Studies on free vibration of FRP aircraft Instruments panel boards

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ABSTRACT
The paper deals with the experimental investigations done on free vibration characteristics of typical FRP aircraft instrument panel boards made of E-glass /Poly vinyl ester composite. Seventeen panel boards are made using the hand lay-up technique with different number of layers, fibre orientations, thickness and fibre contents. Their physical and elastic properties are determined experimentally. The support conditions and the loadings are simulated in the same manner, as they are located on the aircraft. The first three natural frequencies are determined experimentally. These results are compared with the same results obtained using a finite element analysis software package. Apart from these seventeen boards a number of analytical models with variations in the fibre orientations, the number of layers etc. are also studied and the results obtained are discussed.

KEY WORDS
Instruments panel, FRP, Natural Frequency, Free Vibration, Resonance

1 Introduction

An aircraft instrument panel board is housing very sensitive instruments and it is necessary to ensure that the life and sensitivity of these instruments are not reduced due to the vibration of the panel board caused by the running of the aircraft engine, atmospheric turbulence, gust etc. It is essentials to keep the fundamental frequency of the panel board as high as possible and also away from the operating frequencies of the above disturbances so that resonance can be avoided at low frequencies. Conventional aluminium panel boards can be replaced by FRP panel boards to reduce weight and also to take advantage of the directional properties of the fibres to increase the natural frequencies. The orientation of the fibres in different layers can be arranged so as to get symmetric, anti-symmetric laminates. Each arrangement can alter the natural frequencies of the panel board.

Table-1 gives the details of the various instruments with their sizes and weights used in a typical aircraft instruments panel board shown in Figure-1. The positions of these instruments are practically unalterable. The conventional aircraft panel board is made of Al 2024 whose thickness is about 2mm. The first three natural frequencies of this board as reported by Viswanath (1), are 9.294 Hz, 13.196 Hz and 18.025 Hz respectively. Due to increased stiffness and reduced mass the FRP boards can have higher natural frequencies. Proper orientation of the fibers, the arrangement of the laminates and the number of layers (depending on the required thickness) can increase these natural frequencies of the FRP aircraft instrument panel boards as observed by (2), (3) and (4).

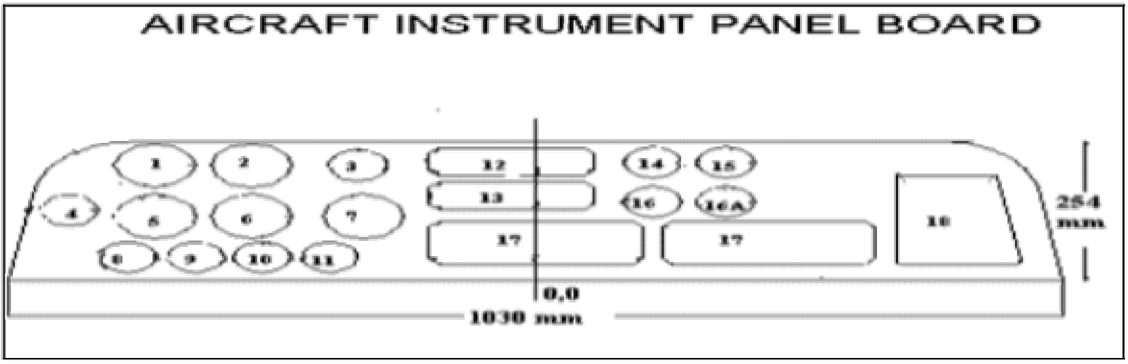

Figure 1: Aircraft instrument panel board

To study the free vibration characteristics of FRP aircraft instrument panel boards experimentally, seventeen E-Glass/Vinyl Ester composite panel boards are made using the hand lay-up technique with unidirectional and bi-directional fibers and angle ply laminates with the following configurations.

Table 1: Instruments' Data

Sl. No.	Instrument	Instrument Diameter (mm)/Area (mm^2)	Depth of the instrument (mm)	Mass of the instrument (Kg)
1	VSI	79.070	100.380	0.344
2	ASI	79.180	48.540	0.088
3	RPM	58.500	65.000	0.915
4	CHRONO	55.990	19.360	0.088
5	ALTIMETER	79.520	99.720	0.374
6	G-METER	79.350	98.710	0.442
7	MPI	79.640	75.100	0.454
8	OPI	55.550	38.240	0.124
9	OTI	55.400	41.400	0.124
10	CHT	55.650	41.600	0.124
11	FPI	54.900	29.310	0.154
12	FLYDAT	162*520	25.000	0.474
13	VHF	162*520	256.000	1.942
14	FQI	57.030	41.100	0.088
15	VOLTAMETER	56.850	30.550	0.120
16	INTERCOM	56.040	122.740	0.280
17	SWITCHES	-	-	-
18	INDICATORS	-	-	-

A - 0 , B – 0 , C – 0 - Three, four and five layered Laminates with Bi-directional fibers placed at 0^o & 90^o orientations respectively. A – 15, B – 15, C – 15 - Three, four and five layered Laminates with Bi-directional fibers placed at 15^o & 105^o orientations respectively. A - 30 , B – 30 , C – 30 - Three, four and five layered Laminates with Bi-directional fibers placed at 30^o & 120^o orientations respectively A - 45 , B – 45 , C – 45 - Three, four and five layered Laminates with bi-directional fibers placed at 45^o & 135^o orientations respectively. UN – 0 – Four layered laminate with unidirectional fibers placed at 0^o orientation. UN – 45 - Four layered laminate with unidirectional fibers placed at 45^o orientation. SYM –45 - Four layered symmetric angle ply laminates with 45^o fiber orientation. (-45, 45, 45,-45)ANSY1-45 - Four layered anti-symmetric angle ply laminates with 45^o fiber orientation. (-45, 45, -45, 45) ANSY2-45 - Four layered anti-symmetric angle ply laminates with 45^o fiber orientation. (-45, -45, 45, 45)

These boards have different thickness and fiber orientations. The material properties such as densities, Young's modulii (E) and the Poisson's ratios (μ) are determined experimentally. The density is determined by water replacement method. The uni-axial tensile tests are conducted on the specimens after fixing the necessary strain gauges. The linear and lateral strains are recorded and the values of Young's modulus (E_l, E_t) and Poisson's ratio (μ_{lt}) are calculated for the three boards. Table-2 shows these properties. The cutouts are made as per their actual dimensions, after air curing the boards for a minimum period of 12 hours.

Table 2: Properties of the FRP Instrument Panel Boards

Panel Board	Fiber		No. of layers	Density Kg/m³	E_l (MPs)	E_t (MPa)	μ_{lt}	t mm
	Type	Ori. Deg.						
A-0	Bi-Dir	0	3	1113	702.052	702.052	0.29	3.000
A-15	Bi-Dir	15	3	1233	715.196	715.196	0.29	3.090
A-30	Bi-Dir	30	3	1324	1028.42	1028.42	0.29	2.750
A-45	Bi-Dir	45	3	1010	793.775	793.775	0.29	3.000
B-0	Bi-Dir	0	4	1010	524.286	524.286	0.30	3.400
B-15	Bi-Dir	15	4	1200	667.254	667.254	0.30	2.600
B-30	Bi-Dir	30	4	1051	589.103	589.103	0.30	2.630
B-45	Bi-Dir	45	4	1039	666.433	666.433	0.30	2.600
C-0	Bi-Dir	0	5	1283	661.630	661.630	0.28	2.700
C-15	Bi-Dir	15	5	1210	698.645	698.645	0.28	2.800
C-30	Bi-Dir	30	5	1425	640.915	640.915	0.28	2.640
C-45	Bi-Dir	45	5	1010	783.367	783.367	0.28	2.700
UN-0	Uni-Dir	0	4	1010	825.687	408.220	0.26	6.290
UN-45	Uni-Dir	45	4	1255	817.367	407.739	0.30	4.400
SYM-45	Angle ply	45	4	1104	401.413	401.413	0.29	6.100
ANSY1-45	Angle ply	45	4	1263	601.518	601.518	0.30	4.210
ANSY2-45	Angle ply	45	4	1169	511.756	511.756	0.28	4.400

A wooden frame is fabricated to fix the panel board exactly in a similar way as it is normally fixed to the aircraft frame at 18 locations (Figure -2). Steel washers, bolts and nuts are used to introduce the effect of the weights of the instruments around the cutouts and to rigidly fix the panel board on the supports. The washers are prevented from having individual vibrations. Figure -3 shows the finite element model of the panel board, with positions of the supports and points at which the weight of the instruments are transferred to the panel board. Table - 3 and 4 show the co-ordinates of the support nodes, and nodes at which the weight of the instruments act with their magnitudes respectively.

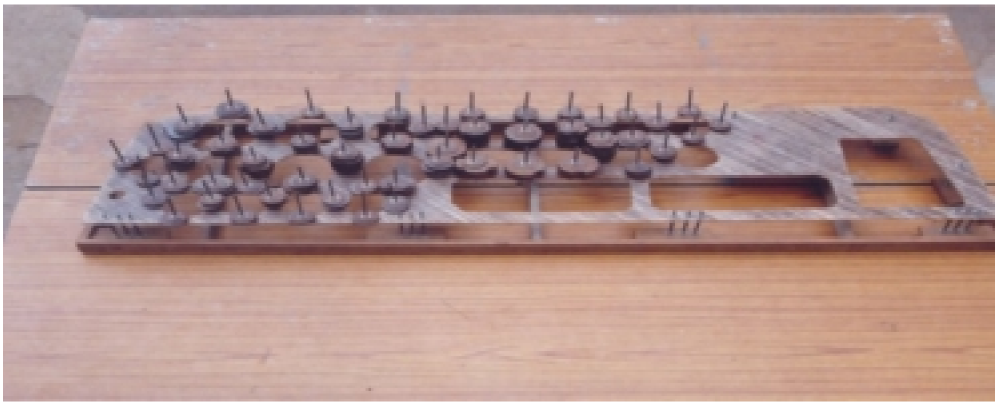

Figure 2: Panel Board with the frame showing the supports and the loadings

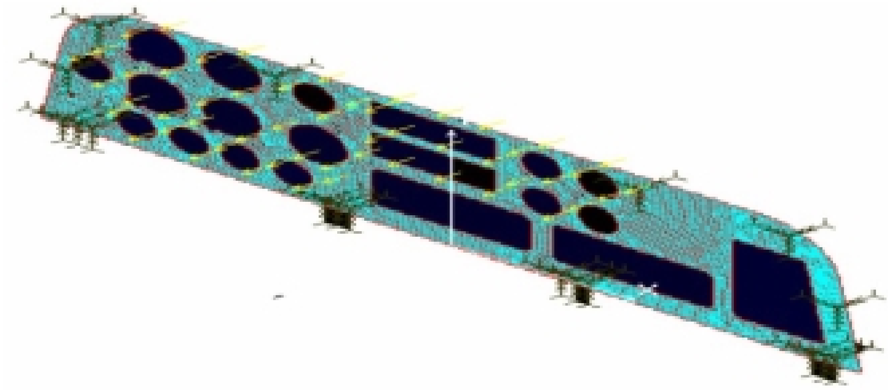

Figure 3: Finite Element Model of the panel board

Table 3: Co-ordinates of the nodes at which the board is supported

Sl. No.	X co-ord. (mm)	Y co-or. (mm)
1	-487.00	120.00
2	-471.50	120.00
3	-457.00	120.00
4	-159.00	120.00
5	-147.00	120.00
6	-135.00	120.00
7	143.00	120.00
8	160.00	120.00
9	175.00	120.00
10	460.00	120.00
11	474.00	120.00
12	485.00	120.00
13	487.50	115.00
14	427.00	232.00
15	240.00	232.00
16	-222.00	232.00
17	-445.00	232.00
18	-483.50	112.00

Table – 4 Magnitudes and the Co-ordinates of the locations of the weights

Sl. No.	Weight (Gms)	Location of the weights (mm)	
		x axis	y axis
1	84.20	-414.00	213.00
2	84.50	-365.00	253.50
3	108.40	-322.00	205.00
4	177.40	-365.00	162.00
5	22.50	-270.50	251.00
6	70.30	-220.00	206.00
7	130.80	-274.00	162.00
8	47.90	-168.00	245.50
9	47.60	-135.00	211.00
10	160.70	-170.00	166.00
11	21.80	-481.00	133.00
12	21.90	-444.00	165.00
13	114.70	-414.50	130.00
14	21.90	-450.00	93.00
15	202.50	-322.00	115.00
16	92.70	-365.00	73.00
17	224.20	-224.50	120.00
18	140.40	-266.00	72.00
19	112.80	-120.00	118.00
20	112.40	-168.00	67.00
21	30.30	-435.50	48.00
22	30.10	-416.50	78.00
23	62.70	-366.50	42.00
24	31.20	-406.50	7.00
25	30.80	-332.50	73.00
26	61.50	300.00	40.00
27	31.30	-332.00	7.00
28	60.90	-233.00	40.00
29	30.80	-266.00	7.00
30	31.20	-199.00	75.00
31	30.90	-163.00	40.00
32	30.00	-197.00	7.00
33	58.80	-112.00	212.00
34	58.30	-79.50	250.00
35	58.00	-16.50	250.00
36	58.70	38.50	250.00
37	80.70	75.00	220.00
38	303.30	38.50	163.50
39	303.00	-20.00	163.50
40	306.90	-79.50	163.50
41	245.60	-111.00	150.00
42	315.60	70.00	155.00
43	250.60	38.50	117.00
44	242.70	-20.00	117.00
45	241.90	-79.50	117.00
46	22.50	110.00	250.00
47	51.60	147.50	219.00
48	90.90	110.00	185.00
49	30.10	187.00	250.00
50	30.80	218.00	216.00
51	31.00	180.00	185.00
52	69.00	146.00	151.00
53	69.20	110.00	113.50

Article I.

2 Convergence study on the SHELL4L element used in the free vibration analysis of the panel board

A convergence study on the shell4L element available in the software elements library for the free vibration analysis of the finite element model of the ortho- tropic instrument panel board shown in Figure 3, without the weights of the instruments has been done and the results are presented in Table 5 and Figure 4. The convergences of the first three modes are found to be satisfactory.

Table – 5 Convergence Study

No. of Elements	Natural Frequencies (Hz)		
	I Mode	II Mode	III Mode
1332	73.148	88.359	100.011
1680	70.248	87.952	100.567
2252	68.324	85.901	96.276
2668	65.921	85.584	95.581
3714	65.083	84.254	95.232
4010	64.995	84.201	94.907

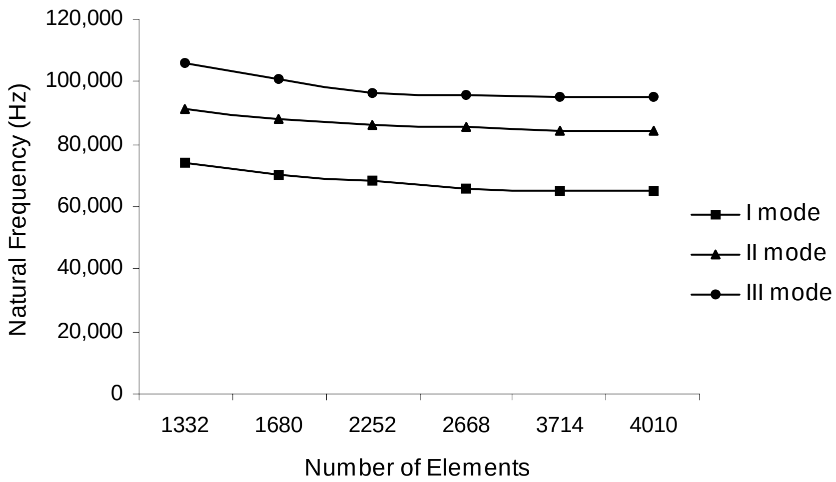

Figure – 4 Convergence Study

3 Static deformation studies

A static deformation test is performed on all the seventeen boards. The deflections perpendicular to the board, due to the weight of the instruments and the self-weight of the board, are measured using high precision deflectometers (Figure-5) at the three nodes listed in Table 6. The deflections at these nodes are also obtained using the FEA package with the material properties obtained experimentally. The same finite element model of the panel board used for the convergence study is used for this study also. The two results are presented in Table 7 and in Figure 6. This part of the analyses are performed to have a check on the experimental values obtained for the physical and elastic properties of the composites and the two results are close enough and found to be satisfactory.

Figure – 5 Static Deformation Test Setup

Table – 6 Co-ordinates of the Nodes at which the Deflections are measured

	Node 1	Node 2	Node 3
X co-ordinate	-323.00	145.00	198.00
Y Co-ordinate	160.00	160.00	160.00

Table – 7 Results of the static deflection test

Sl. No.	Type of panel board	Deformation in Z direction (mm)					
		Node 1		Node 2		Node 3	
		Experimental (Exp)	Analytical (Anl)	Exp	Anl	Exp	Anl
1	A-0	5.230	6.190	5.750	6.342	3.700	3.888
2	A-15	4.830	5.587	5.660	5.734	3.920	3.310
3	A-30	5.520	5.501	5.500	5.584	3.820	3.213
4	A-45	5.500	5.507	4.840	5.631	3.100	3.255
5	B-0	5.350	5.725	6.200	5.930	4.020	4.631
6	B-15	10.30	9.986	11.770	10.100	5.270	5.787
7	B-30	11.880	10.950	11.830	11.080	5.940	6.387
8	B-45	10.380	10.010	9.500	10.110	6.000	5.809
9	C-0	8.240	8.975	9.980	9.114	6.200	5.563
10	C-15	7.770	7.658	7.500	7.793	4.820	4.763
11	C-30	10.070	9.950	12.010	10.070	5.900	6.262
12	C-45	7.910	7.617	8.120	7.719	5.030	4.442
13	UNI-0	0.720	0.598	0.900	0.653	0.520	0.391
14	UNI-45	3.190	3.460	4.200	3.660	2.870	2.324
15	SYM-45	1.900	1.351	1.300	1.471	0.960	0.882
16	ANSY1-45	2.280	2.757	2.030	2.916	1.830	1.827
17	ANSY2-45	1.910	2.667	2.860	2.810	1.770	1.500

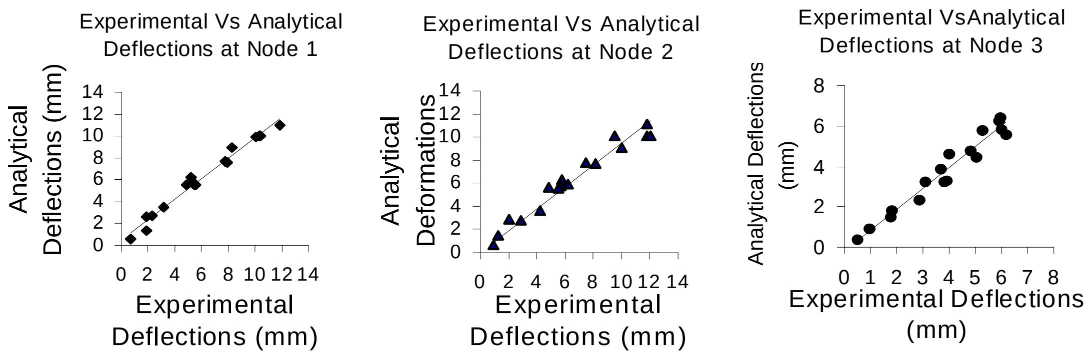

Figure – 6 Experimental Vs Analytical Deflections

4 Experimental free vibration study

The determination of the natural frequencies is performed using an exciter, an amplifier, a pick–up and a digital displacement, velocity and acceleration display unit (Figure - 7). The excitation frequency is varied very gradually and the maximum amplitudes at the location of the pick-up are measured. The excitation frequencies corresponding to the maximum amplitudes for the first few modes are recorded for all the seventeen boards. The occurrences of resonance for each mode are clearly identified for each board. Figure – 8 shows the amplitudes at each reonanace for the unsymmetric antisymmetric and symmetric boards. These amplitudes are measured at a suitably selected position of the pick up. The amplitudes are not absolute and depend on the position of the pick up. However, the resonance frequencies are independent of the position of the pick up.

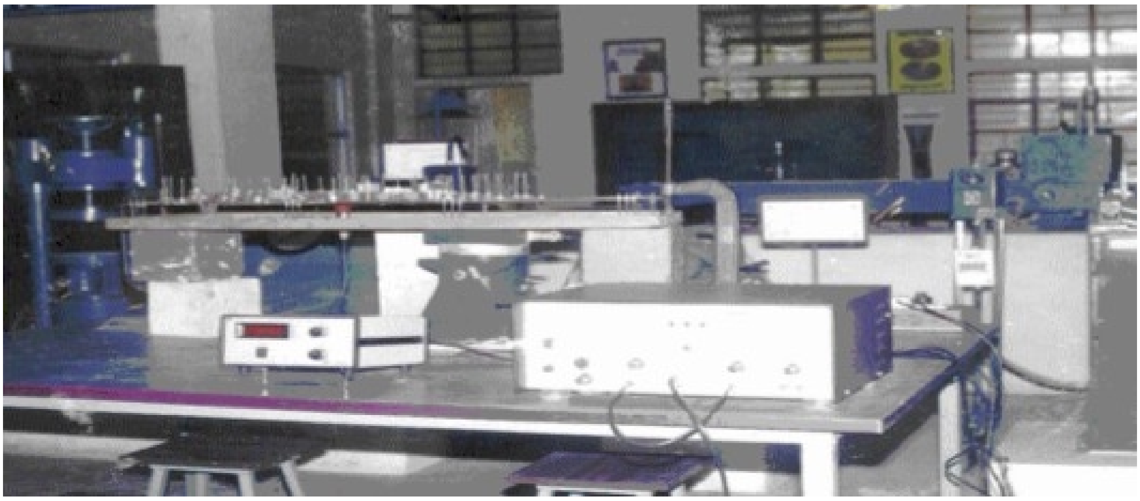

Figure – 7 Experimental set-up for Vibration Analysis

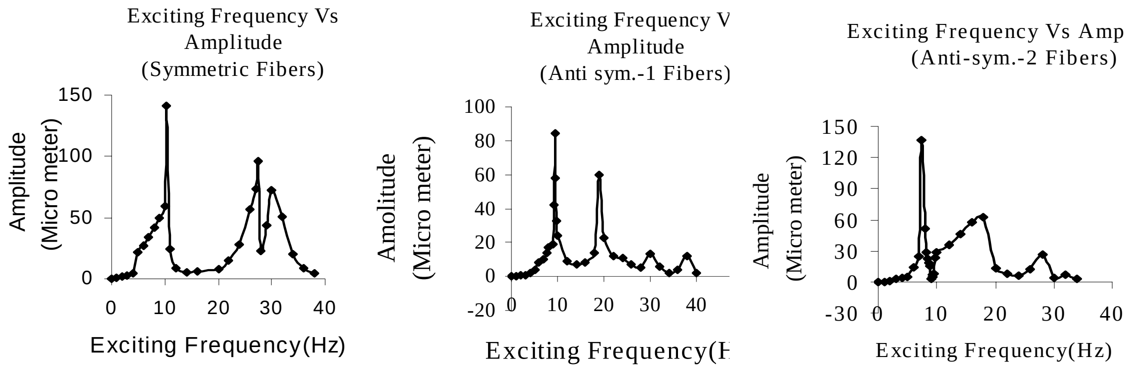

Figure – 8 Exciting Frequency Vs Amplitude Plots

5 Analytical free vibration study

The first three natural frequencies for these seventeen boards are also obtained using the FEA software package with experimentally determined values of the properties for the various boards. These results are given in Table 8 & Figure 9. Better combinations of the fibre orientation and the layer arrangement are attempted.

Table - 8: Experimental and Analytical Values of the Natural Frequencies

Sl. No.	Type of Panel Board	Natural Frequencies (Hz)					
		Mode 1		Mode 2		Mode 3	
		Experi.	Analy.	Experi.	Analy.	Experi.	Analy.
1.	A-0	6.200	5.822	13.000	13.135	23.500	23.987
2.	A-15	5.600	5.230	8.400	11.808	15.435	14.569
3.	A-30°	7.200	6.268	10.000	14.150	17.000	15.856
4.	A-45°	7.150	6.268	9.500	11.315	14.000	14.158
5.	B-0°	6.000	6.085	7.550	9.725	12.230	13.724
6.	B-15°	5.400	4.649	9.700	10.492	12.200	12.984
7	B-30°	6.000	4.585	10.500	9.164	12.150	11.334
8	B-45°	5.400	4.662	8.800	8.535	10.000	10.530
9	C-0°	6.000	4.881	8.600	10.155	11.125	13.620
10	C-15°	6.800	5.298	8.200	11.953	12.500	14.771
11	C-30°	5.000	3.399	8.050	7.6745	9.752	9.460
12	C-45°	5.100	5.340	7.000	12.067	10.215	12.067
13	UNI-0°	8.050	7.721	11.500	10.252	26.000	23.126
14	UNI-45°	7.050	7.829	8.850	9.661	13.500	15.000
15	SYM-45°	10.200	12.509	27.400	28.201	30.000	34.065
16	ANSY1-45°	9.400	8.777	19.000	19.801	30.000	26.472
17	ANSY2-45°	7.400	8.718	18.000	20.119	28.000	26.906

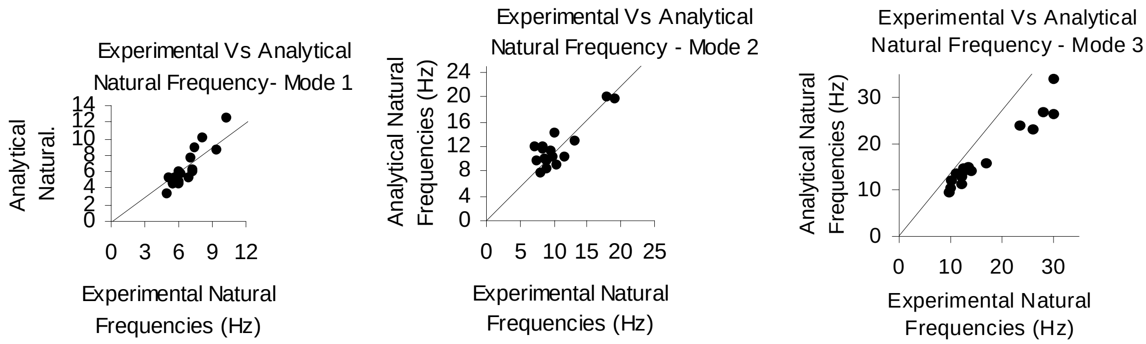

Figure – 9 Experimental and Analytical Natural Frequencies

The values and the Figure 9 clearly indicate that the experimental and analytical values of the first three natural frequencies for the seventeen boards are close enough and ensure that the mathematical modeling of the panel board, the material properties used and the results obtained for the free vibration analysis using the software package gives satisfactory values of the natural frequencies. Based on this conclusion a few other fiber orientations are worked out using the software package for better free vibration characteristics.

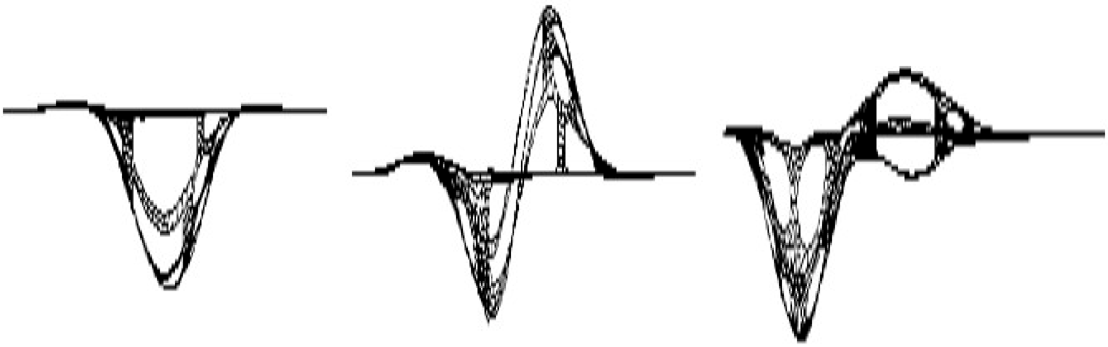

Figure – 10 The First, the Second and the Third Mode Shapes

The Figure – 10 shows the first three mode shapes of the FRP panel board and these mode shapes reveal the coupling of the axial, bending and torsional modes of vibration. It is found to be very difficult to identify any difference in the mode shapes for the different fiber orientations, due to the fact that the mode shapes are basically depend on the overall geometry and the boundary conditions rather than the material and elastic properties. However, the numerical values of the amplitudes show noticeable variations for the different fiber orientations.

To compare the natural frequencies of the FRP panel board of weight equal to the weight of the 2 mm aluminium panel board, the first three natural frequencies of a symmetric (-45/45/45/-45) and an anti-symmetric (45/-45/45/-45) angle-ply laminates are determined and the results are given in Table - 9. The values shown within the brackets are the percentage increase in the +three natural frequencies with respect to the aluminium boards.

Table – 9 Natural Frequencies of Aluminium and FRP Panel Boards of Equal Weights

Sl.No.	Type of the Panel Board	Natural Frequencies (Hz)		
		I Mode	II Mode	III Mode
1	Aluminium (2mm thick)	9.294	13.196	18.025
2	Sym-45 Angle Ply (5.23 mm thick)	10.481 (12.77%)	23.565 (78.58%)	28.461 (57.90%)
3	Antisym-45^o Angle Ply (4.79 mm thick)	10.404 (11.94%)	23.392 (77.27%)	28.291 (56.95)

6 A few fibre orientations and lamina arrangements

The few cases of layer arrangements and fibre orientations for six layers are worked out analytically to study the free vibration characteristics of these panel boards and the results obtained are presented in Table-10. These configurations are selected based on earlier studies, which suggest that the frequencies are higher for symmetric and anti-symmetric arrangements when the fibre orientations are between 15o and 25o and the 0o and 90o layers at the top and bottom bring the FRP boards closer to an isotropic material. The values obtained are marginally higher than that of the symmetric and the anti-symmetric 45o angle ply laminates. When the 0o and 90o fibre orientations are placed near the middle surface the frequencies are found to be still higher.

Table – 10 Natural Frequencies of Some Specific Layer Arrangements (Four layers with 0 and 90 and two layers with different orientations)

Type of Panel Board	Arrangement of layers	t mm	Natural Frequencies (Hz)		
			I Mode	II Mode	III Mode
Sym.	0,90,15,15,90,0	5.23	10.775	23.108	28.456
Sym.	0,90,20,20,90,0	5.23	10.820	23.214	28.626
Sym.	0,90,25,25,90,0	5.23	10.870	23.126	28.507
Sym.	0,90,30,30,90,0	5.23	10.808	23.019	28.355
Sym.	0,90,45,45,90,0	5.23	10.752	22.924	28.220
Sym.	**45,90,0,0,90,45**	**5.23**	**10.927**	**23.405**	**28.427**
Anti-sym.	-90,-180,-15,15,0.90	4.79	10.701	22.798	28.040
Anti-sym.	-90,-180,-20,20,0.90	4.79	10.703	22.802	28.041
Anti-sym.	-90,-180,-25,25,0.90	4.79	10.695	22.787	28.047
Anti-sym.	-90,-180,-30,30,0.90	4.79	10.687	22.774	28.054
Anti-sym.	-90,-180,-45,45,0.90	4.79	10.683	22.769	28.069
Anti-sym.	**45,0,90,0,90,-45**	**4.79**	**10.851**	**23.236**	**28.260**

7 Observations and Discussions

Based on the results obtained the following observations are made.

1. The static deflection tests are performed both experimentally and analytically and these results match to a fairly acceptable limits and they ensure that the experimentally determined material and elastic properties and used in the analyses.
2. For a plate of aspect ratio unity, the natural frequencies at 0º and 90º are equal. In this case the frequency values are different as 0º unidirectional fibre orientation is along the longer direction (1130 mm) and 90º unidirectional fibre orientation is along the shorter direction (254 mm).
3. The first three natural frequencies obtained using the FEA software package are experimentally verified for the seventeen FRP panel boards and the results are found to be satisfactory and acceptable
4. For the same weight the thickness of the symmetric and antisymmetric FRP 45o angle ply laminate panel boards, corresponding to the 2mm thick Al panel board, is found to have thickness of 5.23mm and 4.79mm respectively and the increases in the natural frequencies for the first three modes are found to be around 12%, 78% and 57% respectively for the three modes. (Table – 9).
5. The natural frequencies of the antisymmetric 45o angle ply laminate are slightly lesser than the symmetric 45o angle ply laminate. This suggests that the symmetric laminates will have higher frequency values than the antisymmetric laminates for any given ply angle and in general for both arrangements higher frequency values are observed when the fibre orientations in the range of 15o and 30o as reported in Ref.2.
6. Panel boards with fibres arranged like 0,90,45,45,90,0 or 45, 0, 90, 90, 0,-45 are found to give even better results and provide further scope for the study.
7. The present study suggests that the variation of fibre orientations and the arrangement of these fibres in specific patterns can effectively modify the values of the natural frequencies. Depending on the operating frequency of the aircraft engine and the other factors influencing the forcing frequencies of the panel board, the thickness and the fibre orientations can be designed to increase the life and the performance of the precision instruments fitted in the panel board of the aircraft.

8 Conclusions

FRP panel boards comparatively lighter and stiffer than the conventional aluminium boards. With proper design of the thickness of the board, the orientation of the fibres and the optimum volume fraction of the selected composite the absolute values of the lower natural frequencies can be increased to the desired values to avoid resonance and excess amplitudes of vibration at low frequencies and to reduce the damage to the precision instruments fitted in an aircraft panel board.

Further investigations are being taken up to use other fibre/resin combinations instead of the Vinyl ester/E-glass composite and some preliminary analytical studies on this composite also seem to give higher fundamental frequencies due to higher stiffness values (2). The cut outs and the outer edges of the FRP panel boards are stiffened for higher stiffness to mass ratio to achieve optimum frequency levels. The volume fraction of the fibres is being considered as one of the parameters for obtaining better free vibration characteristics.

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