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Finite Element Failure Analysis on Carbon Glass Fiber Reinforced Polymer Laminates

Elamvazhudi Balasubramaniyan*[1], Arul Karthikeyan Oppilamani[2], Dhinagaran Selvakumar[3], Kathiravan Elango[4], Navinkumar Sargunaraj[5]

[1]*Department of Mechanical Engineering, IFET College of Engineering, Villupuram, Tamil Nadu, India,* elamvazhudib@gmail.com
[2]*Department of Mechanical Engineering, IFET College of Engineering, Villupuram, Tamil Nadu, India, arulkarthikeyan2310@gmail.com*
[3]*Department of Mechanical Engineering, IFET College of Engineering, Villupuram, Tamil Nadu, India, harinilakshmi71@gmail.com*
[4]*Department of Mechanical Engineering, IFET College of Engineering, Villupuram, Tamil Nadu, India, kathiravan062003@gmail.com*
[5]*Department of Mechanical Engineering, IFET College of Engineering, Villupuram, Tamil Nadu, India, navinkumar605108@gmail.com*

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Hybrid composites, simulation, Fracture toughness, Displacement, Laminate

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Abstract

This research focuses on comprehensive analysis on investigating the interlaminar fracture toughness and displacement behaviour of carbon and glass fiber reinforced hybrid polymer composites utilizing epoxy matrices. Delamination is the separation of layers within composite materials and interlaminar fracture toughness are an essential quality of measures that indicates the ability of a material to resist delamination. Predicting and preventing the failure of hybrid composites requires an understanding of their interlaminar fracture toughness values. Since delamination is a common failure mode of composite materials, it strongly affects the mechanical properties and load carrying ability of the structure. Such that assessing its interlaminar fracture toughness allows engineers to anticipate potential points of weakness, and prevent these areas from becoming problematic through any number of techniques designed to combat delamination. In hybrid composites, the capacity for energy dissipation and fracture in the matrix must be well evidenced before predicting structural integrity. This paper applies ANSYS simulation to model and evaluate the effects of five combinations of hybrid laminates, on both fracture toughness and displacement characteristics, to prove stress mitigation. The specific area that was researched involved fibre stacking sequences, fibre orientations, fibre types and thickness of lamina in an attempt to analyse the absorbent impact toughness of the different laminates. The parameters of interest are examined to not only determine the level of the interlaminar fracture toughness but also analyze the structure's displacement fields. The results will benefit the field of composite mechanics in gaining a better understanding of composite designs for the integration of composite structures into new generations of multipurpose and high fracture resisting materials for practical applications in engineering.

1. Introduction

The advancement of composite materials and their strengthening through multi-field coupling: A voluminous region in the field of materials science and engineering remains a never-ending quest for materials that possess superior mechanical properties [1]. On the top of the tympanic membrane for this exploration is the use of hybrid composites, an elaborate class of materials that are manufactured from the confluence of multiple fibers and matrices for the provision of a desired balance of strength, stiffness, and durability. In this extensive study, the in-depth analysis starts with a deeper probe of the identified subject, Interlaminar Fracture Toughness, which is arguably the most significant parameter for determining the strength and durability of a composite material [2]. Hybridization comes out as a viable method of leveraging on the compounding strengths of two or more fiber types to overcome the perennial problem of how to achieve the best blend of characteristics that can be obtained from the various types [3]. More specifically, the study considers hybrid composites and their production based on the combination of carbon as well as glass fibers with epoxy matrices. The idea for this investigation comes from understanding that for composites to be useful in extended applications, it cannot be restricted by conventional means. To advance the mechanical proficient of these hybrid composites, epoxy matrices experience reforming skills in reinforcement and strengthening. Hence the combination of all the above elements gives a material system of integrated heterogeneous elements that require a comprehensive and complicate analytical models [4]. Specialized computer resource that allows the use of virtual testing methodologies that can be used to study the mechanical response of intricate structures. Compared to typical measurements and analyses, this study also goes further than examining the interlaminar fracture toughness and revealing the performance of hybrids in the dance of the displacements of the composite structures [5]. This method enables understanding of how these variations affect equally, the fracture toughness and displacement geometry [6]. One of the main focuses of this study is the evaluation of the variability connected to the proportionality of carbon and glass fiber. Due to the variability of the properties governing these fibers, the study aims at understanding the role of their quantities in the mechanical properties of the hybrid composites by adjusting the ratio of each of them. The present composite combines high strength carbon fibers with more flexible glasses fibers that indicate an element of confusion that can result in generating new knowledge about performance characteristics under different loading conditions [7]. Simulation has been identified as an effective tool for analyzing the mechanical behavior of materials within a comparatively shorter time and using less experimental data than would otherwise be required [8]. This makes ANSYS effective to offer researchers the virtual exposure to different situations in order to be more directive in the subsequent experimentations and optimization approaches [9]. The incorporation of simulation work into materials research helps material researchers to progress more quickly in their work, and is instrumental in enabling them to create better materials with specific characteristics. While this is important, interlaminar fracture toughness is one composites parameter; what makes this study stand out is that it also includes displacement analysis [10]. This is even more important when the material has to resist external loads and retain its shape and functionality the need to know and understand how these composite materials deform and displace under given load patterns is a challenge. A recent study for instance investigated the influence of surface modified and unmixed nano-CaCO3 particles on the ILSS and fracture toughness of carbon fiber reinforced epoxy composites.

Conclusively, the result showed that by adding 2 wt.% of nano-CaCO3 into epoxy matrix it has potential to enhance ILSS as high as 24% and fracture toughness as high as 32. It was reported that tensile and flexural strength of the composites containing 5 wt.% nano-CaCO3 were improved by 3% compared to the composites without nano-CaCO3 [11]. One article examined the mechanical properties of laminated composites incorporated from glass, carbon and aramid fibers. The studies involved tensile and bending tests in which it was discovered that the composites containing carbon fibers were beater compared to other samples. The laminated composite which uses glass fiber reinforced epoxy material using aluminum and carbon fibers for the substrate resulted to the highest tensile and bending strengths, which suggests the possibility for high performance application [12]. Fracture toughness is one of the most essential parameters that may be used for characterization of composite materials and their potential endurance and reliability. Suppose in fracture mechanics, FEA has played an important role as the researchers got the permission to model the crack initiation and crack propagation under different loading conditions [13]. The displacement analysis allows for getting the overall vision regarding the material's efficiency in responding to external expectations, which is especially useful in understanding how the hybrid composites act in real-life scenarios. Such an approach enriches studies into the mechanical characteristics of materials, as well as general approaches to material analysis. The conclusions drawn from this research have important repercussions in designing better composites and in improving the material parameters of composites. By untangling the layers of complexity of hybrid composites through differentiating the fibres types [14]. The reading offers engineering and material scientists a blueprint on how they may be able to examine the interlaminar characteristics of laminates without subjecting them to tensile tests. The findings might further extend novel materials with enhanced fracture toughness, thus coupling desirable structural properties with precisely controlled and analytically predictable displacement profiles [15]. Such materials are useful in applications as diverse as aerospace, automotive or other fields, were resistance to the dynamic loading is of significance [16-17].

2. Method

The hand layup technique is the simplest method of processing composite material with the use of various fibers like glass or carbon fiber set on a matrix which is mostly epoxy. The step by step fabrication procedure explained as follows: Make sure the mold is clean, and have no residues of the previous mixture to compromise the final product. Apply a release agent on the surface of the mold to facilitate ease while demolding the composite part once it has set. Prepare the fiber reinforcements (carbon or glass fiber) by measuring and cutting them for the mold size and shape. Layers will need to overlap slightly at the edges. Mix the resin and hardener in a container, ensuring complete and uniform mixing to avoid any uncured spots. Use a roller or a brush to compact the fibers and eliminate any air pockets or voids between the layers, as these can weaken the composite. Lay additional fiber layers, ensuring each is properly saturated with resin and void of air pockets. The orientation of the fibers in each layer can be varied to optimize the strength and stiffness characteristics of the final product. Curing time can vary based on the ambient temperature and the type of epoxy used. Once fully cured, carefully remove the composite part from the mold. Tools like wedges or air can be used to gently separate the part from the mold surface. Each laminate has six ply and a thickness 4-5 mm. The stacking sequence of set1 laminate is mentioned as (G90/G0/C90)$_S$. In (G90/G0/C90)$_S$ laminates glass fibers are reinforced at top and bottom as well as in core and carbon fibers are placed in intermediates. In (C90/G90/G0)$_S$ laminate, high-strength carbon fibers are layered on the top and bottom, and glass fibers layered in between carbon fibers. The stacking sequence represented by (C90/G90/G0)$_S$. In set 3 laminate, glass fibers are layered in the core and other top and bottom, intermediate layers are reinforced by carbon fibers and stacking sequence represented by (G90/C0/G90)$_S$. The stacking sequence of all the three laminates shown in Figure 1. Symmetrically balanced laminates enhances its stiffness and strength.

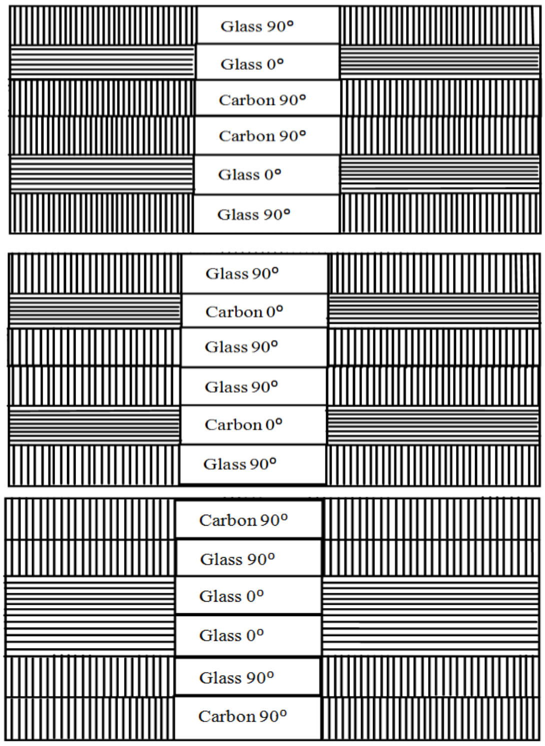

Figure 1. Stacking sequence of (a) (G90/G0/C90)$_S$ (b) (C90/G90/G0)$_S$ (c) (G90/C0/G90)$_S$ laminate

3. Finite Element Analysis

Finite Element Analysis stands as an elaborate numerical tool that is widely applied in engineering, physics, and numerous scientific fields in order to investigate and predict the behavior of diverse structures. This is based on the principle of approximating complex shapes or structures or overall behavioral patterns by subdividing it into smaller structures called finite elements which are connected at nodes to depict the structure as a whole. [18]. FEA employs mathematical formulations based on principles from continuum mechanics to describe the behavior of materials and the interactions between different components [19]. Engineers create digital models of the systems under study, specifying parameters such as geometry, material properties, boundary conditions, and applied loads. These models are then discretized into finite elements through meshing processes. Once the model is prepared, specialized software is used to solve the system of equations governing the behavior of each finite element and their interactions [20]. Through iterative numerical methods, the software converges to a solution, providing detailed insights into various aspects such as stress distribution, deformation, vibration modes, thermal effects, and more. FEA has widespread applications across industries, including aerospace, automotive, civil engineering, biomechanics, and manufacturing, enabling engineers to optimize designs, analyze performance, and enhance reliability while minimizing development time and costs [21-22].

3.1 Modeling

Reduced representation of the real world entity with a set of mathematical equations, computer simulations, physical models or conceptual systems depending upon the context in which they will be used. Starting with how modeling is used for engineers to design, optimize and validate the behavior of the system, allowing them to simulate performance under different conditions and in different scenarios. In scientific research, modeling method becomes an important tool for testing hypotheses, interpreting data and developing theories to understand how natural phenomena works and how they will perform in the future. Useful modeling requires a compromise between capturing relevant aspects of the system and not adding un-needed detail (iterative improvement; compare to empirical data). Modeling in all can do is an indispensable tool for advancing knowledge-driven innovation, and solving bigger challenges of modeling. SHELL181 element type is specifically used for meshing the layered laminates and COH3D8 element is used for meshing the interface. The laminate modeled using ANSYS is shown in Figure 2. The laminates are fixed at the left end and right end is crack allowed to propagate.

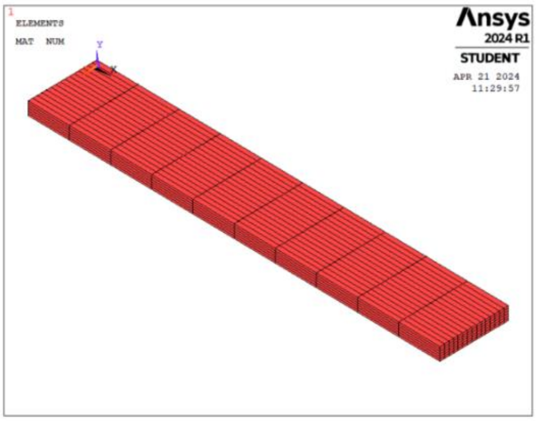

Figure 2. Laminate

3.2 Cohesive Element

Specialized for modeling interfaces and cracks in materials, the cohesive elements shown in Figure 3.

present a category of finite element analyses that consider discontinuities, localized failure mechanisms [23]. These elements model cohesive zones along interfaces of materials that adhered, described by cohesive laws, where traction is a function of relative displacement. By discretizing the interface or crack path into cohesive elements that are assimilated with the surrounding bulk material elements, their response during simulation is governed by cohesion in the form of tractions under loading and potential separation or debonding when their strength thresholds are exceeded [24]. Maximum normal traction and shear traction of 80 MPa and 100 MPa for assigned for cohesive zone model.

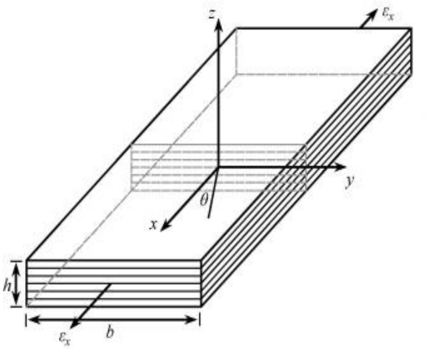

Figure 3. Cohesive Layer Modeling

3.3 Interlaminar Fracture Toughness

The material properties of the fibers are tabulated in Table 1. Interlaminar fracture toughness is the resistance of a composite material to delamination, or separation between layers (commonly known as laminas) within the composite structure [25]. Among the most important properties to evaluate in these materials, which is reflected in their structural quality and durability under other deformation mechanisms (bending, impact or fatigue).

Table 1. Material properties

Material	E in N/mm^2	Poisson's ratio
Glass	70-75 GPa	0.2-0.25
Carbon	230-240 GPa	0.2
Epoxy	2-4 GPa	0.35-0.4

The layer specific properties are considered for accurately simulating the behaviour of laminates. High interlaminar fracture toughness means increased delamination growth arrest and reduced crack propagation within a material, which benefits the global strength and endurance of composite structures. Loading at the middle layer ensures the uniform load distribution throughout the laminates. The interlaminar fracture toughness to optimize the formulation of the composite material, manufacture process and structural designs to maintain the performance and durability of load-carrying structure [26]. Usually interlaminar fracture toughness is determined by testing in situ fracture of the laminates together with measurement of delamination deflection resistance and G_{IC} which are obtained from double cantilever beam (DCB), end-notched flexure test (ENF) or three-point shearing files. Where the equation 1 is for the interlaminar fracture toughness of the laminate [27-28].

$$G_{IC} = \frac{3p\delta}{2B(a+|\Delta|)} \qquad (1)$$

Where, GIC interlaminar fracture toughness values P-load applied, δ-cross head displacement, B- specimen width, a-crack length and |Δ|-correction factor.

4. Simulation

In hybrid composites the materials are added in specific proportion by choice of designer. ANSYS simulation is performed to imitate the structural response of composite under different loads. This simulation setup includes a refined meshing technique for both the model and the considerations boundary conditions, and load application to represent a real condition [29-30]. These simulations are supposed to reproduce both the interlaminar fracture toughness and displacement fields in a composite structure. The results of these simulations serve as the foundation for a thorough examination on the hybrid composites and details about their mechanical characteristics, which guide in discussing about the manner enhancement can be done regarding those other applications and tricks. The particular hybrid composite being examined also is characterized by its layered construction, which includes seven layers and a core layer. This setup provides an extra layer of simulation difficulty, in that the cohesive layer is essential in regulating the way that the carbon and glass fiber reinforced layers interact with each other. In this 6-layer layout have a special focus on the third layer referred to as the cohesive layer. High decisions are taken place in this layer as it processes between Infinity and building materials. These can include user-defined properties we assign to the cohesive layer (i.e., cohesive zone modeling parameters) that are able to represent the bonding and debonding events at the interface, playing a large role in our overall fracture toughness simulations [31-32]. The simulation methodology in ANSYS is further developed to hold these nuances. The meshing approach is extended to model the detailed inter-layer transitions with a special attention for convergence in zones of high stress concentrations such as the interfaces and the cohesive layer. Boundary conditions are carefully assigned such that there are realistic loadings and cohesive elements are adopted to model the interface behavior accurately within the cohesive layer. Within this refined framework, the simulations consider both global structural response and layer-specific contributions to the interlaminar fracture toughness and displacements [33-34].

5. Results & Discussion

The degree of deformation and induced stresses within the laminates were predicted by considering the layer specific properties. Simulating the structural response of hybrid composite materials is essential for predicting their performance in various applications. In this work, interlaminar fracture toughness of three sets of a hybrid composite laminate is investigated. Deformation mechanisms such as matrix cracking, delamination and fiber breakage are observed during simulation. Simulated results were compared with the experimental values (ASTM D5528). The simulated laminates after applying load is shown in the Figure 4. The stress and displacement plot for the laminates are shown in Figure 5 and Figure 6 respectively. The laminates are characterized by individual displacement and stress values.

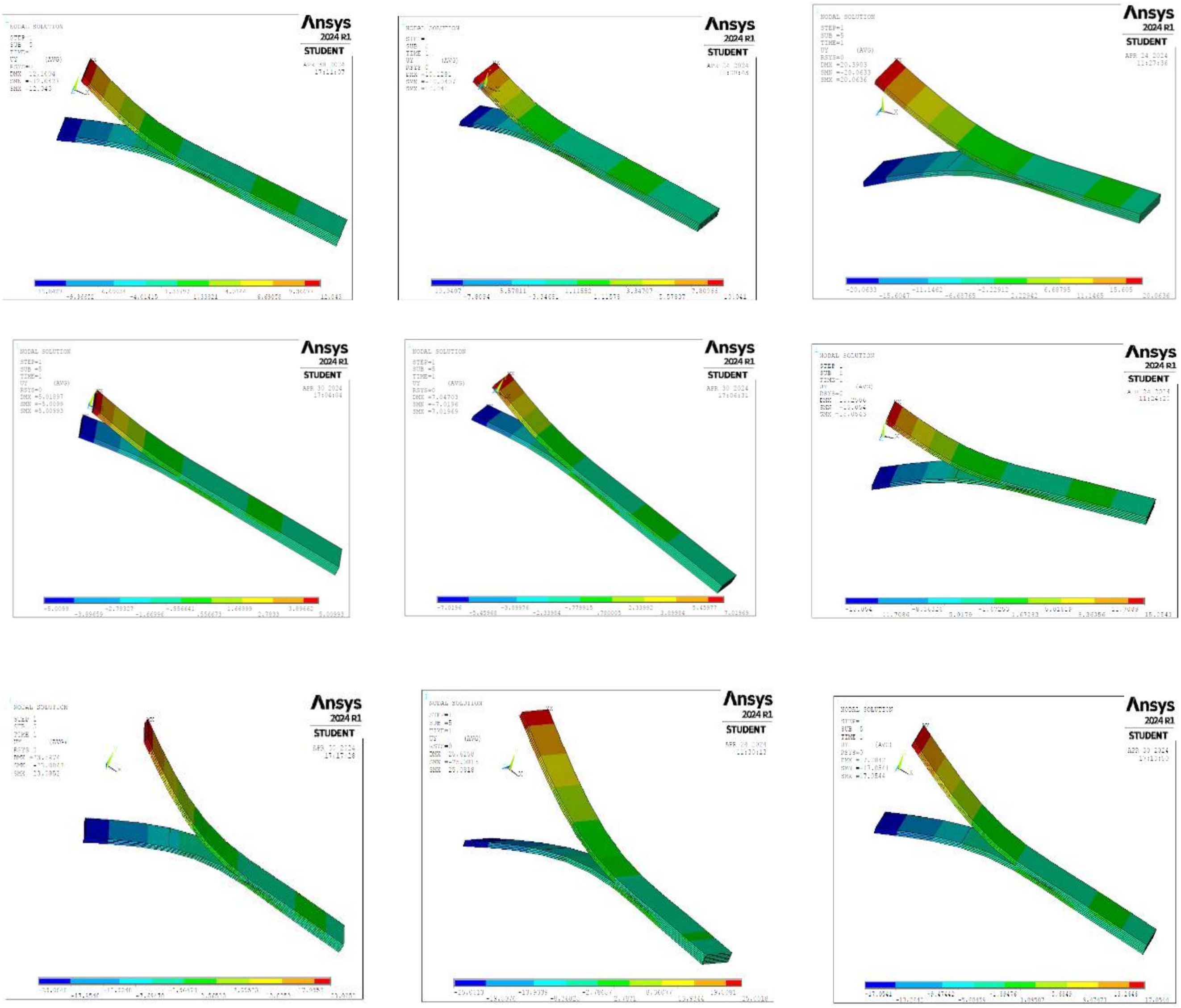

Figure 4. Delamination of (G90/G0/C90)$_S$ (b) (C90/G90/G0)$_S$ (c) (G90/C0/G90)$_S$ laminate

The laminate (G90/ G0/ C90)$_S$ exhibits a relatively low displacement value of 5 mm, accompanied by minimum stress value of 15.2 MPa. The result indicates a modest degree of deformation and minimum internal stresses are induced within the composite [34-35]. The carbon-carbon interface in the core exhibits in linearly along the angle of orientation 90°. The recorded low displacement value is due to the covalent bond exhibit between the carbon-carbon interfaces. The 90° carbon and glass fibers orientation were strategically placed in the laminates carries maximum load and exhibit maximum stress. The results showed that the (C90/G90/G0)S laminate exhibits a relatively maximum stress and moderate displacement. This indicates a modest degree of deformation and internal stress induced within the composite. Maximum stress of 24.5 MPa and displacement of 5.76 mm observed in this stacking sequence. The carbon fibers on the top of the laminate results high stress in the laminate. Table 2 summarized the displacement value and stress of different laminates.

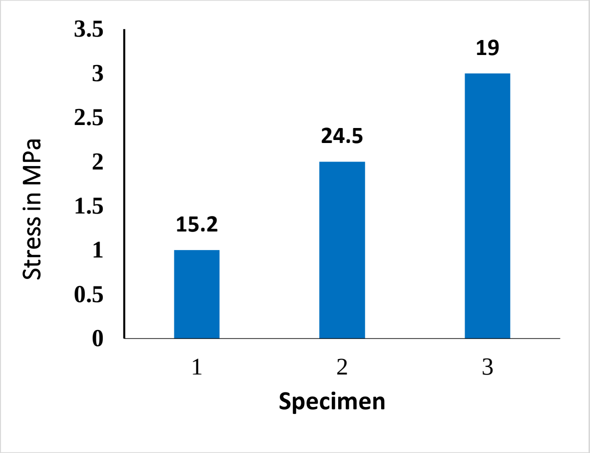

Figure 5. Maximum stress plot

Table 2. Stress and displacement comparison

Stacking sequence	Stress (MPa)	Displacement (mm)
(G90/G0/C90)s	15.2	5.0
(C90/G90/G0)s	24.5	6.4
(G90/C0/G90)s	19	8.6

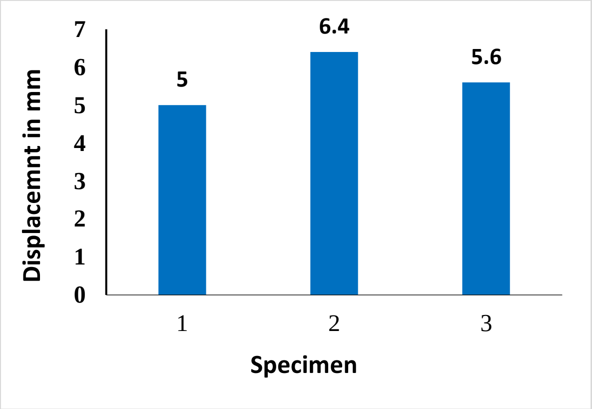

Figure 6. Displacement plot

The (G90/C0/G90)s exhibits displacement value of 6.4 mm, accompanied by moderate stress value of 19 MPa. Laminate with (G90/C0/G90)s stacking sequence shows G-G interface in the core is exhibit in linearly along the angle of orientation 90º. The high displacement value is due to the strong glass-glass interfaces. The findings of this study revealed key differences in the structural response of each set under simulated conditions. (G90/G0/C90)s, featuring a C-C interface at the core aligned at a 90° orientation, demonstrated superior performance in terms of lower displacement (5 mm) and moderate stress (5 MPa). The configuration of carbon fibers at the core and glass fibers at the peripheral layers and orientation of fibers effectively optimized the material's strength and toughness. The covalent bonding at the Carbon-Carbon interface in (G90/G0/C90)s appears to significantly enhance the laminate's ability to resist deformation under stress. The interlaminar toughness of laminates can be improved by varying the parameters such as thickness, matrix material and by changing the orientation and type of fibers. The observed variations in displacement and stress values underscore the dynamic nature of structural response within hybrid composites. Additionally, further research into interlaminar fracture toughness and cohesive layer behaviour will contribute to a comprehensive understanding of the composite's mechanical properties and performance characteristics.

6. Conclusion

As such, these hybrid composite sets are bound to portray a dynamic response of structures under various displacement and stress conditions. Knowing the critical points of their failure and addressing the stress concentrations can significantly boost the integrity and reliability of composite materials. The simulation study on interlaminar fracture toughness and displacement analysis of carbon/glass fiber-reinforced hybrid composites has given some insightful data regarding the behavior of three different sets of hybrid laminates under different stress conditions. In this research, an effort is made to study changes in composite structure and orientation with a view to knowing the overall structural performance by observing the toughness and displacement values for each set. It has been demonstrated that this hybrid composite configuration, which is (G90/G0/C90)s, copes the best to sustain lower displacement and even with moderate levels of stress to help enhance the interlaminar fracture toughness of the material. The findings outline the key nature of proper fiber placement and orientation strategies that are critical when one tries to design a hybrid composite for ensuring the needed mechanical properties towards any specific application.

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Author contributions

Elamvazhudi Balasubramaniyan: Conceptualization, Ideation **Arul Karthikeyan Oppilamani:** Fabrication, Modeling **Dhinagaran Selvakumar:** Analysis, Comparison **Kathiravan Elango:** Literature, References **Navinkumar Sargunaraj:** Editing, Correction

Conflicts of interest

The authors declare no conflicts of interest.

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