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Modal Analysis for Free Vibration Behavior of FRP Panels

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Abstract – Applications such as aircraft wings, structural panels and roof panels of buildings experience huge vibration that can be controlled by choosing proper Fiber Reinforced Polymer (FRP) material which has appropriate thickness and fiber orientations in the panels. Modal analysis is an important technique to determine the vibration characteristics for structural and engineering materials, where natural frequencies and mode shapes can be studied. In this paper, modal analysis is carried out on Jute, Flax, Sisal and Hemp FRP composite cantilever beam by using ABAQUS/CAE 6.14 software. The natural frequency response and mode shapes are studied. The results are validated with theoretically calculated values of natural frequencies. In addition, an analysis is carried out to by replacing the top and bottom natural fiber layers with Kevlar-29 fabric, which shows substantial increase of around 54% in natural frequency. Out of all the varieties of panels under study, the hybrid panel made of Kevlar and Hemp showed maximum natural frequencies of 21.2 Hz, 132.5 Hz and 336.4 Hz for first, second and third flexural mode respectively.

Keywords* — *Free Vibration, Hybrid composite,* Hemp, *Natural fibers, Natural frequency

I. INTRODUCTION

Natural fiber from plant with man-made fibers are used to fabricate hybrid Fiber Reinforced Polymer (FRP) composite which has significant potential over conventional FRP. The applications like aerospace, windmills, automobile, marine structures, building's roof and duct requires mechanical strength as well as dynamic vibrational stability[1]. The structures in these type of applications are frequently subjected to wider range of dynamic load conditions which can produce excessive vibrations [2]. The proper combination of various natural and synthetic fibers to make hybrid FRP composite have many advantages such as light weight, low cost, high specific strength, stiffness and eco-friendly nature over present synthetic FRP composites[1]. To attain the right grouping of material properties and service performance, the study of dynamic behavior is important to avoid the difficulties caused due to vibration. It is important to study i) the natural frequency of structure, ii) modal shapes to strengthen the critical regions and iii) damping factors corresponding to the natural frequencies [3]. Numerical modelling and modal analysis are the important tools for recent researchers along with experimentations.

Chemical treatment on natural fibers is required in fabrication of FRP composite. The purpose of chemical treatment on natural fibers is to improve the desired mechanical and vibration properties of FRP by the enhancement of interfacial bonding between fiber and matrix for better natural frequencies of Sisal and Banana FRP [4]. Rajni et al. [5] studied the free vibration behavior of chemically treated coconut FRP with the improvement in natural frequency. J. Alexander [6],[14] worked on GFRP and basalt FRP fabricated by hand lay-up technique and found that the natural frequency and damping factors are almost close numerically using ABACUS software. The natural frequency of owen fabric BFRP was found higher than unidirectional BFRP. The dynamic behavior of hybrid FRP depend upon different types of fiber lay-ups indenting to get better damping without compromising on their stiffness. The desired lay-up has to be selected depending upon natural frequency and damping at different modes. The modal analysis was carried out using FEM software (ANSYS-11). Modal numerical study was carried out on Jute epoxy composite with cantilever condition to find out natural frequency that ranges from 72.50 Hz to 263.90 Hz. The FEA approach was used for six nodes to predict dynamic behavior [7].

Dynamic characteristics in terms of natural frequency and damping ratio were estimated and found higher in case of 45^0 and 90^0 ply orientation for coconut FRP. The natural frequency varies from 21 Hz to 177 Hz with the damping

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ratio of 0.09 to 0.481 [8]. M. Rajesh [4] observed the natural frequency of 24 Hz to 633 Hz in Sisal FRP with the damping ratio of 0.11 to 0.40 in free vibration damping. Flax FRP shows 51.03% higher vibration damping property than GFRP which means natural fibers used in hybrid FRP has better results at lower as well as higher frequency range [9]. Damping ratio of Hemp FRP was relatively constant at around 0.14 with the natural frequency upto 200Hz [10]. The natural frequency and mode shapes for Hemp epoxy composite were analyzed using FFT analysis and results were promising as compare to other FRPs [11]. Natural fiber FRPs of Sisal and Flax were studied numerically for the manufacturing of aircraft wings as core materials using APDL ANSYS software and satisfying results were found [12]. Hemp, Flax and Sisal FRP composites have been investigated for natural frequency and damping factors and found that damping behavior is better in bidirectional than unidirectional orientation of fibers using ANSYS 15.0[13]. Kevlar FRP shows maximum natural frequency of 74 Hz to 1245 Hz [3]. Referring various journals, the natural frequencies of different natural fiber FRP are found very less as compared to kevlar fabric FRP as shown in the Table 1 and also represented in Figure 1. There is wide scope to enhance the natural frequency of FRP composite by combining natural fiber with kevlar and there is no evidence so far about the study of the dynamic behavior of such hybrid configuration.

Sr. No.	FRP	Frequency(Hz)			Ref.
		Mode 1	Mode 2	Mode 3	
1	Kevlar-FRP	74.56	458.09	1245.2	[3]
2	Jute-FRP	72.5	201.39	243.54	[7]
3	Flax-FRP	50.76	157.6	367.79	[13]
4	Sisal-FRP	24	233	633	[4]
5	Hemp-FRP	22.1	40.76	130.67	[11]
6	Coconut-FRP	21.92	177.37	-	[8]
7	Basalt-FRP	14.64	122.89	315.19	[14]

Table 1: Literature data of FRP composite

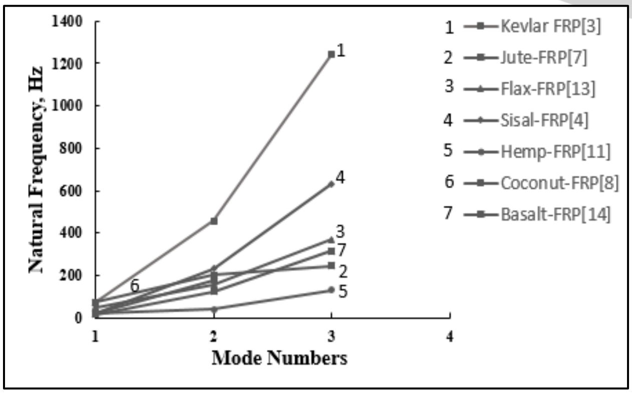

Figure 1: Literature data for natural Frequencies of different FRP composite and Kevlar

In this paper, four different types of FRP panels made of Jute, Flax, Sisal and Hemp were studied through modal analysis. Further, the effect on natural frequency of these panels were studied by adding Kevlar fabric at the facesheet. The natural frequency and mode shapes are determined by using ABAQUS/CAE 6.14 software. This numerical simulation would be helpful to decide the suitable combination of synthetic and natural fibers to develop hybrid panels for new wide range of applications.

II. MATERIALS AND METHODS

A. Materials

Four kinds of composite panels are considered for the analysis. The panels are made by reinforcing the natural fibers like Jute, Flax, Sisal and Hemp in the thermoset epoxy resin. Each panel consists of six layers. The thickness of each layer is close to 0.65 mm as shown in Figure 2. The overall thickness of panel is 4 mm. The panels made of Jute, Flax, Sisal and Hemp fabric are represented as Jute-FRP, Flax-FRP, Sisal-FRP and Hemp-FRP. The configuration of panels are as follows:

i) Jute/Jute/Jute/Jute/Jute/Jute – Jute-FRP

ii) Flax/Flax/flax/Flax/Flax/Flax – Flax-FRP

iii) Sisal/Sisal/Sisal/Sisal/Sisal/Sisal – Sisal-FRP

iv) Hemp/Hemp/Hemp/Hemp/Hemp/Hemp – Hemp-FRP

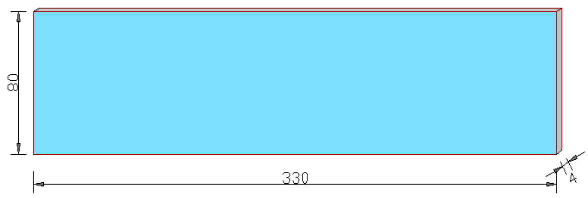

Figure 2: FRP Panel

The modal analysis is carried out for the above panel by using software. The natural frequency for three modes are determined by theoretical formulae. The theoretical results are compared with the numerical results to validate the numerical methodology.

The configuration of each type of panel is then modified by adding the Kevlar-29 fabric facesheet at the top and bottom by replacing the natural fabric layer. However, the same thickness i.e. 4 mm is maintained for the panel. The modified layer wise stack configuration is as below:

i) Kevlar/Jute/Jute/Jute/Jute/Kevlar – Jute-K FRP

ii) Kevlar/Flax/Flax/Flax/Flax/Kevlar – Flax-K FRP

iii) Kevlar/Sisal/Sisal/Sisal/Sisal/Kevlar – Sisal-K FRP

iv) Kevlar/Hemp/Hemp/Hemp/Hemp/Kevlar–Hemp-K FRP

The natural frequencies and corresponding mode shapes are determined by software for the above panels. The change in the natural frequency is observed and suitable panel is identified.

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B. Theoretical Analysis for Free Vibration of cantilever beam

The cantilever beam with rectangular cross section is subjected to bending vibration by giving small displacement at the free end. The natural frequency can be calculated for cantilever beam for the first three mode shapes using Euler-Bernoulli beam theory' as shown in Figure 3 and 4 respectively.

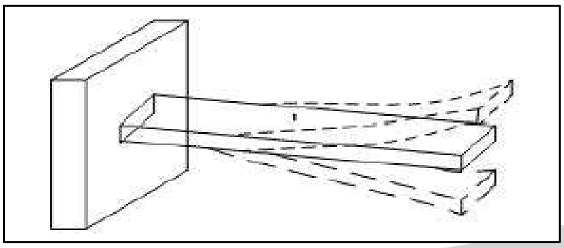

Figure 3: A cantilever beam under free vibration [15, 16]

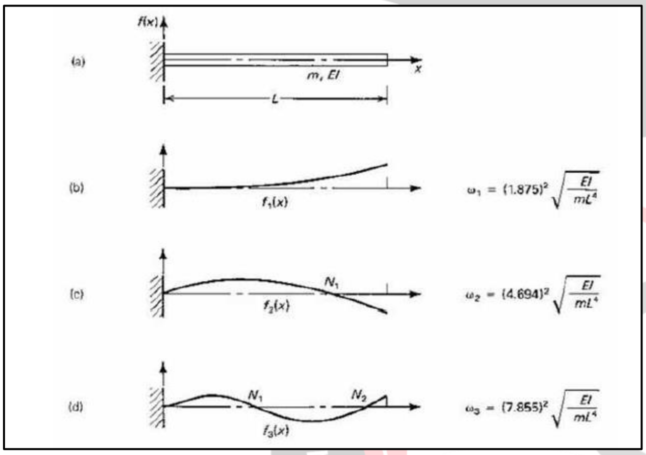

Figure 4: First three undamped natural frequencies and corresponding mode shaped of cantilever beam [15, 16]

The first natural frequency is calculated using [15, 16]

$$\omega_{1} = \beta L\sqrt{\frac{EI}{mL^4}}$$ ----------------------------- 1

Above equation can be written as

$$\omega_{1} = \beta L\sqrt{\frac{EI}{\rho AL^4}}$$

Where ω_1- Circular frequency (rad/sec), E- Young's modulus, I- Moment of inertia, A- cross section Area (b x h), b & h- width and thickness of beam, ρ- Density of material, L-length of beam, βL – constant (1.875, 4.694 and 7.855 etc.)

I- moment of inertia = $\frac{bh^3}{12}$ for rectangular cross section

By putting value of I and A in equation 1,

We get, $\omega_{1} = \beta L\sqrt{\frac{Eh^2}{12\rho L^4}}$ ----------------------------- 2

Sample calculation is done for Jute-FRP considering the following nomenclature.

L = 330mm, b = 80mm, h = 4mm, E = 5.8 x 10^9 N/m^2,

ρ = 1300Kg/m^3 (From Table 2)

First natural frequency for Jute-FRP,

$$\omega_{1} = (1.875)^2\sqrt{\frac{5.8\ X\ 10^9\ X\ (0.004)^2}{12\ X\ 1300\ X\ (0.33^4)}}$$

= 78.714 rad/sec

The natural frequency f_{n1} is calculated as,

f_{n1} = 78.714/ 2π Hz

f_{n1} = 12.534 Hz

Similarly values of natural frequency for all FRP panels are calculated for first three modes. The material properties of all the layers are given in Table 2, Elastic constant along fiber directions are determined though tension test on UTM. However, other properties are estimated by referring journal papers and by using halpin-sai equation. As the elastic modulus along fiber direction (E_x and E_y) is mainly affecting the bending behavior under free vibration of cantilever beam, the values of same is used in the formula. The theoretical natural frequencies are calculated using above equation for all panels and values are shown in Table 3.

Table 3: Theoretical natural frequency of natural FRP composite

Natural FRP	Frequency, Hz		
	Mode 1	Mode 2	Mode 3
Jute- FRP	12.53	78.55	219.98
Flax-FRP	13.71	85.95	240.73
Sisal-FRP	10.76	67.72	189.65
Hemp-FRP	14.30	89.46	250.50

C. Numerical Modal Analysis

The modal analysis is carried out to find the natural frequency of the composite panels. The simulation is done in ABAQUS/CAE-6.14 software. The layered solid model of the dimensions 330 mm X 80 mm is created with the thickness of 4 mm as shown in Figure 5. The solid element (20 noded brick) are used to mesh the above model. The element size is 10 mm along the length and width. Single element is taken along the thickness of each layer and total numbers of elements and nodes generated in the model are 264 and 2056 respectively as shown in Figure 6. The orthotropic material properties are assigned to each layer as shown in the Table 2. The meshed panel is clamped at one end to simulate the condition of cantilever. The natural frequencies and the corresponding mode shapes are determined using Block Lanczos method, inbuilt in ABAUS software.

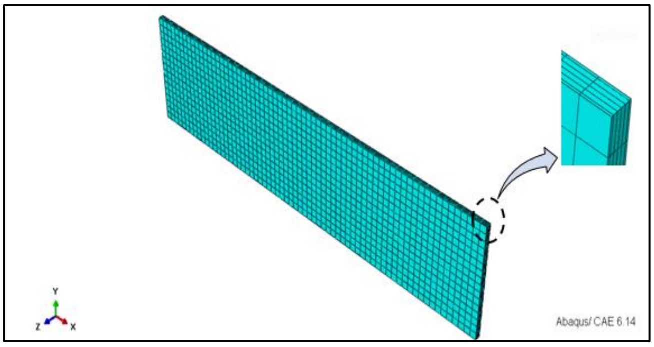

Figure 5: Constrained model of FRP panel

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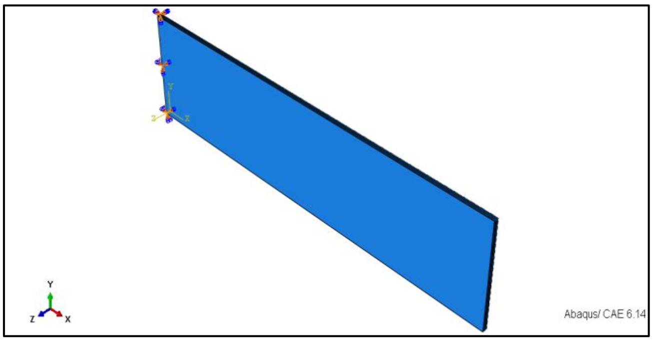


Figure 6: Mesh Solid layered FRP panel

The natural frequencies of various FRP composite panels are determined and compared with the theoretical values as shown in the Table 4.

Table 4: Comparative table of modal frequencies

Natural FRP	Theoretical Frequency, Hz			Numerical Frequency, Hz		
	Mode 1	Mode 2	Mode 3	Mode 1	Mode 2	Mode 3
Jute-FRP	12.53	78.55	219.98	12.71	79.48	222.85
Flax-FRP	13.71	85.95	240.73	13.90	86.91	243.51
Sisal-FRP	10.76	67.72	189.65	10.93	68.35	191.55
Hemp-FRP	14.30	89.46	250.50	14.40	90.09	252.21

The numerical values matches well with theoretical values and the maximum error is less than 2%. It validates the numerical model of modal analysis. Figure 7 shows the numerical results of natural frequency at three mode shapes by dashed lines for Jute, Flax, Sisal and Hemp-FRP and the natural frequency for all FRP's from literature review are shown with continuous lines. C. Srinivasan et al. [7] experimentally found out the natural frequencies of Jute-FRP ranging from 72 Hz to 243 Hz. S. Madhu et al. [13] observed the natural frequency of 50 Hz to 367.7 Hz in cantilever beam of Flax-FRP. Rajesh et al. [4] compares the sisal-FRP with other FRP's and determined the values in the range of 24 Hz to 633 Hz after chemical treatment. Natural frequency of Hemp-FRP calculated by Muthuraj et al. [11] which spreads over 22 Hz to130 Hz for first three modes. The difference in the values of natural frequency is due to variation in the thickness of the specimen panel but the overall trend is same.

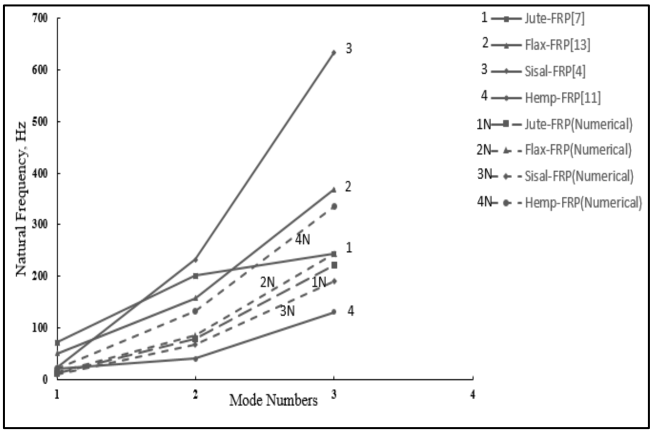
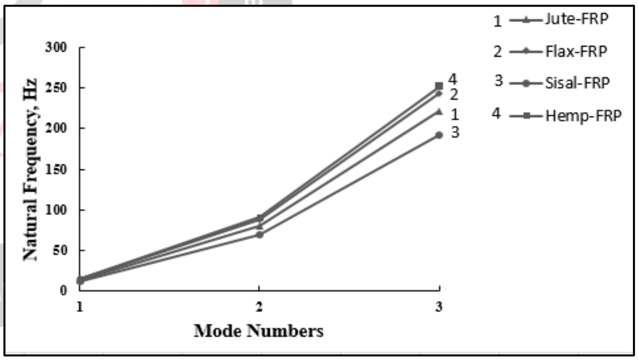


Figure 7: Validation of natural frequencies of different FRP'S

Same analysis is repeated by replacing the top and bottom natural fabric layer with kevlar-29. However, the thickness of panel is maintained at 4 mm.

III. RESULTS AND DISCUSSION

Modal analysis has been done to get the natural frequency and mode shapes of Jute, flax, Sisal and Hemp natural fiber FRP composites for three modes using ABAQUS/CAE-6.14 software. Results are shown in Table 5 and Figure 8. The natural frequencies are in the range (1) from 10 Hz – 260 Hz for first three flexural modes. Hemp-FRP is observed to have maximum natural frequency of 14.4 Hz, 90.09 Hz and 252.21 Hz respectively for first three flexural modes.



Sr. No	FRP	Frequency (Hz)		
		Mode 1	Mode 2	Mode 3
1	Jute-FRP	12.71	79.48	222.35
2	Flax-FRP	13.9	86.91	243.51
3	Sisal-FRP	10.93	68.35	191.55
4	Hemp-FRP	14.4	90.09	252.21

Table 5: Natural frequencies of different natural fiber composite
Figure 8: Natural frequencies of different natural fiber FRP

The numerical simulation is repeated on the hybrid FRP panels i.e. Jute-k FRP, Flax-K FRP, Sisal-K FRP and Hemp-K FRP. The results are shown in Table 6 and Figure 9. The corresponding mode shapes are also shown in Figure 10.

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Sr. No.	FRP	Frequency (Hz)		
		Mode 1	Mode 2	Mode 3
1	Jute-K FRP	19.9	125.42	310.21
2	Flax-K FRP	20.87	130.45	328.96
3	Sisal-K FRP	19.68	122.84	292.13
4	Hemp-K FRP	21.21	132.56	336.42

Table 6: Natural frequencies of different natural and kevlar fiber composite

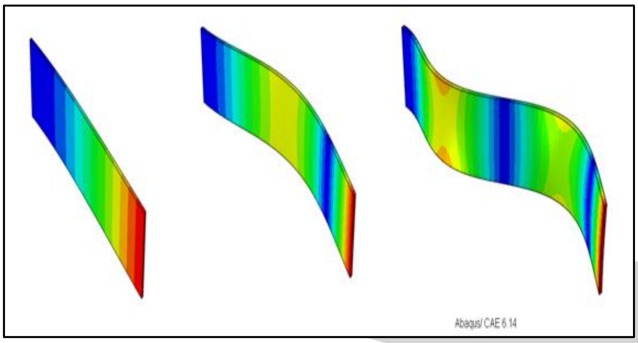

Figure 9: Natural frequency of hybrid natural and Kevlar FRP panels

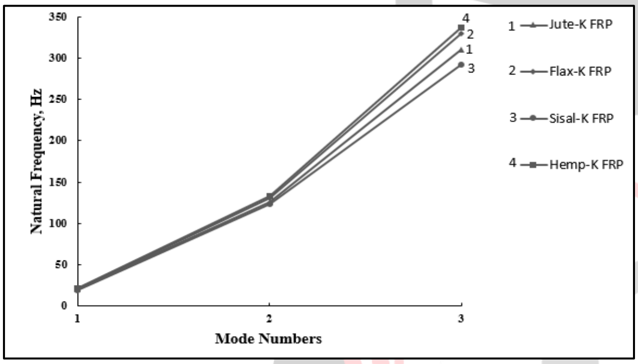

Figure 10: Mode shape 1, 2, 3 in modal analysis of FRP panel

There is substantial increase of natural frequencies of FRP panels by replacing the top and bottom natural fiber layer by Kevlar layer. The average percentage increase of natural frequency of Jute- K FRP, Flax-K FRP, Sisal-K FRP and Hemp-K FRP is 60%, 45%, 70% and 42.5% respectively (Figure 11). The natural frequencies are observed to be maximum for Hemp-K FRP. The values are 21.21 Hz, 132.56 Hz and 336.42 Hz respectively for first, second and third mode shapes.

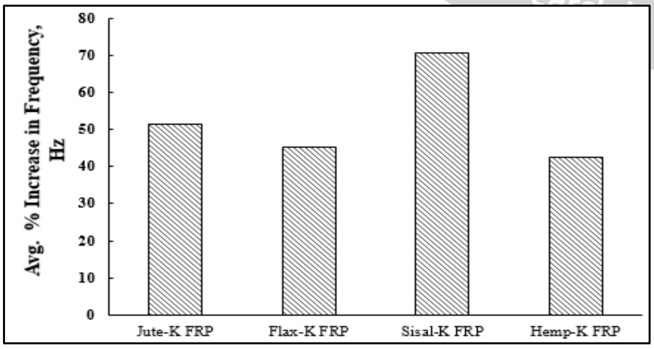

Figure 11: Avg. % increase in natural frequency with Kevlar face sheet in hybrid FRP panel

IV. CONCLUSION

1. Four varieties of FRP panels: Jute-FRP, Flax-FRP, Sisal-FRP and Hemp-FRP are numerically simulated to determine the natural frequency. The analysis is repeated for Jute-K FRP, Flax-K FRP, Sisal-K FRP and Hemp-K FRP panels where only top and bottom layers are replaced by Kevlar. Thereafter, the effect on natural frequency is observed for the modified configuration.

2. Out of all natural fiber FRP's, Hemp- FRP is observed to have maximum frequency of 21.21 Hz, 132.56 Hz and 336.42 Hz respectively for first, second and third mode shapes

3. There is substantial increase of around 54% of natural frequency by placing Kevlar layer at top and bottom in the modified configuration of FRP.

4. The Hemp-K FRP hybrid panel, where Hemp fabric layer are placed in between the Kevlar fabric have shown the maximum values of natural frequency.

It is observed that combination of Kevlar fabric with natural fiber provide better dynamic vibrational stability to FRP panels and further can be investigated for mechanical properties such as flexural strength, impact resistance, damping etc.

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Table 2
Properties of the different layers of FRP panel [1, 4, 7, 8, 11, and 14]

Material	Density (Kg/m3)	E_x (GPa)	E_y (GPa)	E_z (GPa)	υ_{xy}	υ_{yz}	υ_{zx}	G_{xy} (GPa)	G_{yz} (GPa)	G_{zx} (GPa)
Kevlar-29/epoxy	1440	29	29	9.3	0.10	0.18	0.18	18	15	15
Jute/epoxy	1300	5.8	5.8	2.4	0.3	0.15	0.15	2.50	1.86	1.86
Sisal/epoxy	1580	5.2	5.2	2.1	0.33	0.2	0.2	1.69	1.25	1.25
Flax/epoxy	1520	8.1	8.1	3.9	0.32	0.2	0.2	2.71	1.90	1.90
Hemp/epoxy	1470	8.5	8.5	4.1	0.26	0.21	0.21	2.75	1.95	1.95

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