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The effect of hybridization and boundary conditions on damping and free vibration of composite plates

Abstract: In this study, the influence of hybridization on natural frequency and damping properties of laminated composite plates consisting of various combinations of fibers and boundary conditions are examined. Carbon (C), Kevlar® (K), and S-glass fibers are used as reinforcement with epoxy resin for hybridization. Experiments are conducted on hybrid composites under the combinations of clamped, free, and simply supported boundary conditions. Natural frequency analyses of hybrid composites are performed using finite element analysis software ANSYS. Vibration test results obtained from experimental and numerical studies are compared with each other. Results show that hybridizations with three different fibers and their substitutions in the layers have strongly effected the damping and vibration characteristics of composite plates.

Keywords: damping; free vibration; hybrid composites.

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1 Introduction

Hybrid composite materials are commonly used in aerospace, marine, automotive industries due to high strength-to-weight ratios, good fatigue resistance, and longer durability as compared with metals. Behaviors of vibration characteristics of composite materials are of great concern in structural design systems in engineering applications. It is possible to understand these behaviours with studies on free vibration of composite plates having various boundary conditions, aspect ratios (length-to-width and length-to-thickness), and fiber orientation angles [1–4]. The fibers and their geometrical parameters significantly affect vibration behavior of composite plates [5]. Vibration characteristics of stiffened (U and T types) glass/polyester composite plates were investigated by Thinh and Quoc [6]. It was found that composite plates with U type stiffeners have higher natural frequency than composite plates with T type stiffeners. Some studies have been made on free vibration of woven fiber laminated composite plates subjected to hygrothermal effects [7, 8]. It has been reported that there is a reduction in natural frequency with an increase of temperature and moisture concentration for laminates due to reduction of stiffness. Some imperfections such as cutout, delamination, and crack can also affect stiffness and vibration behavior of composite plates [9–12].

One of the ways to achieve improved high mechanical properties of composite materials is hybridization. It is possible to combine different types of fibers or matrices, or both, to form a new material to get the desired requirements. Adali and Verijenko [13] presented the optimum stacking sequence of symmetric multilayered graphite-epoxy/glass-epoxy hybrid composites undergoing free vibration. They used high stiffness plates for outer layers and low stiffness plates for inner layers. Dynamic characteristics of cylindrical hybrid panels made of graphite/epoxy with viscoelastic core were investigated by Oh [14]. A viscoelastic damping model with co-cured, free and constrained layers was developed by the application of the refined finite element method based on the layer-wise shell theory. Chen et al. [15] studied vibration behavior of aluminum-epoxy/glass-epoxy hybrid composite plates considering the effects of thickness ratio, layer number, and material type. It was reported that the natural frequency was decreased with the increasing of the layer thickness ratio and stacked layer number. Chen [16] investigated buckling and vibration behavior of initially stressed hybrid composite plates consisting of glass fiber reinforced plastics (GFRP) and aluminum materials. It was found that both buckling and natural frequency values were the most significantly sensitive to thickness ratio and initial stress.

Besides various mechanical properties, vibration damping capacity is very important as it affects systems' safety, reliability, and performance. Kyriazoglou and Guild [17] investigated damping of GFRP composites and laminates. Experimental studies have been carried out to predict the damping response of GFRP for different fiber configurations. It was reported that successful development of force-displacement relationship leads to identifying damping of more geometrically complicated structures. Botelho et al. [18] investigated damping behaviors of carbon fiber/epoxy composites. carbon/epoxy, glass/epoxy, and combinations of them with aluminum sheets were considered for dynamic stability of composite plates. It was shown that damping ratio of glassepoxy/aluminum hybrid composite plate was approximately 44% higher than carbon-epoxy/hybrid composites. Abderrahim et al. [19] analyzed the damping behavior of unidirectional, orthotropic composites and laminates using different sizes of beam samples. Damping values were determined for first three bending modes with different stacking sequences.

There is less available literature on the effects of hybridization on damping and natural frequency of hybrid composites. It is necessary to utilize a combination of two or more different type fibers to obtain better vibration damping and vibration for design requirement. Previous studies mentioned here have investigated only laminated composites that are made of two different fiber-fiber and fiber-metal combinations. In this paper, three combinations of carbon, Kevlar, and S-glass fibers are used to determine damping and natural frequencies of hybrid composite plates under clamped-free-clamped-free (C-F-C-F), clamped-free-free-free (C-F-F-F), and simply supported-free-simply supported-free (SS-F-SS-F) boundary conditions. First two natural frequencies are experimentally determined and validated with ANSYS. Then, numerical studies are extended to get the first five natural frequencies and mode shapes.

2 Materials and methods

Plain woven carbon fiber (200 g/m^2), plain woven Kevlar fiber (170 g/m^2), and plain woven S-glass fiber (200 g/m^2) were used as reinforcements in the layers. An epoxy resin (MOMENTIVE-MGS L285), a hardener as catalyst (MOMENTIVE-MGS H285), and a releasing agent (Dost Kimya-OZ 5111) were used in the production of hybrid composites. Laminated fabrics were first laid on the flat mold, then subjected to 0.2 MPa pressure for 1 h curing time at 80°C temperature. After the production process, specimens were cut into the desired dimensions (length=200 mm, width=240 mm). Stacking sequences and fiber configurations of produced test specimens are given in Table 1.

Table 1 Lay-up sequence of produced specimens.

Material number	Material property	Lay-up sequence
1	Kevlar/epoxy	$[(0^\circ_K/90^\circ_K)_3]_S$
2	Hybrid	$[(0^\circ_K/90^\circ_K)/(0^\circ_C/90^\circ_C)/(0^\circ_G/90^\circ_G)]_S$
3	Hybrid	$[(0^\circ_K/90^\circ_K)/(0^\circ_G/90^\circ_G)/(0^\circ_C/90^\circ_C)]_S$
4	Hybrid	$[(0^\circ_C/90^\circ_C)/(0^\circ_K/90^\circ_K)/(0^\circ_G/90^\circ_G)]_S$
5	Carbon/epoxy	$[(0^\circ_C/90^\circ_C)_3]_S$
6	Hybrid	$[(0^\circ_C/90^\circ_C)/(0^\circ_G/90^\circ_G)/(0^\circ_K/90^\circ_K)]_S$
7	Hybrid	$[(0^\circ_G/90^\circ_G)/(0^\circ_K/90^\circ_K)/(0^\circ_C/90^\circ_C)]_S$
8	Hybrid	$[(0^\circ_G/90^\circ_G)/(0^\circ_C/90^\circ_C)/(0^\circ_K/90^\circ_K)]_S$
9	S-glass/epoxy	$[(0^\circ_G/90^\circ_G)_3]_S$

Mechanical properties of woven carbon, Kevlar, and S-glass materials with epoxy were experimentally determined according to the ASTM.D638-10 standard test method [20]. A Shimadzu AG-X series testing machine (Shimadzu Corporation, Kyoto, Japan) and an Ni-9237 data acquisition card (National Instruments Corporation, Austin, TX, USA) were used for tensile testing as shown in Figure 1. Mechanical properties of carbon/epoxy, Kevlar/epoxy, and S-glass/epoxy plates are listed in Table 2.

2.1 Vibration tests

Modal characteristics of produced test specimens were determined using an experimental set-up as shown

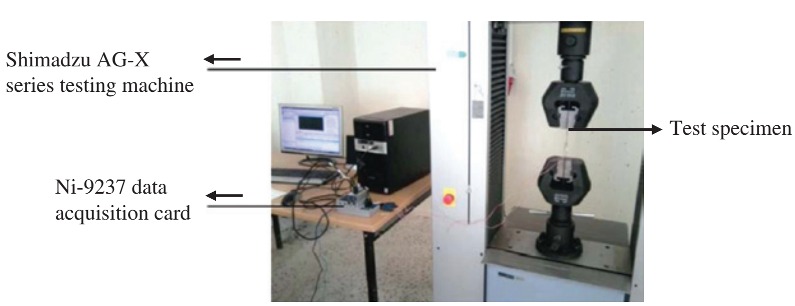


Figure 1 Experimental test set-up.

Table 2 Mechanical properties of produced test specimens.

Material	E_1=E_2 (Gpa) Elastic modulus	v_{12}=v_{21} Poisson's ratio	G_{12}=G_{21} (Gpa) Shear modulus	ρ (kg/m^3) Density
S-glass/epoxy	19.5	0.15	3.7	1710
Carbon/epoxy	49	0.10	3.2	1440
Kevlar/epoxy	26.5	0.09	1.5	1250

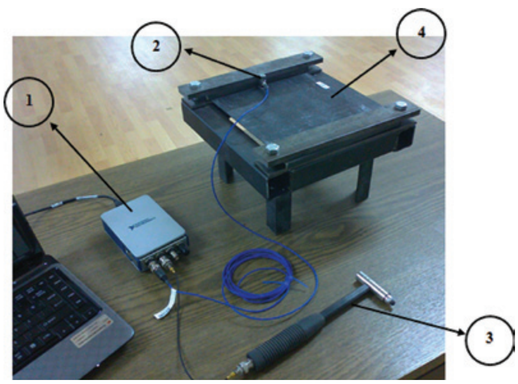


Figure 2 Experimental modal analysis set-up. (1) Data acquisition card, (2) accelerometer, (3) modal impact hammer, (4) test specimen.

in Figure 2. A general purpose PCB 352C03 ceramic shear ICP® accelerometer (Brüel & Kjær Sound & Vibration Measurement A/S, Nærum, Denmark) was used for output signal acquisition, a PCB 086C03 general purpose modal impact hammer was used for stimulus force signal, a National Instrument product NI 9234 data acquisition device with LABVIEW software was used in the experiments. For the C-F-C-F case, the specimen was first mounted in the frame, and then excited by an impact hammer to five points of the plate. Vibration responses were captured to predict natural frequencies after the specimens were excited with a hammer. Struck points, accelerometer position, and plate dimensions are shown in Figure 3.

As can be seen in Figures 2 and 3, the accelerometer was located on the plate near the clamped edge to eliminate the effects of weight of the accelerometer on natural frequency.

Table 3 shows natural frequencies of produced test specimens under the C-F-C-F, C-F-F-F, and SS-F-SS-F cases. Maximum and minimum natural frequencies were recorded in material 4 and material 7 for hybrid arrangements, respectively. It is obvious from Table 3 that replacements of carbon fiber have considerable effects on natural frequency. For example, replacement of carbon fibers between the middle and most upper layers leads to approximately 27% differences in natural frequency values.

2.2 Damping ratios (half-power bandwidth method)

Damping ratios of the hybrid composites were determined using a half-power bandwidth. Firstly, maximum amplitude of first mode frequency was determined from the frequency response curve, then ω_1 and ω_2 frequencies corresponding to Z_1 and Z_2 points were found by dividing the maximum amplitude value of first mode to the value of $\sqrt{2}$ as shown in Figure 4. Then damping was calculated following equation [21].

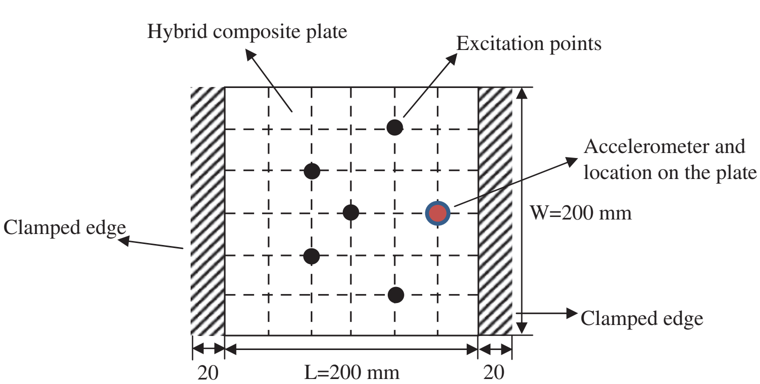


Figure 3 Struck points and location of accelerometer on the hybrid composite plate for the C-F-C-F case.

Table 3 First two natural frequencies of composite plates.

Material number	C-F-C-F		C-F-F-F		SS-F-SS-F	
	Mode 1 (Hz)	Mode 2 (Hz)	Mode 1 (Hz)	Mode 2 (Hz)	Mode 1 (Hz)	Mode 2 (Hz)
1	315.45	337.28	50.76	76.43	145.51	165.92
2	319.59	345.67	52.13	79.19	147.53	175.67
3	286.23	289.06	44.61	73.65	128.38	154.50
4	374.48	386.71	61.50	85.45	163.84	198.69
5	398.38	427.43	65.17	91.28	173.19	199.84
6	367.66	370.48	56.76	83.28	159.03	190.31
7	270.01	285.00	41.93	71.67	119.85	152.19
8	293.98	323.81	46.41	74.27	137.55	162.98
9	230.76	263.19	36.52	68.52	115.41	145.07

$$\xi = \frac{\omega_2 - \omega_1}{2\omega_n}$$

Where ξ is the damping ratio, ω_n is the natural frequency of the first mode and ω_2-ω_1 is the bandwidth. Figure 5 shows the variation of damping ratios of composite plates. The maximum and minimum damping ratios were obtained with Kevlar/epoxy and carbon/epoxy, respectively. The damping ratio is maximum in Kevlar/Epoxy composite plate because of the viscoelastic behavior of Kevlar fiber. Material 3 ($[(0°_K/90°_K)/(0°_G/90°_G)/(0°_C/90°_C)]_S$) has

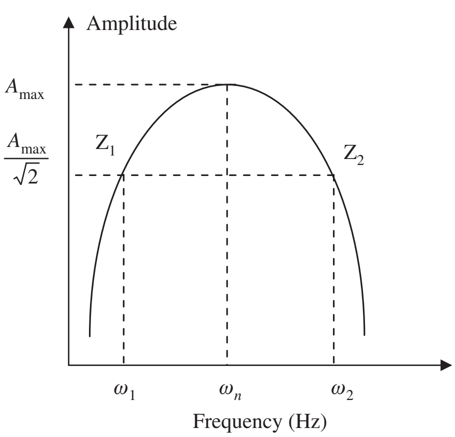


Figure 4 Half-power bandwidth method.

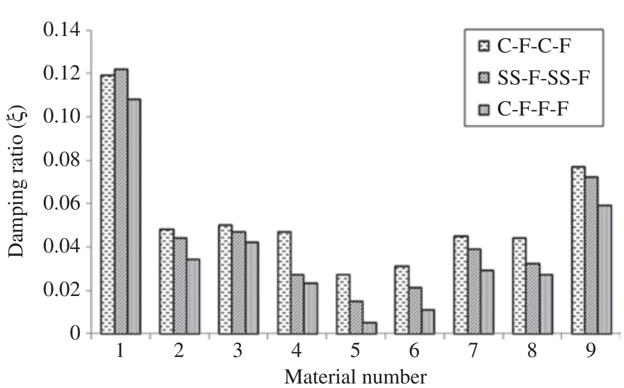


Figure 5 Damping ratios of hybrid composite plates.

Table 4 Comparison of numerical and experimental results.

Material number	Natural frequency (Hz)					
	Mode 1			Mode 2		
	Exp.	ANSYS	% Diff.	Exp.	ANSYS	% Diff.
C-F-C-F						
1	315.45	320.76	-1.68	337.28	331.16	1.81
2	319.59	326.73	-2.23	345.67	338.52	2.07
3	286.23	292.01	-2.02	289.06	305.75	-5.77
4	374.48	373.58	0.24	386.71	387.68	-0.25
5	398.38	406.83	-2.12	427.43	422.02	1.27
6	367.66	366.91	0.20	370.48	383.59	-3.54
7	270.01	274.35	-1.61	285.00	295.06	-3.53
8	293.98	303.00	-3.07	323.81	324.10	-0.09
9	230.76	237.78	-3.04	263.19	261.74	0.55
SS-F-SS-F						
1	145.51	142.05	2.38	165.92	173.18	-4.38
2	147.53	144.37	2.14	175.67	179.46	-2.16
3	128.38	128.87	-0.38	154.50	165.14	-6.89
4	163.84	165.30	-0.89	198.69	195.67	1.52
5	173.19	180.02	-3.94	199.84	206.67	-3.42
6	159.03	162.28	-2.04	190.31	190.81	-0.26
7	119.85	121.93	-1.74	152.19	156.13	-2.59
8	137.55	133.68	2.81	162.98	170.24	-4.45
9	115.41	120.93	-4.78	145.07	152.34	-5.01
C-F-F-F						
1	50.76	50.77	-0.02	76.43	77.43	-1.31
2	52.13	51.59	1.04	79.19	80.51	-1.67
3	44.61	46.06	-3.25	73.65	72.15	2.04
4	61.50	59.07	3.95	85.45	86.02	-0.67
5	65.17	64.33	1.29	91.28	92.37	-1.19
6	56.76	58.00	-2.18	83.28	84.57	-1.55
7	41.93	43.24	-3.12	71.67	70.69	1.37
8	46.41	47.79	-2.97	74.27	74.02	0.34
9	36.52	37.42	-2.46	68.52	67.18	1.96

better damping capability compared with other hybrid composites.

3 Numerical studies

Finite element analyses were performed to compute natural frequencies in higher modes of the hybrid composite plates. The plates were modeled using SHELL 99 element type [22], which have four nodes and each node has six degrees of freedom, translation in x, y, z and rotation in x, y, and z directions. The number of elements used in the analyses was 1600. In the finite element solutions, the Block-Lanczos method was used to extract eigen values for first five modes. The comparison of numerical and experimental results for first two natural frequency values are given in Table 4.

As can be seen in Table 4, there is no noticeable discrepancy between ANSYS (ANSYS, Inc., Berkeley, USA) and experimental results. Material 4 has higher natural frequencies in all modes and boundary conditions due to the arrangements of carbon fibers in the layers.

Natural frequencies are significantly affected by boundary conditions and are increased due to a reduction in the degrees of freedom at the edge supports. Maximum and minimum natural frequency values were recorded in boundary condition of C-F-C-F and C-F-F-F, respectively.

Figure 6 shows the variation of first five natural frequencies of the plates for different boundary conditions. It is evident from Figure 6 that natural frequency values of composite plates are increased by increasing the mode number from mode 1 to mode 5.

Mode 1 and mode 2 are bending modes and mode 4 and mode 5 are torsion modes who's values are nearly same. Mode 3 is a bending-torsion coupling mode for C-F-C-F and SS-F-SS-F boundary conditions. Table 5 shows the variation of mode shape plots by means of boundary

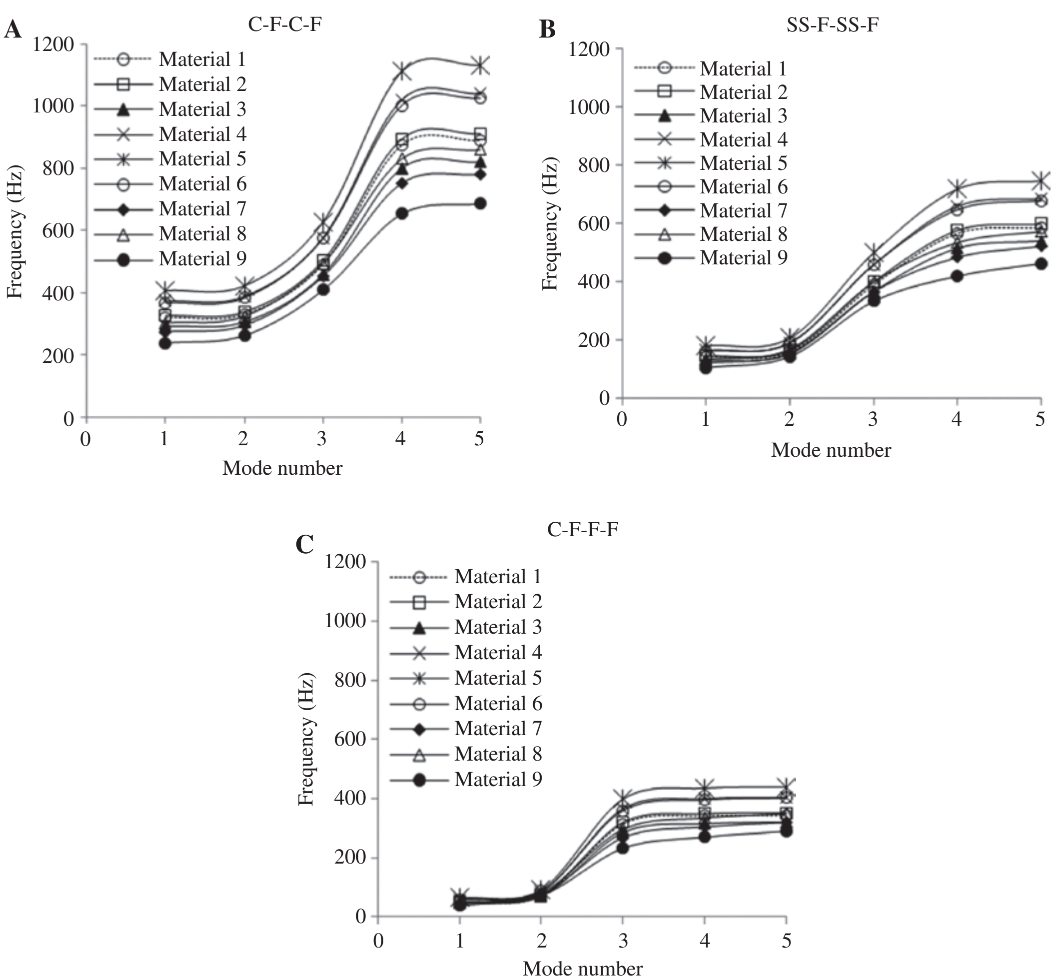
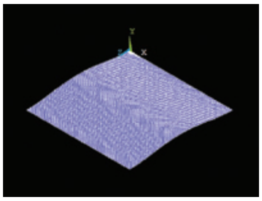
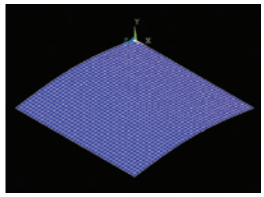
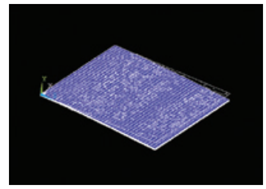
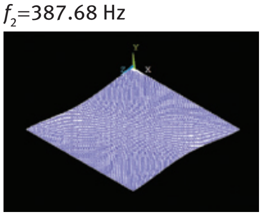
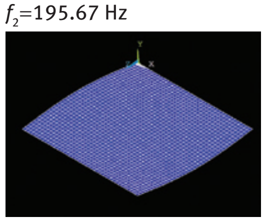
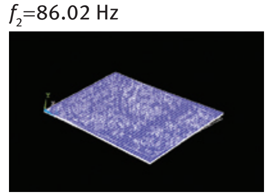
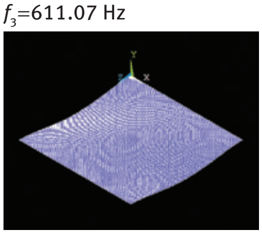
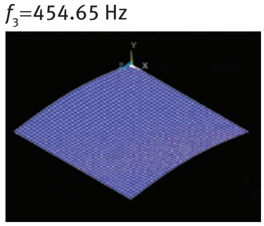
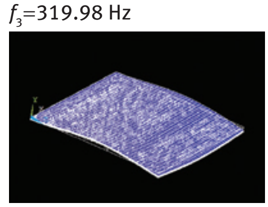
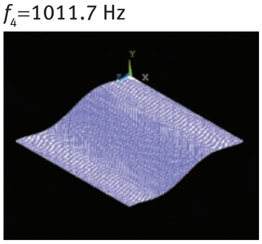
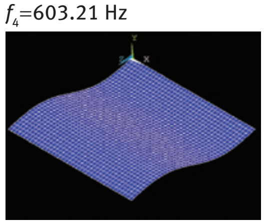
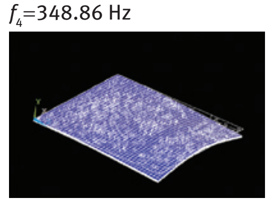
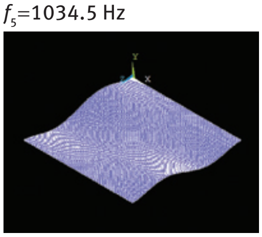
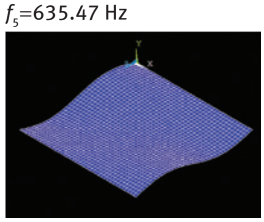
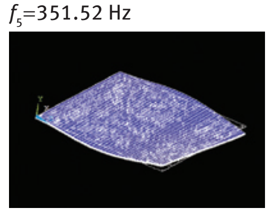


Figure 6 First five natural frequencies of laminated hybrid composite plates obtained from ANSYS. (A) C-F-C-F case, (B) SS-F-SS-F case, (C) C-F-F-F case.

Table 5 Comparison of mode shapes of material 4 for different boundary conditions.

Boundary conditions		
C-F-C-F	**SS-F-SS-F**	**C-F-F-F**
f_1=373.58 Hz 	f_1=165.30 Hz 	f_1=59.07 Hz 
f_2=387.68 Hz 	f_2=195.67 Hz 	f_2=86.02 Hz 
f_3=611.07 Hz 	f_3=454.65 Hz 	f_3=319.98 Hz 
f_4=1011.7 Hz 	f_4=603.21 Hz 	f_4=348.86 Hz 
f_5=1034.5 Hz 	f_5=635.47 Hz 	f_5=351.52 Hz 

conditions. Mode shapes of C-F-C-F are nearly same with SS-F-SS-F case, but different from C-F-F-F case due to consraints applied to the edge of the plate.

4 Conclusions

In this study, effects of fiber types and their combinations on the natural frequencies and damping values of the hybrid composite plates with various boundary conditions are investigated. The main conclusions can be drawn as follows:

1. Hybridization considerably effects damping and natural frequency of the composite plates,
2. For all modes, material 9 with stacking sequence of $[(0°_G/90°_G)_3]_S$ had a minimum natural frequency less than other materials due to lower bending stiffness of the S-glass fiber,
3. For all modes, material 5 with stacking sequence of $[(0°_C/90°_C)_3]_S$ had a maximum natural frequency

higher than other materials due to higher bending stiffness of Carbon fibers,
4. Natural frequencies of laminated hybrid composite plates in higher modes are considerably effected by replacements of Kevlar, carbon, and glass fibers in the layers,
5. While natural frequencies are increased by the use of fibers which have higher stiffness in the upper layer, damping is reduced due to lower viscoelasticity of the fiber,
6. The maximum and minimum damping ratios are obtained in $[(0°_K/90°_K)_3]_S$ and $[(0°_C/90°_C)_3]_S$ stacking sequences, respectively, since the viscoelastic behavior of Kevlar fiber is significantly greater than carbon and glass fiber,
7. When the damping properties are important for the structural design, Kevlar fiber should be used in the upper layer,
8. It is possible to increase damping capacity of hybrid composites by using fibers with high damping performance in outer layers and also possible to increase natural frequency by using fibers with higher stiffness in the outer layers,
9. Finally, natural frequencies and damping properties of laminated hybrid composite plates are considerably affected by the boundary conditions. The maximum and minimum frequency values are recorded in C-F-C-F and C-F-F-F edge conditions, respectively.

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