Pak. j. sci. ind. res. Ser. A: phys. sci. 2018 **61A**(2) 84-90

Vibration Analysis of Cracked Composite Laminated Plate

Muhammad Imran*, Rafiullah Khan and Saeed Badshah
Department of Mechanical Engineering, International Islamic University, Islamabad, Pakistan

(received July 28, 2017; revised March 29, 2018; accepted March 30, 2018)

Abstract. An analysis of the free vibration response of the carbon fibre reinforced composite plate with delamination is presented here. The influence of the delamination size on the free vibration characteristics are studied. The composite material used is carbon fibre reinforced polymer with delamination at the middle of the plate. The experimental procedure consists of exciting the specimens with flexural modes for twelve modes for each delamination length. The effect of the delamination size was easily depicted by experiments by comparing the natural frequencies of laminated composite plate with and without delamination.

Keywords: carbon-fibre reinforced polymer, experimental model, delamination, composite plate.

Introduction

Composite structures have been widely used for various purposes ranging from simple laptop cases to complex high performance aircraft components, helicopter rotor blades, underwater hockey swim fins, boat hulls, swimming pools and bridges due to their stronger, lighter and up to date geometrics properties. The usage of carbon-fibre reinforced polymers (CFRP) have hugely increased due to lighter weight and high strength carbon fibres. CFRP have been used for light strength to weight ratios in aerospace engineering, automotive engineering, civil engineering and other applications and whenever high strength applications are considered. Cracks or delamination in composite plates are unavoidable during service period. There can be different parameters that effect its performance like service conditions, temperature or pressure variations. It has been experimentally validated that any specific delamination in a structure affects the dynamic performance of the whole structure. Moreover resonance or crack propagation within surface induce huge displacements or dislocations that leads to the structure failure. Because of their important applications, unique properties and widespread usage, the linear or non-linear criterion of these cracked/ delaminated structures, is to be investigated with great interest. Earlier, many numerical techniques were taken into consideration for predicting the behavior of vibrations in composite plates (Abbas *et al*., 2016).

Campanelli and Engblom (1995) compared the vibration analysis with modeling analysis for delaminated graphite/PEEK composite plates. Luo and Hanagud (1996) conducted experiments to find the vibration behaviour of glass fibre/epoxy composite plate with strip delamination. Hammami *et al*. (2016a) conducted experiments to find the linear and nonlinear vibration characteristics of composites with delamination. Jian *et al*. (1997) investigated the effect of circular delamination on thin unidirectional glass- fibre composite plates. Similar tests were also conducted by Kim *et al*. (2003); Kessler *et al*. (2002); Diaz Valdes and Soutis (1999); Paolozzi and Peroni, (1996) and Tenek *et al*. (1993). However, Penn *et al*. (1999) investigated through experiments that first six natural frequencies have very negligible influence of delamination presence. But the investigations done by Hou and Jeronimidis (1999) on circular composite plates concluded that significant increase in natural frequencies observed with an impact induced delamination. Experiments conducted by Hou and Jeronimidis 2000) found that increase in the bending stiffness values caused an increase in the frequency. Babu and Vasudevan (2017) conducted vibration analysis of tapered delaminated composite plate. Hirwani *et al.* (2016) conducted an experimental study to find the delamination effect on the vibration behaviour of woven glass/epoxy composite plate. Mohanty *et al.* (2012) conducted free vibration analysis of woven fibre glass/epoxy composite plate with delamination. For small delamination length, natural frequencies are less effected (Lou *et al*., 1997; Thornburgh and Chattopadhyay, 2002). Lee *et al*. (2003) investigated the effect of delamination length on multi-delaminated composite beam experimentally. Natural frequency decreased as the number of delamination increased. This finding was reported by Zhu *et al*. (2005) and Lee *et al*. (1995). Luo and Hanagud (2000) carried out experimental analysis on through-width delamination in composite beam. Experimental results were compared with Shen and

*Author for correspondence;
E-mail: Muhammad.imran@iiu.edu.pk

Grady (1992). Hammai *et al*. (2016b) found the nonlinearity relation with delamination. Kumar and Shrivastava (2005) used thick square composite plate with rectangular cutout as reported by Reddy and Phan (1985). Azouaoui *et al*. (2007) investigated the delamination influence of glass/polyester composite plates. Krawczuk *et al*. (1997) studied the dynamics of cracked composite material structure. Chang *et al*. (1998) investigated the vibration analysis of composite plate with delamination under axial loads.

The review of the above experimental work highlighted the lack of studies on vibration analysis of delaminated composite plate using experimental techniques. The literature of experimental analysis on natural frequencies for carbon fibre reinforced polymer is very poor.

Therefore in the present study, free vibration of carbon reinforced polymers delaminated composite plate is investigated experimentally. The effect of other parameters like influence of delamination size, number of layers, ply orientation and boundary conditions on natural frequencies of carbon fibre reinforced polymer is largely studied.

Materials and Methods

The composite material presently studied is the carbon fibre reinforced polymer (CFRP) with unidirectional layers of epoxy and fibres matrix. The specimens are manufactured using handy layup method at room temperature. Teflon film is placed centrally at the mid span of the composite plate during manufacturing as shown in Fig. 1. Teflon layer is considered as delamination.

The delaminations have been incorporated at 5% to 75% with each 5% of CFRP plate. The natural frequencies of sixteen-layered carbon fibre composite plates with and without delamination have been determined experimentally using an accelerometer. The experimental configuration used is similar to earlier works (Hammami *et al*., 2016a; Idriss *et al*., 2015; Novak *et al*., 2012; Van Den Abeele *et al*., 2000). The specimens are tested for each delamination size. All tests performed are free vibration ones.

The dimensions of the carbon fibre reinforced polymer composite plate is 250mm×250mm×20mm. Thickness of each layer is 1.25 mm with 16 number of layers. Square size delamination was provided at the middle of the pate. (0/45)4s and (0/90)4s 16-layered were considered for the experimental study.

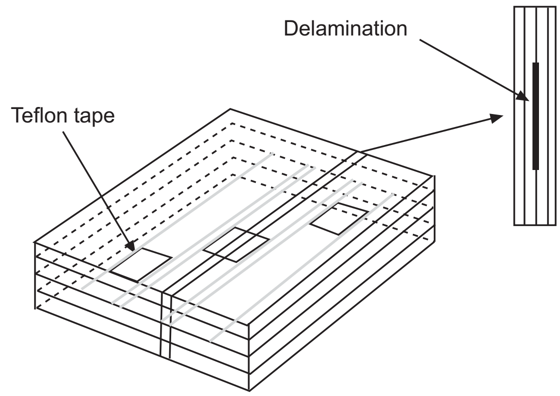


Fig. 1. Incorporation of Teflon tape for delamination (Lee *et al*., 2003)

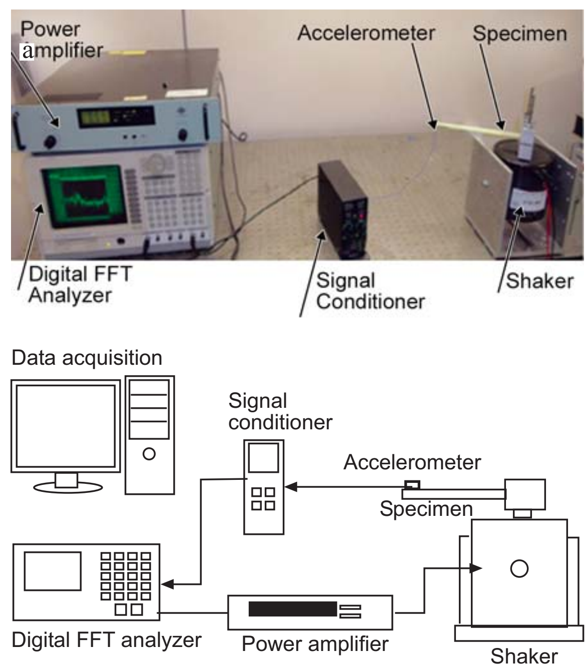


Fig. 2. Experimental setup for modal tests (Hammami *et al*., 2016a)

Following boundary conditions are considered for the experimental technique

F-F-F-F – Four edges free
S-S-S-S – Four edges simply supported
C-C-C-C – Four edges clamped
C-F-F-F – Cantilever supported

Finite element method FEM. For FEM analysis of the composite plate specified, ANSYS APDL was used for modelling, preprocessing, meshing, and solving. In

ANSYS, it is not possible to easily simulate pre-delaminated regions using shell elements. For this composite plate, the thickness to length ratio is just over 10%, so it is questionable whether or not shell elements will capture the true behaviour of the composite. For this simulation, solid elements were used with one element in the thickness direction for each prepeg layer. In order to properly simulate the fibre orientation for each laminate layer, custom coordinate systems were specified for each layer corresponding to the fibre orientation needed. For the simply supported constraint case, the bottom edges of the plate were constrained to have zero displacement in all cartesian axes. The different configurations of the plate simulated were as follows:

Stacking sequences

[0/45]
[0/90]

Delamination conditions

0% delamination
25% delamination

Each composite plate stacking sequence was simulated with every possible boundary condition and delamination condition. Therefore, 48 total simulations were performed corresponding to the possible configurations of the plate. Prepeg layers 1-3 and 5-8 were modelled using quadrilateral solid elements with an average size of 4 mm. Layers four and five, were modelled using triangular solid elements with an average size of 4 mm. The complete specifications of the mesh were as follows:

Total elements: 15,116
Total nodes: 76,649
Element aspect ratio

Maximum: 19.185; Minimum: 1.8351; Average: 2.838; Standard Deviation: 1.3095.

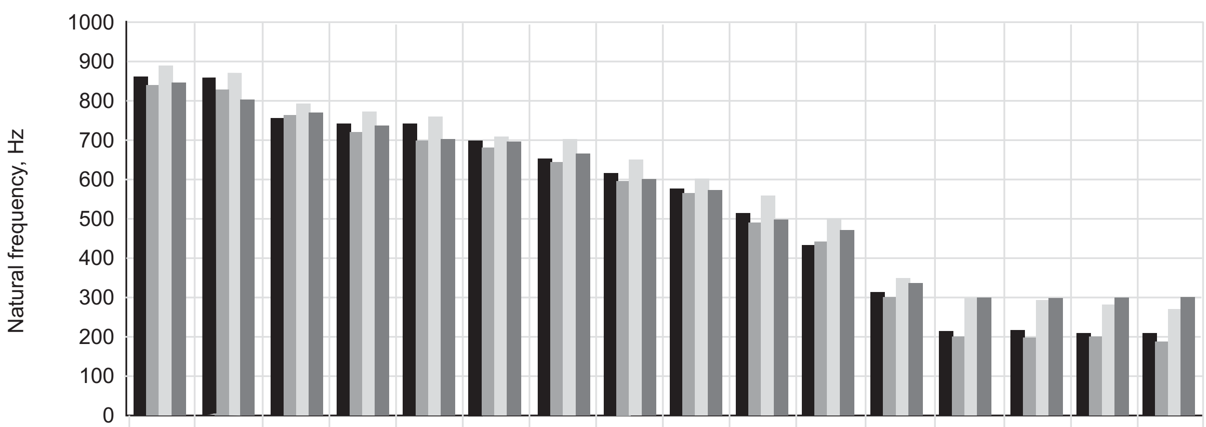
The orthotropic material properties of the carbon prepeg layers were as specified:

E1 = 70 GPa
E2 = 70 GPa
G12 = 5 GPa
ν = 0.1 (all directions)
$\rho = 1600 \frac{kg}{m^3}$

Results and Discussion

Experimental results for free vibration analysis of CFRP composite plates with delamination are presented in first section and in second section finite element analysis results are presented.

Effect of delamination size. For the experiments, it has been clear from Fig. 3 that the delamination size has significant impact on the natural frequencies of the



	0	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75
S-S-S-S	862	861	758	741	736	696	655	613	576	512	430	312	212	210	207	207
F-F-F-F	840	828	760	721	699	683	643	598	566	487	441	300	201	198	198	194
C-C-C-C	888	871	787	770	760	705	695	649	601	555	501	349	299	290	278	271
C-F-F-F	847	801	766	732	703	695	666	601	571	489	471	336	301	300	298	297

% DELAMINATION

Fig. 3. Effect of delamination area for different boundary conditions with (0/90) layup.

delaminated composite plate. For all boundary conditions, fundamental natural frequencies decrease with an increase in delamination size for a layup configuration of (0/90), However, natural frequencies declining is consistent for the delamination of 60%, 65%, 70% and 75%. For high delamination area (75%), the natural frequency is least affected for (0/90) layup method.

The same study was extended to (0/45) layup method as shown in Fig 4. For (0/45) layup configuration, cantilever plate has highest natural frequency than other configurations. Frequency drop for simply supported plate is less affected by delamination size as compared to the frequency drop of cantilever supported CFRP plate. For high delamination area, natural frequency is least affected for the simply supported plate. For low delamination area, four-sided clamped plates have highest natural frequencies. All sides' free constraints showed traditional response i.e., it declined rapidly initially and then steady decline was observed as the delamination length increased as shown in Fig. 4.

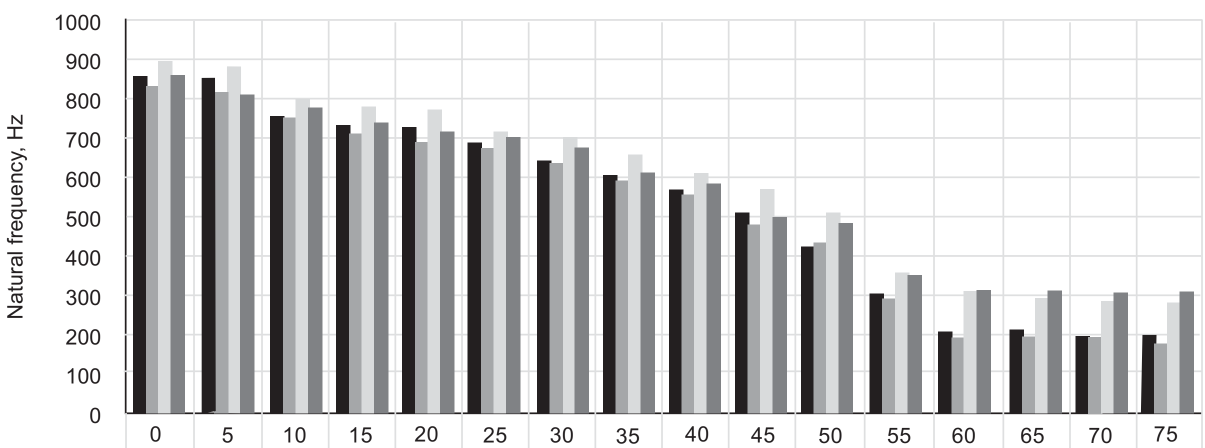
Effect of boundary conditions. The specimen taken for the analysis was of sixteen layered composite plate having stacking sequence of (0/45)4s with 55% delaminated area.

The natural frequencies obtained at 55% delamination area is presented in Table 1.

Least mode frequencies are observed for 1st, 2nd, 3rd, and 4th modes for F-F-F-F (four side free), S-S-S-S (four sides simply supported) and C-F-F-F (Cantilever) boundary conditions and the highest natural frequency is observed for C-C-C-C (four sides clamped) boundary condition. These behaviours were also observed by Mohanty *et al.* (2012). Table 1 shows that natural frequencies are highly affected by boundary conditions.

Table 1. Natural frequencies of experimental results for 55% delaminated area for (0/45) layup configuration

Boundary conditions	Experimental modes (Hz) 1st	2nd	3rd	4th	5th	6th	7th	8th	9th	10th	11th	12th
F-F-F-F	151	260	363	415	590	672	741	799	892	945	1005	1090
S-S-S-S	170	290	370	455	549	612	714	802	888	923	998	1150
C-C-C-C	191	316	498	578	689	776	879	942	1050	1189	1275	1356
C-F-F-F	80	175	250	326	446	501	589	634	701	775	816	848



	0	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75
S-S-S-S	857	856	753	736	731	691	650	608	571	507	425	307	202	205	202	202
F-F-F-F	833	821	753	714	692	676	636	591	559	480	434	293	194	191	191	177
C-C-C-C	897	880	796	779	769	714	704	658	610	564	510	358	308	299	287	280
C-F-F-F	858	812	777	743	714	706	677	612	582	500	482	347	312	311	309	308

Fig. 4. Effect of delamination area for different boundary condition with (0/45) layup.

Finite element results. The natural frequencies for each plate configuration were determined. Because the natural frequencies for the simply supported case and the free vibration case are extremely low, they have been separated from the clamped cases in order to show the effect of delamination size most effectively. Table 2 and Fig. 5 show data for boundary conditions CCCC & CFFF.

Effect of delamination size. Interestingly, the size of the delaminated region had negligible effect on the average natural frequency for each mode shape for both of the clamped boundary conditions. The difference in natural frequency for each mode number is very small. This may be due to the physical effect of the clamped boundary condition. This effect seems to dominate the analysis, not allowing for the delaminated region size to have a sizeable impact. Conversely, for the free vibration and simply supported cases, the delaminated region does have an impressive effect on the natural frequency for each mode. The minimum observed natural frequencies were for a delamination size of 25% as seen in Table 2

Table 2. Average natural frequencies for CCCC & CFFF using Finite element analysis

Mode number	0%	25%
1	484.58	484.88
2	983.01	982.67
3	1172.69	1175.9
4	1598.46	1604.18
5	1969.09	1979.05
6	2205.5	2206.31
7	2724.95	2749.8
8	2741.46	2764.95
9	3347.73	3386.06
10	3636.25	3649.73
11	3698.216667	3696.266667
12	4170.15	3970.8

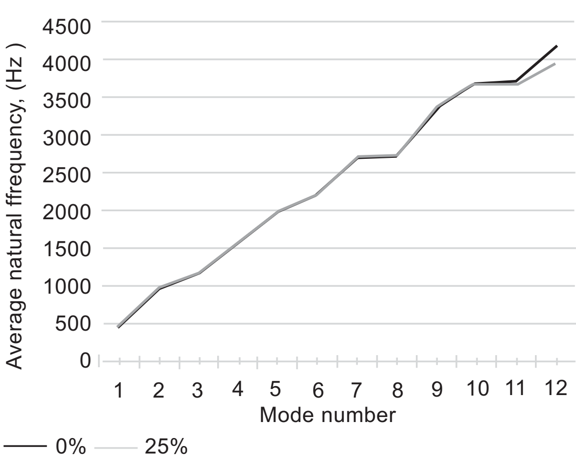


Fig. 5. Comparison of average natural frequencies for each delamination region size.

Effect of boundary conditions. The maximum natural frequencies observed with respect to boundary conditions belonged to the plates having clamped constraints on all sides. The next highest frequencies belonged to the plates having clamped constraints on one side. This makes logical sense, because vibrations in each mode are harder to achieve the more constrained the boundary conditions. For the simply supported and free vibration cases, the free vibration case had maximum natural frequencies between mode numbers 1-7 as shown in Table 3.

Table 3. Average natural frequencies for CCCC, FFFF, SSSS and CFFF boundary condition

Mode number	CCCC	FFFF	SSSS	CFFF
1	884.12	303.0	291.0	156.32
2	1730.96	345.0	331.0	306.36
3	1732.78	375.0	365.0	656.66
4	2431.01	412.0	392.0	812.308
5	2914.53	429.0	420.0	909.36
6	3089.72	442.0	437.0	1330.46
7	3518.50	456.0	451.0	1773.94
8	3686.26	465.0	470.0	1801.70
9	4431.66	473.0	486.0	2008.65
10	4856.44	489.0	501.0	2347.98
11	4953.73	504.0	510.0	2390.11
12	5296.78	511.0	530.0	2752.2

Conclusion

In this research, influence of delamination size and boundary conditions, for carbon fibre reinforced composite plate, with delamination at the mid-plane are investigated. It is concluded by both experimentally and finite element methods that the natural frequencies decrease with an increase of delamination area. Effect of delamination depends on size of delamination and boundary conditions. For clamped-clamped boundary conditions, maximum natural frequencies observed for both finite element and experimental results.

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