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Investigation of Natural Frequencies on Kevlar/Glass Hybrid Laminated Composite Plates Using Finite Element Simulation

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Abstract

This paper investigates the effect of various lamination schemes, boundary conditions, and fiber compositions on natural frequencies of hybrid laminated composite plates. A 150mm x 75mm plate model made of kevlar/glass hybrid composite laminate under free vibration was developed using a Finite Element Software (ANSYS). Parameters analyzed involved various lamination schemes (cross-ply and unidirectional ply), boundary conditions Free-Free-Free-Free (FFFF), Clamp-Free-Free-Free (CFFF), and Clamp-Clamp-Clamp-Clamp (CCCC); and various compositions of Kevlar and glass fibers. Finite element simulations were performed for each case and the natural frequencies of hybrid laminated composite plates were determined. Mode shapes were also presented to exhibit the plates' deformation behaviour. The results show that for cross-ply laminates, increasing the Kevlar composition has increased the plates' natural frequencies. In terms of boundary conditions, it shows that CCCC produced the highest natural frequency (859.49Hz), while CFFF produced the lowest natural frequency (37.248 Hz). This study contributes significant knowledge to better understand the effect of various fiber compositions and boundary conditions on the natural frequencies of hybrid laminated composite plates.

Disciplinary: Mechanical Engineering (Composite Materials; Mechanical Vibrations & Simulation).

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1 Introduction

Recent trends denote the increased application of composite laminates in modern structures, high-speed racing vehicles, aircraft, pressure vessels and other precision applications.

This is mainly due to their tailorable properties, where the laminate properties can be improved by varying the lamination schemes and fiber compositions. Therefore, it is important to understand the mechanical behaviour and limitations of composite laminates before designing a specific application. Amongst the main parameters that would substantially affect the good serviceability of a structure are the natural frequencies and mode shapes. The resonant phenomenon in the laminated composite occurs when the external vibration coincides with one of the natural frequencies of laminated composites and this will cause the structure to experience catastrophic failure. Thus, a thorough investigation would be necessary prior to the final laminate design. Findings from recent research show that laminated composites will produce lower natural frequencies and could also contribute significantly to the resonant phenomenon (Shi et al, 2020). Nevertheless, this phenomenon of resonant is still poorly understood especially for laminated composites. Thus, the underlying theory to define this phenomenon is crucial. Literature proves that to date, it is critical to investigate the natural frequencies of laminated composites due to their potential for application on precision and high-speed structures such as pressure vessels, aerospace structures, and race cars. Recently, the analysis of the natural frequencies of laminated composite has become a widespread means of finding mode shapes of vibration. Be that as it may, the study of natural frequencies of hybrid laminated composite plates is still not well explored.

2 Literature Review

Composite materials have been a common choice for design because their properties are tailorable to suit specific structural design requirements. The application of composite laminates has widespread uses such as in aircraft, ships, cars, robots, rail vehicles, sporting goods; and yet the development of composite laminates is still growing (Cankaya, 2020). The growth in research has driven researchers to look for better compositions of composite laminates by venturing into various parameters and combining materials. Different properties could be achieved by varying the fiber orientation, stacking sequences, and volume fraction (Kanitkar et al., 1986). The idea of hybrid laminated composites is essentially the combination of two or more laminas made of different fiber materials and the purpose of this is to reduce the cost of producing laminated composites, while maintaining their excellent properties. This has led to the hybrid combination of high and low modulus fiber. The high modulus fiber provides excellent stiffness and load-bearing capability, while the added low modulus fiber makes the composite laminate stronger and cheaper (Ghani & Mahmud, 2018; Shaari & Jumahat, 2018). Inspired by this idea, this study focuses on the hybridizing of Glass epoxy lamina into the Kevlar epoxy lamina fibers that would produce a material that has improved impact resistance and tolerance, high strength, and lightweight.

The natural frequency refers to the dynamic properties, exhibiting the level of vibration in relation to the mass and stiffness of a structure (Zainal et al., 2018). To avoid sudden and catastrophic failure, it is essential to understand the dynamic characteristics of a structure. Structures made of laminated composites exhibit complex dynamic characteristics. A study by Imran et al. (2019) discussed the initiation of delamination that had caused the major failure of laminated composite structures, affected by the dynamic characteristics and vibration properties. Other investigations and experiments are also conducted, which for example, Nayak (2018) conducted physical tests and numerical simulations for free vibrations of woven fiberglass/epoxy laminated composite plates. Norman et al. (2018) investigated the free vibrations of the laminated composite beam due to the effect of lamination schemes using ANSYS software and an analytical approach, based on the earlier research by Khayal et al. (2019). Shi et al. (2019) established an analytical approach for free vibrations analysis of cross-ply composite laminates with shallow shells by incorporating semi-analytic method into arbitrary classical and elastic boundary conditions. There are also studies related to free vibrations of thick laminated composite plates (Xue et al.,2020) and laminated composite plates with cuts-out (Padhi, 2014).

In terms of hybrid laminated composites, numerous past studies focused on employing numerical simulations to analyze the natural frequencies. The research interests include investigating the effect of different ratio of fiber volume fraction (Pingulkar & Suresha, 2016) and various stacking sequences (Madhu & Kumarasamy, 2017) on hybrid laminates' natural frequencies. Rout et al. (2019) conducted an experimental-simulation (finite element method) analysis for hybrid laminated composite beams. Other than that, the natural frequencies and mode shapes were also studied on hybrid laminated composites such as Glass-epoxy, Carbon-epoxy and Graphite fiber reinforced polyimide materials (Suragimath, 2019), E-Glass fiber (60%) and Kevlar (40%) (Jadhav et al., 2019), and laminated composites hybrid with Shape Memory Alloy (SMA) materials (Rasid et al., 2018).

Based on the literature, it can be concluded that natural frequency is an important property to be considered when designing hybrid laminated composites under dynamic loading conditions. Therefore, it is crucial to investigate the dynamic characteristics of kevlar/glass hybrid laminated composite plates. The main focus of this study is to investigate the effect of various lamination schemes, boundary conditions, and fiber compositions on natural frequencies of kevlar/glass hybrid laminated composite plates under free vibration. The free vibration characteristics of Kevlar/Glass hybrid laminated composite plates for various compositions under various boundary conditions; will be revealed for the first time. This work is novel as there has been no recorded study that uses this method before. Moreover, the new data generated in this study could be useful for validation, comparison or reference prior to designing kevlar/glass hybrid laminated composite plates.

3 Method

In general, the work covers finite element modelling and simulation, commercial software (ANSYS v16.0 2014 SAS IP, Inc.). The built-in modal analysis functions are easy to use and thus were used for setting up the case studies. For a better explanation, the description of the research methodology is divided into two stages.

Stage 1: Numerical Validation

To validate the finite element simulation procedure for performing the free vibration analysis of a hybrid of the laminated composite plate, the current simulated results are compared to the results from available past literature. The numerical validation was conducted based on the work of Pingulkar & Suresha (2016). The composite plate was made of hybrid carbon and glass fiber composites with dimensions of 150 mm long and 75mm wide. The ply thickness for the glass fiber lamina was 0.15 mm and the ply thickness for carbon fiber lamina composite was 0.13 mm. The plate was meshed into 20 x 20 elements using shell 281 element type. The lamination schemes analysed were [0g/+45c/-45c/90g]s and [0c/+45g/-45g/90c]s.

Stage 2: Determining Natural Frequency

In this study, the effects of various lamination schemes, boundary conditions, and fiber compositions on natural frequencies of hybrid laminated composite plates are analysed. The lamination schemes analysed were unidirectional [0/0/0/0]s and Cross Ply [0/90/0/90]s, where the lamina arrangement consists of 4 plies of Kevlar Epoxy and 4 plies of Glass Epoxy. The plate was modelled as a rectangle with the dimensions of 150mm (length) x 75mm (width) using ANSYS. The ply thickness for both Kevlar Epoxy and Glass Epoxy lamina was 0.15mm. The various arrangement of lamina sequence, as well as different numbers of lamina, will reflect the fiber compositions. The properties of Glass Epoxy and Kevlar Epoxy are shown in Table 1. The plate was meshed into 20 x 20 elements using eight noded quadrilateral shell elements (SHELL 281). To investigate the effect of boundary conditions, three types of boundary conditions (Free-Free-Free-Free (FFFF), Clamp-Free-Free-Free (CFFF), and Clamp-Clamp-Clamp-Clamp (CCCC)) around the plate were analysed. Finally, the Block Lanszoc mode extraction method was used to determine the first five mode shapes and natural frequencies.

Table 1: Material Properties for Kevlar Epoxy and Glass Epoxy

Kevlar Epoxy		Glass Epoxy	
E1	80.0 GPa	E1	44.930 GPa
E2 = E3	5.5 GPa	E2 = E3	14.040 GPa
$\nu 12 = \nu 13$	0.34	$\nu 12 = \nu 13$	0.2481
$\nu 23$	0.33	$\nu 23$	0.3775
G12=G13	2.2 GPa	G12=G13	5.263 GPa
G23	1.8 GPa	G23	5.101 GPa
Density	1381.0 kg/m3	Density	2081 kg/m3

(Sources: Wang et al. 2011; Pingulkar & Suresha, 2016)

4 Result and Discussion

The numerical validation procedure conducted prior to the free vibration analysis, has proven the accuracy of the current finite element procedure and finite element models. This simulation results are compared to the results of Pingulkar & Suresha (2016), see Table 2. The obtained mode shapes, as well as the natural frequencies of the hybrid E-glass/T300 carbon Epoxy, laminated composite plates are similar to the results of Pingulkar & Suresha (2016), where the maximum difference percentage was found to be less than 5%, thus validating the accuracy of the finite element model and procedure. The results also show that the mode shapes change when varying lamina sequences, but the results are similar to the past study. Therefore, it is concluded that good agreement has been obtained between the natural frequencies determined in this work compared to the literature.

Table 2: Simulated natural frequencies and modes shape compared to literature.

Laminate	*Mode	Pingulkar & Suresha (2016)	This Work	
		Numerical Simulation (Hz)	Numerical Simulation (Hz)	% Diff.
$[0^{g}/45^{c}/-45^{c}/90^{g}]_{s}$	1B	37.374	37.737	0.97
	1T	165.05	163.29	1.07
	2B	231.26	233.99	1.17
	2T	528.39	524.4	0.76
	1C	645.65	653.14	1.15
$[0^{c}/45^{g}/-45^{g}/90^{c}]_{s}$	1B	54.697	56.665	3.53
	2B	137.08	142.31	3.74
	1T	341.24	353.54	3.51
	3B	495.24	514.39	3.79
	2T	654.56	666.21	1.76

**B- Bending, T- Torsion, C – Combined*

4.1 Effect of Boundary Conditions on Natural Frequencies

Figure 1 shows the effect of changing the boundary conditions, which are CCCC, CFFF, and FFFF on the modes shape of vibrations and natural frequencies for a cross-ply [0/90/0/90]s laminated composite plate. The results show that the CCCC boundary condition produced the highest natural frequency and the CFFF boundary condition produced the lowest natural frequency. This phenomenon confirms that different type of boundary conditions provides unique constraints in the response to the dynamic load application, and thus generating different vibration behavior. In terms of computational mechanics, applying different boundary conditions (constraints) on the model will develop different sets of simulation equations, thus generating unique mathematical solutions, in terms of the mode shapes and the values of natural frequencies. Observing Figure 1 and Figure 2, it can be observed that the trend of mode shapes for the present study is similar to the trend obtained by other studies (Pingulkar & Suresha, 2016). Different boundary conditions applied (Ivanychev, 2021) have resulted in different reactions (force/moments) at the supports and at the same time, this situation affected the stiffness of the hybrid laminated composite plates. The results show that while the stiffness of the vibrating system changes, the mass still remains the same.

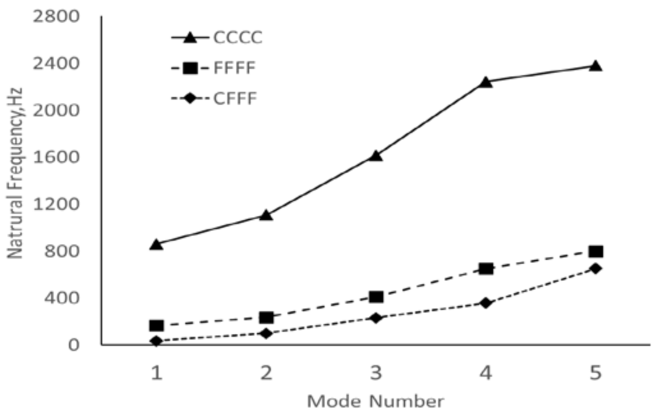

Figure 1: The simulated natural frequencies of [0/90/0/90]s composite laminates under various boundary conditions (see Figure 2 for the corresponding mode shape).

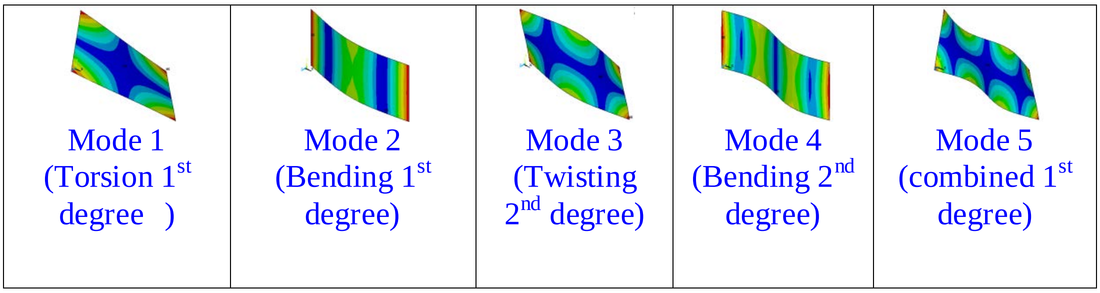

Figure 2: Examples of mode shapes of [0/90/0/90]s composite plate with boundary condition of Free-Free-Free-Free (FFFF).

4.2 Effect of Hybridization on Natural Frequencies

Figure 3 illustrates that composition [G/K/K/K/K/K/K/K] produced the highest natural frequency. In contrast, composition [K/K/G/G/G/G/G/G] produced the lowest natural frequency in cross-ply, constrained with CCCC boundary condition. It clearly shows that changing the laminate stacking sequence will affect the dynamic behavior of the composite. Even though the components have similar properties, the component's stacking sequence will give a different value of natural frequencies. The changes in composition bring a greater degree of flexibility to the structure design of composite material. The significance of this knowledge is to give inspiration to engineers to make improvements based on the laminate's composition instead of redesigning the complete structure. Figure 4 shows the changes in natural frequency when the number of Kevlar fibers increases in the hybridization composition of cross-ply laminate [0/90/0/90]s. It shows the composition with all Kevlar [K/K/K/K/K/K/K/K] has generated the highest natural frequency. The increasing number of Kevlar fiber (lamina) in the hybrid composite laminates also contributes to the increased value of natural frequency. The increasing trend of natural frequencies is also observed around 0.1% until 3.0% at the first mode and fifth mode of vibrations respectively.

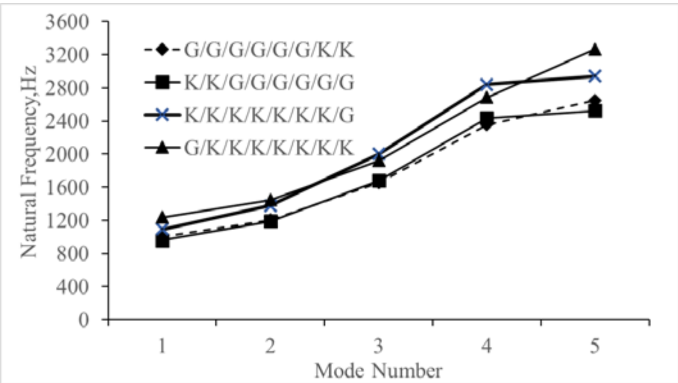

Figure 3: Simulated natural frequencies of [0/90/0/90]s composite plates under CCCC boundary conditions for various hybridization compositions.

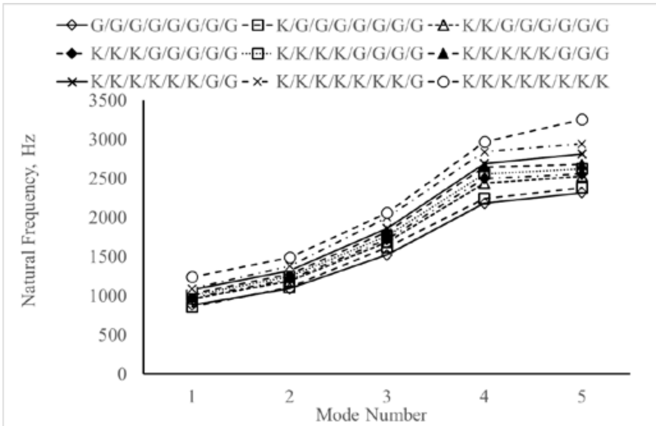

Figure 4: Natural frequencies of [0/90/0/90]s composite laminates (CCCC) for an increasing number of Kevlar fiber (lamina) composition.

5 Conclusion

In this study, modal analysis has been performed on hybrid composite laminates made of Kevlar/Glass epoxy using finite element software. This work focuses and predicts the laminate mode shapes under various lamination schemes, boundary conditions, and fiber compositions.

Based on the three types of boundary conditions analyzed, CCCC has produced the highest natural frequency, while CFFF produced the lowest. Another finding is that the mode shape changes according to the types of boundary conditions. It is also found that the angle of fiber orientation and laminate stacking sequences yield substantial differences in the laminate's dynamic behaviour. The natural frequency produced varied results even though the laminate has the same geometry, mass, and boundary conditions. This study proves that finite element simulation is found to be useful for vibration analysis as it is capable to generate graphical results related to fundamental frequencies and mode shapes. The generated data and outcomes of this study could be used by composite manufacturers in designing structures with reduced vibration levels by just considering the effects of boundary conditions or laminate stacking sequences. Therefore, it could be concluded that this study has provided knowledge to better understand the finite element procedures of hybrid composite laminates and their effects on natural frequency and mode shapes.

6 Availability of Data And Material

Data can be made available by contacting the corresponding author.

7 Acknowledgement

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