. [C–G–G–G]s, [G–G–C–G]s, [G–G–G–C]s and pristine glass composite with [G–G–G–G]s configuration. Only ten plies are considered for each combination so as to maintain the thickness of the
fabricated composite laminate below 3mm. Interlayer hybrid laminates are fabricated with eight plies of UD glass fiber and two plies of UD carbon fiber. Pristine glass composite is fabricated with 10 plies of UD glass fiber. The pristine glass fiber laminate is used to generate the baseline data. The tensile properties like tensile strength and modulus are determined experimentally as per ASTM 3039 standard. The modal properties like frequency, damping and mode shapes are determined for free-free-free-free (F-F-F-F) and clamped-free-free-free (C-F-F-F) boundary conditions. Frequency response function are investigated using the modal analysis software. The effects of interlayer hybridization on tensile properties, natural frequency and damping behaviour are discussed in this paper.

2. Experimental work

2.1. Materials used

The materials used in the laminate fabrication for this experimental work are:

- UD Glass (Type 92145) fiber, supplied by Mark Tech Composites Pvt. Ltd, India.
- UD Carbon (Tenax 796) fiber, supplied by Mark Tech Composites Pvt. Ltd, India.
- Araldite-LY556 and HY-951 hardener supplied by Zenith Industrial, India.

The Glass and Carbon fabric used are shown in figure 1. The fiber specification provided by supplier is mentioned in table 1.

2.2. Fabrication of Laminates

In this research work the mechanical and modal properties of interlayer composite will be compared with the pristine glass laminate. Hence 2 types of the laminates were fabricated i.e. glass/epoxy and interlayer hybrid laminates made up of glass/carbon/epoxy.

The fabrication of the composite laminates is performed using a simple layup process followed by vacuum bagging. The details of the composites fabricated along with their stacking sequence are shown in table 2. The graphical view of the symmetric stacking sequence is shown in figure 2.
The process for fabricating pristine Glass laminate [G-G-G-G-G]s is described. The glass fabric were cut into dimension of 1000 mm*500 mm and 10 plies. The weight of each ply used are weighed. The fabrication is performed over a flat stone bed. Polishing wax is first applied on the flat stone surface to ease the release of the laminate after curing. Then first ply of glass fabric is placed on the stone bed. The Epoxy Resin LY 556 is thoroughly mixed with Hardener HY951 in the ratio of 10:1. Each of the 10 plies of the glass fiber are wetted with matrix and then stacked one over the other. It is necessary to ensure that the resin mixture is uniformly applied along the entire length and width of the ply and that no air bubbles are formed. A breather cloth is placed over the laminate to absorb any extra resin. Later a Mylar sheet is placed on the laminate to create a closed chamber and sealed using sealant. A vacuum pump is connected to this closed chamber through a small port. The composite laminate is subjected to vacuum pressure of 680 mm Hg for 120 min. After subjecting the laminate to vacuum pressure, the mylar sheets are removed and then the composite laminate is cured at room temperature for 24 h. After this, the laminate is cured in hot air oven at 80°C for 1 h. After curing in hot air oven, pristine glass composite laminate with [G-G-G-G-G]s is ready to use for testing purpose. The tensile and modal test specimens were prepared from composite laminates. The same process is followed for fabricating the hybrid laminates.

During the manufacturing process of composites using hand layup there is always possibility of formation of voids. The voids can reduce the strength of the laminates. It is important to know the void content in the laminates. The void content was determined as per equation shown below.

\[
V_o = \left( \frac{\rho_{ct} - \rho_{ex}}{\rho_{ct}} \right)
\]

Theoretical density of the composite specimens was computed using relation:

\[
\frac{1}{\rho_{ct}} = \frac{W_f}{\rho_f} + \frac{W_m}{\rho_m}
\]

where \(W_f\) and \(W_m\) denote the weight fraction of fiber and matrix, \(\rho_f\), \(\rho_{ct}\) and \(\rho_m\) are the density of the composite laminate, fiber and matrix. The experimental density (\(\rho_{ex}\)) was calculated by using simple water immersion method. The details of the void contents for the laminates with different stacking sequence are tabulated in table 3.

### Table 2. Laminates fabricated.

| Sl. no. | Material | Laminate naming | Nos of Plies | Stacking sequence | Fiber %Wt | Epoxy %Wt | Ply orientation |
|---------|----------|-----------------|--------------|-------------------|-----------|------------|----------------|
| 1       | GFRP     | G1              | 10           | [G-G-G-G-G]S      | 60        | 40         | 0° degree      |
| 2       | Hybrid   | H1              | 10           | [C-G-G-G-G]S      | 60        | 40         | 0° degree      |
| 3       | Hybrid   | H2              | 10           | [G-G-C-G-G]S      | 60        | 40         | 0° degree      |
| 4       | Hybrid   | H3              | 10           | [G-G-G-G-C]S      | 60        | 40         | 0° degree      |

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### 2.3. Experimental tensile testing

The composite laminates were evaluated for their tensile properties on a table top universal testing machine (make: Tinius Olsen) as shown in figure 3, as per the ASTM D3039 standard. The ASTM D3039 is used for evaluating the in-plane tensile properties of polymer matrix composites reinforced by high-modulus fibers.
The specimen dimensions are 250 mm × 25 mm × 2.6 mm as shown in figure 4. The tensile strength and modulus were determined for five samples and the average values were reported.

Table 3. Laminates Fabricated.

| Laminate | Glass fiber %Wt | Carbon fiber %Wt | Epoxy %Wt | Theoretical density g/cc3 | Experimental density g/cc3 | Void content |
|----------|-----------------|-----------------|-----------|--------------------------|---------------------------|--------------|
| G1       | 60              | 0               | 40        | 1.744                    | 1.694                     | 2.87         |
| H1       | 48              | 12              | 40        | 1.689                    | 1.637                     | 3.08         |
| H2       | 48              | 12              | 40        | 1.689                    | 1.645                     | 2.61         |
| H3       | 48              | 12              | 40        | 1.689                    | 1.642                     | 2.78         |

The specimen dimensions are 250 mm × 25 mm × 2.6 mm as shown in figure 4. The tensile strength and modulus were determined for five samples and the average values were reported.

2.4. Experimental modal analysis

Traditional strike method is used for conducting the experimental modal analysis. The setup consists of a piezoelectric hammer, accelerometer, data acquisition system/software. The specimen’s dimension is
150 mm $\times$ 150 mm for F-F-F-F boundary condition and 170 mm $\times$ 150 mm for C-F-F-F boundary conditions as shown in figure 5. Effective area of the modal testing for both F-F-F-F and C-F-F-F is 150mmx150mm. On each specimen 49 grid points are marked to trigger and get the response. The composite specimen is triggered at each of the grid point using a piezoelectric hammer and the response is measured by accelerometer. The accelerometer is connected to data acquisition system. The response measured is processed by data acquisition software into frequency, mode shapes and damping values. At each grid point, the specimen is excited eight times and average value is noted so as to nullify any experimental error. Frequency response function (FRF) are studied with the help of the modal analysis software. The modal parameters like frequency, mode shapes and % damping are acquired from FRF measurements.

2.4.1. Experimental setup and test procedure for F-F-F-F boundary condition
The experimental arrangement for conducting the modal analysis with F-F-F-F boundary condition is shown in figure 6. It consists of an impact hammer, accelerometer, 4-channel FFT analyser and data acquisition software. To replicate the F-F-F-F boundary condition, the composite specimen is suspended from a frame using an elastic thread as shown in figure 6. The specimen was excited at each of the grid point by means of impact hammer and the response were measured by an accelerometer mounted onto the specimen.

2.4.2. Experimental Setup and Test Procedure for C-F-F-F boundary condition
The experiment with C-F-F-F boundary condition was conducted using the arrangement shown in figure 7. The test specimen is fastened to the fixture using 4 threads. The composite specimen was excited at each of the grid point marked using impact hammer and the response measured by an accelerometer fixed to the specimen using wax.
3. Results and discussions

3.1. Tensile properties for laminates

The tensile properties obtained from the experimental testing for pristine and hybrid laminates are tabulated in table 4. The stress-strain curves for each stacking sequence are shown in figure 8.

From the stress strain curves, the tensile strength of the G1 is 492 MPa and failure strain 5.48 %. The G1 exhibited lower strength and higher strain values compared to hybrid composite. The H1 laminate with stacking sequence [C-G-G-G-G]s shows enhanced strength of 542 MPa and failure strain of 5.38 %. Among the hybrids H1 displays higher strain before failure. An enhancement in tensile strength and modulus is seen for the hybrid composites along with lesser strain values. Among the hybrid, H3 laminate with [G-G-G-G-C]s stacking sequence exhibited higher strength of 669 MPa. It can be attributed to the higher resistance offered by high modulus carbon fiber and due to good adhesion between the fiber and matrix.

From the literature [1] it is seen that glass carbon based hybrid composite exhibit a step-wise drop in stress strain curve during tensile testing as carbon fiber possess lesser ductility compared to the glass fibers and fail at lesser strain level. A stress drop will result in load transfer to glass plies after the carbon fiber failure. The failure of glass plies would result in failure of hybrid composite.

From the figure 8, the step wise drop is not seen in the stress strain curve, which can be attributed to stress intensification due to breakage of carbon layers. The failure of carbon fibers will lead to an increase in the stress transfer onto the glass fibers and add up to transverse shear stresses such that its value exceeds the ultimate
The strength of glass plies [28]. The glass fibers will not be able to withstand enhanced level of stress and fail. The pristine glass laminate G1 displayed catastrophic brittle failure. The hybrid laminates displayed debonding and splitting at the edges before the failure as shown in figure 9.

The effect of stacking sequence of carbon ply in the hybrid laminate [C-G-G-G-G]s, [G-C-G-G]-s, [G-G-G-G-C]-s and pristine glass composite with [G-G-G-G-G]-s configuration on tensile strength and modulus are shown in figures 10 and 11.

From the figure 10 it is seen that, the hybrid H3 with stacking sequence [G4C]-s exhibits the highest tensile strength among other laminates. Compared to pristine G1 laminate the tensile strength of hybrid H3 was enhanced by 36 %. Among the hybrid laminates there is a variation in the tensile strength based on the stacking sequence of carbon ply. It is observed in H3 laminate with carbon plies stacked at the neutral axis, the tensile strength is highest among the laminates. Based on the experimental test results it can be inferred that the placement of the low and high elongation fibers has significant effect on the tensile strength.

The results are in agreement with the experimental results reported by Pandya et al [8] that in hybrid composites, by stacking glass fibers on the outside and carbon fibers towards the centre of the laminate results in higher tensile strength.
The results obtained experimentally are in good agreement with that reported by Song et al.\textsuperscript{29} stating that accumulation of carbon layers in the centre of hybrid composite laminate results in increase of tensile strength. During tensile testing even though all the plies in a hybrid laminate are equally loaded, the difference in strain among glass and carbon resulted in the variation in tensile strength.

The tensile modulus of hybrid laminates is seen to increase with inclusion of the carbon plies as shown in figure 11. The carbon fibers have significantly higher modulus when compared to the glass fibers which contributed in enhancing the modulus of the hybrid composites. The tensile modulus is highest when the carbon plies are stacked at the laminate neutral axis. The hybrid H3 exhibits the highest tensile modulus among other laminates. The modulus of H3 laminate is enhanced by 50% compared to the pristine G1 laminate. The interlayer hybrid composites showed enhanced tensile strength and modulus compared to pristine glass laminate based on the stacking sequence of carbon fiber about the neutral axis of the hybrid laminate.

### 3.2. Modal properties for F-F-F-F boundary condition

Modes obtained from modal analysis are the inherent properties of the structure. Each mode is described by modal parameters i.e. natural frequency, mode shape & damping. The modal properties obtained from experimental testing for pristine and hybrid laminates with F-F-F-F boundary conditions are tabulated in table 5. The effect of stacking sequence of carbon ply in the hybrid laminate on frequency and % damping are shown in figures 12 and 13.

The first six frequencies with F-F-F-F boundary condition are rigid and are not reported. The next set of 3 natural frequencies obtained for the pristine glass G1 composite are 153 Hz, 251 Hz and 400 Hz. It is seen from figure 12, that the frequencies of hybrid H1 with the carbon fiber stacked at the outer side increased by 19%, 17%, 18% compared to pristine glass G1 composite for the 1st, 2nd and 3rd modes. The frequencies of hybrid H2 increased by 17%, 16%, 17% compared to pristine glass G1 composite for the three modes. The frequencies of hybrid H3 increased by 15%, 13%, 13% compared to pristine glass G1 composite.

| Laminate naming | Modal Parameters | Modes |
|----------------|------------------|-------|
|                |                  | 1st Mode | 2nd Mode | 3rd Mode |
| G1             | Frequency, Hz    | 153      | 251      | 400      |
|                | % Damping        | 1.41     | 0.595    | 1.20     |
| H1             | Frequency, Hz    | 183      | 294      | 474      |
|                | % Damping        | 1.25     | 0.343    | 1.03     |
| H2             | Frequency, Hz    | 180      | 292      | 469      |
|                | % Damping        | 1.08     | 0.507    | 0.83     |
| H3             | Frequency, Hz    | 176      | 285      | 454      |
|                | % Damping        | 1.30     | 0.933    | 0.99     |
Hybrid H1, H2 and H3 with carbon ply stacked at different stacking position showed enhanced frequencies compared to pristine G1 laminate. The modulus and stiffness of carbon fiber is higher compared to glass fiber. This helps in increase of frequency of the H1 compared to the pristine glass laminate. The hybrid H1 with carbon ply stacked outside showed the highest frequency among other hybrid laminates. The magnitude of the frequency reduces as the stacking sequence of the carbon ply is moved towards the inside of the laminate. Among the hybrids, H3 with carbon stacked at the 5th and 6th position exhibited the lowest frequency. Addition of the carbon fiber has increased the stiffness of the laminates and hence the frequencies of the hybrid laminates like H1, H2, and H3 have increased compared to pristine G1 laminate.

Mode shapes were also obtained for the F-F-F-F boundary condition for all specimens from the modal analysis software. The mode shapes illustrate the deformed behavior of the composite laminates at various modal frequencies. The type of fixation used while conducting the experimental modal analysis has an influence on the mode shapes. Only the first three modes are considered for the discussion. Each mode exhibited symmetry in the mode shape behavior. The laminates i.e. G1, H1, H2 and H3 under F-F-F-F condition exhibited similar mode shapes for the first three frequencies. Mode 1 indicated the first symmetric torsion, mode 2 indicated first symmetric bending and mode 3 indicated the second symmetric torsion.

The damping values were obtained experimentally for each frequency. The damping values showed a variation for each mode. From the figure 13, it is seen that the 1st mode exhibits highest damping compared to the other two modes. The 3rd mode exhibits better damping compared to the 2nd mode. The 2nd mode being the bending mode displayed the lowest damping values. This damping behaviour is in agreement to that reported by Zillur Rahman [30] that twisting response displays broader resonance peaks than the bending response peaks of the composite beam. Hong et al [31] reported from his studies that the damping values were higher for the twisting modes (due to increased twisting energy dissipation) than the damping due to the bending modes. Berthelot et al [32] observed that for composite beam twisting modes amplified the damping
values for fiber with 0° and 90° orientation, which was mainly attributed due to the increase of in-plane shear deformation of the composite.

### 3.3. Modal properties for C-F-F-F boundary condition

The modal properties with C-F-F-F boundary conditions obtained from experimental testing for pristine and hybrid laminates are tabulated in Table 6. The effect of stacking sequence of carbon ply in the hybrid laminate on frequency and % damping are shown in Figures 14 and 15.

The first 3 natural frequencies obtained experimentally for the pristine glass laminate G1 is 64Hz, 102Hz, 297Hz. It is seen from Figure 14, that the frequencies of hybrid H1 increased by 59%, 46%, 22% compared to pristine glass laminate G1 for the 1st, 2nd and 3rd modes. The frequencies of hybrid H2 increased by 40%, 26%, 13% compared to pristine glass. The frequencies of hybrid H3 increased by 14%, 10%, 10% compared to pristine glass. 

| Laminate naming | Modal Parameters | Modes | 1st Mode | 2nd Mode | 3rd Mode |
|-----------------|-----------------|-------|----------|----------|----------|
| G1              | Frequency, Hz   | 63.5  | 102      | 297      |
|                 | % Damping       | 0.345 | 1.48     | 1.01     |
| H1              | Frequency, Hz   | 101   | 149      | 365      |
|                 | % Damping       | 0.351 | 0.95     | 0.854    |
| H2              | Frequency, Hz   | 89.2  | 129      | 337      |
|                 | % Damping       | 0.672 | 1.18     | 1.06     |
| H3              | Frequency, Hz   | 72.7  | 113      | 328      |
|                 | % Damping       | 0.553 | 1.69     | 1.04     |

![Figure 14. Frequency with C-F-F-F boundary condition.](image)

![Figure 15. Damping with C-F-F-F boundary condition.](image)
pristine glass laminate G1. There is an increase seen in the magnitude of frequency values of hybrid composites with the introduction of the carbon fiber in the laminate.

The hybrid H1 is stacked with the carbon fiber at the outer sides ie at position 1 and 10. The modulus and stiffness of carbon fiber is higher compared to glass fiber. This helps in increase of frequency of the H1 interlayer hybrid laminate compared to the pristine glass laminate. The hybrid H1, H2 and H3 with carbon ply stacked at different stacking position showed higher frequencies compared to pristine G1. The H1 laminate with carbon ply stacked outside showed the highest frequency among other hybrid laminates. The magnitude of the frequency reduces as the stacking sequence of the carbon ply is moved towards the neutral axis of the laminate. Among the hybrid laminates H1, H2 and H3, laminate H3 with carbon stacked at the 5th and 6th position exhibited the lowest frequency.

Mode shapes were also obtained for C-F-F-F boundary condition for all specimens from the modal analysis software. The mode shapes illustrate the deformed shape of the rectangular laminates at various modal frequencies. The type of fixation used for conducting the experimental modal analysis has a significant effect on the mode shapes. Only the first three modes are considered for the discussion. The specimens which are in square dimension show the mode shapes of bending and torsion in the initial modes. In the present work laminates ie G1, H1, H2 and H3 under C-F-F-F condition exhibited similar mode shapes for the first three frequencies. Mode 1 indicates the first bending, mode 2 indicates first torsion and mode 3 indicates the first chord wise bending.

The damping values were obtained experimentally for each frequency. The damping values showed a variation for each mode. From the figure 15, it is seen that the 2nd mode exhibits highest damping compared to the other two modes. The 1st mode being the bending mode displayed the lowest damping. This damping behaviour by the composite laminates is in agreement to that reported by ZillurRahman [30], Hong et al [31] and Berthelot et al [32], that the damping values were higher for the twisting modes.

4. Conclusions

The tensile and modal properties of symmetric interlayer hybrid composites were compared with pristine E-glass/epoxy composite and the finding of this research are listed below:

- The experimental work demonstrates that interlayer hybrid composites fabricated displayed positive synergy for symmetric stacking sequence of the carbon plies.
- Even though hybrid laminates were fabricated with carbon & glass in the ratio of 20%:80% they displayed enhanced tensile properties. Designers can use interlayer hybridization technique with lesser percentage of high-cost carbon fibers to obtain enhanced properties. The carbon fibers can be stacked in the hybrid laminate along the load bearing path.
- The stacking sequence and number of plies of the low elongation (LE) and high elongation (HE) fibers about the neutral axis in the laminate play a very vital role in the mechanical properties.
- The interlayer hybridization can be used as an effective methodology for tailoring the modal properties like frequency and damping in hybrid composites by varying the stacking sequence and thereby the thickness of the high and low modulus fibers in the laminate.
- The experimental modal analysis showed that twisting modes exhibited higher damping compared to bending modes.
- Based on experimental results it can be inferred that a diverse combination of structures with different mechanical and modal properties can be fabricated by using the same quantity of material and without affecting the time and cost involved in manufacturing.

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Data availability statement

The data generated and/or analysed during the current study are not publicly available for legal/ethical reasons but are available from the corresponding author on reasonable request.

Declaration of conflicting interests

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