ISSN 2278 – 0149 www.ijmerr.com
Vol. 1, No. 2, July 2012

Research Paper

DELAMINATION DETECTION OF COMPOSITE LAMINATES USING NATURAL FREQUENCY VIBRATION METHOD

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Composite materials are widely used in aeronautical, marine and automotive industries, because of their excellent mechanical properties, low density and ease of manufacture. However, composite laminates are susceptible to delaminations, which may not be visible externally, but can substantially affect the performance of the structure. Vibration test, in particular delamination detection, in the composite structures is an active research area. D'Alembert principle is used to determine the theoretical natural frequency of laminated orthotropic composite plate. The present free vibration experimental study of simply supported square laminated plates is based on the comparison between natural frequencies of healthy and delaminated composite plates. The test square plates made of hand lay up 8 layers E-glass woven fibre and epoxy resin are used. The present paper discusses the observations made on the measured natural frequencies of vibration testing from both the healthy and the delaminated square simply supported plates. The possibility of the delamination detection by vibration test is also introduced. The effects of delamination area on the natural frequencies of the plate are presented. The delamination in composite laminates has considerable effect on the natural frequencies of the plate.

Keywords: Laminated composite material, Free vibration, Delamination

INTRODUCTION

The applications of composite materials have become common in different industries. These materials have higher stiffness and strength to weight ratio (Shokrieh and Najafi, 2006). Although composite materials offer many advantages in the designing and manufacturing of structures .The application of

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woven fabric composites in engineering structures has been significantly increased due to attractive characteristics, such as flexible processing options, low fabrication cost, while also possessing adequate mechanical properties (Hu and Wang, 2009).

The laminated composite plates are basic structural components used in a variety of engineering structures. Composite plate structures often operate in complex environmental conditions and are frequently exposed to a variety of dynamic excitations. Measurement of the natural frequency by vibration testing is a very attractive method of Non-Destructive Test (NDT). The vibration test would not require access to the whole surface and the time taken to perform the test can be very small. Thus the vibration response of a composite plate can be used as an indicator of damage (Houa and Jeronimidis, 1999).

The presence of delamination may degrade severely the stiffness and strength of composites and in some cases leads to catastrophic failure. The presence of delamination occurs in composite laminates (Pagano and Pipes, 1973). Delamination may arise during manufacturing (e.g., incomplete wetting, air entrapment) or during service (e.g., low velocity impact, bird strikes). Delamination may not be visible or barely visible on the surface, since it is embedded within the composite structures. The delamination detection methods based on modal analysis is that delamination reduces the dynamic stiffness of a structure, causing reduction of the natural frequencies which can detected by vibration testing. Zak *et al.* (1999) and Diaz and Soutis (1999) investigated the effect of delamination on the natural frequencies of laminated composite beams. Zhang et al. (2010) developed a vibration monitoring method for detecting the delamination in composite structures based on change in natural frequencies before and after damage. Shiau and Zeng (2010) presented the effects of delamination length, delamination location in the thickness wise, span wise directions, and aspect ratio of the plate on the natural frequencies.

Delamination can be captured by measured natural frequencies of the non-defected material (healthy material) and the defected material (delaminated material) is highlighted depending on the natural frequency reduction. Ullah and Sinha (2011) introduced dynamics behaviour of the composite plates with and without delamination based on the experimental study at which the test plate made of E-glass fibre and epoxy resins. The dynamics of the delaminated composite plates were then compared with a healthy composite plate when the vibration experiments have been conducted.

In the present study, D'Alembert principle (Victor, 2012) is used to determine the theoretical natural frequency of laminated orthotropic composite plate. A free vibration testing is performed on square simply supported composite plates where the delaminations are reproduced inserting a thin silver foil coated with chemical wax to simulate the delamination between two layers. Experimental measured natural frequencies are compared for both the healthy and the delaminated simply supported hand lay-up square E glass woven fiber composite plates.

DETERMINATION OF NATURAL FREQUENCY USING *D'*ALEMBERT PRINCIPLE

D'Alembert principle was used to determine the natural frequencies of orthotropic laminated composites in another research (Almasry *et al.*, 2011). In the present study, the lateral load is replaced by D'Alembert load $\left(-\rho\frac{\partial^2 w}{\partial t^2}\right)$ based on static analysis. Where ρ is the mass of unit area, is the w lateral deflection, and t is the time variable.

The basic differential equation has been obtained in the form:

$$D_{1111}w^{1111}+2D_{1122}w^{1122}+4D_{1212}w^{1212}+D_{2222}w^{2222}-\rho\frac{\partial^2 w}{\partial t^2}=0 \quad ...(1)$$

The solution of Equation (1) for a four sided simply supported rectangular orthotropic laminate plate, shown in Figure 1, can be written as presented in Equation (2).

$$M^4D_{1111}+2M^2N^2D_{1122}+4M^2N^2D_{1212}+N^4D_{2222}-\rho\omega^2=0 \quad ...(2)$$

where

ω is angular frequency of free vibration

$M=\frac{m\pi}{a}$, $N=\frac{n\pi}{b}$

m and n = 1, 2, 3, …

D_{1111}, D_{2222}, D_{1122}, D_{1212}, are the flexural rigidities of the orthotropic laminate, which can be expressed, in terms of material properties E_{11}, E_{22}, v_{12}, v_{21} and G_{12} with the laminate thickness (h).

$$D_{1111}=\frac{h^3E_{11}}{12\left(1-v_{12}v_{21}\right)}$$

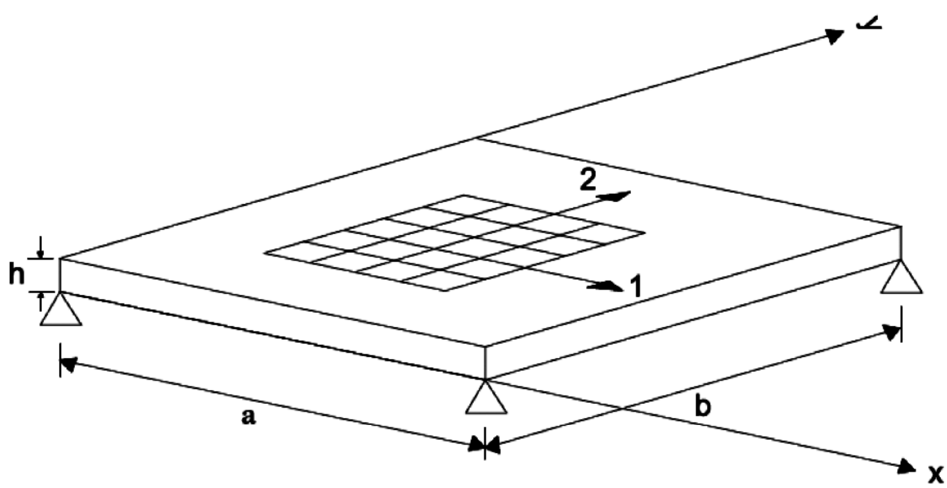
$$D_{2222}=\frac{h^3E_{22}}{12\left(1-v_{12}v_{21}\right)}$$

$$D_{1122}=\frac{h^3v_{12}E_{22}}{12\left(1-v_{12}v_{21}\right)}$$

$$D_{1212}=\frac{h^3}{12}\left(G_{12}\right) \quad ...(3)$$

when,

Figure 1: Simply Supported Orthotropic Plate



$m = 1$ and $n = 1$ leads to the first mode of vibration,

$m = 2$ and $n = 1$ leads to the second mode of vibration,

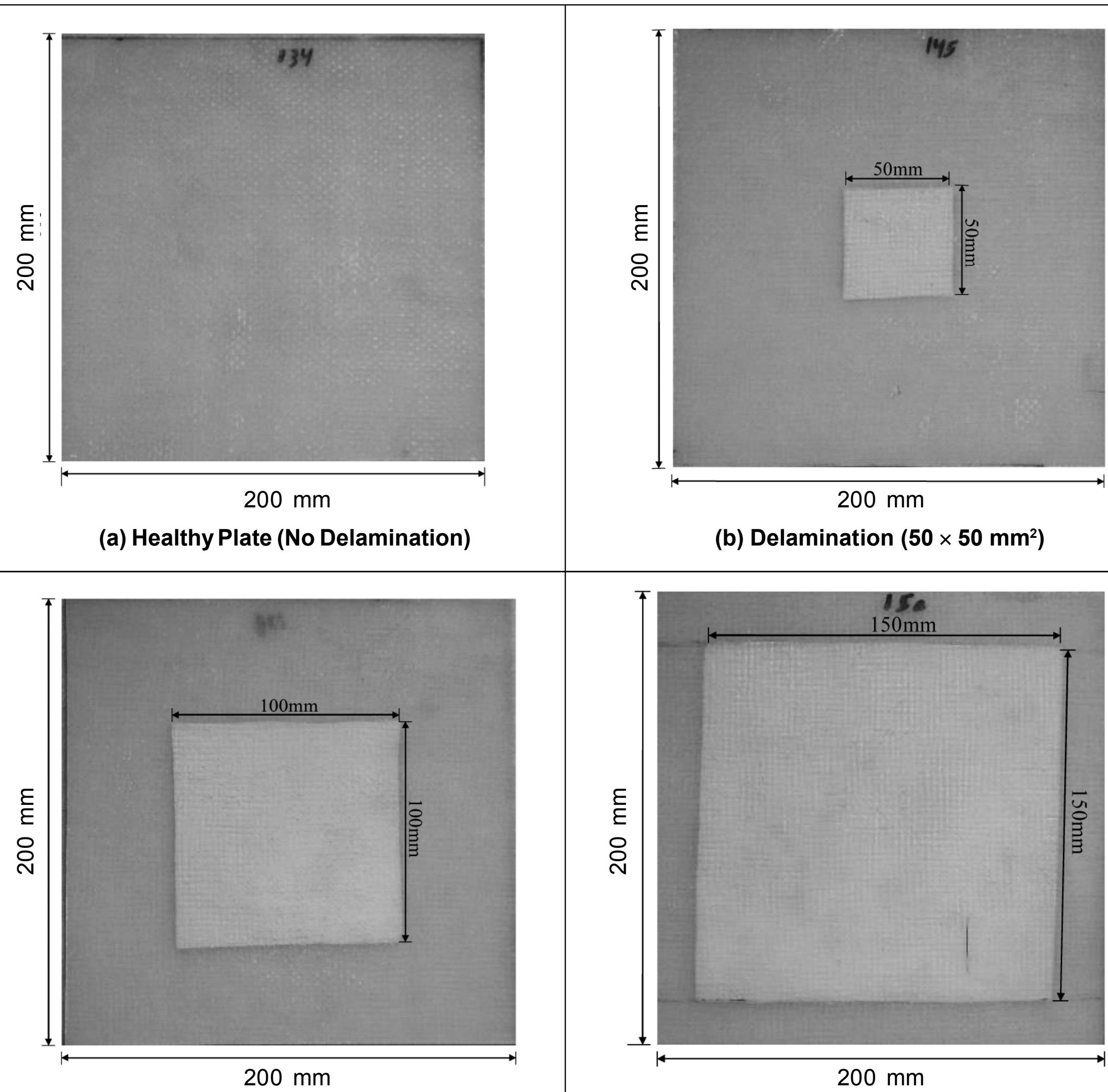
$m = 1$ and $n = 2$ leads to the third mode of vibration, and

$m = 2$ and $n = 2$ leads to the fourth mode of vibration.

PREPARATION OF THE TEST SPECIMENS

The composite plate specimens used in this experiment are made from woven eight plies (0/90) with ($\rho = 3.75$ kg/m^2) composite of *E* glass fiber and epoxy matrix with hardener (Epolam, 2017). After the curing process at room temperature, four test specimens of size ($200 \times 200 \times 2.5$)mm^3 are cut from a plate of

Figure 2: Test Specimens



(a) Healthy Plate (No Delamination)

(b) Delamination (50×50 mm^2)

(c) Delamination (100×100 mm^2)

(d) Delamination (150×150 mm^2)

8 plies laminate by using cutting machine, with different area of mid plane artificial delaminations (50×50, 100×100, 150×150)mm^2. All the test specimens are finished by abrading the edges on a fine sand paper as shown in Figure 2.

TENSILE TEST

Nine specimens are prepared for tensile test using material test system machine as relevant to ASTM standard code (D 3039). The mechanical properties of 8-layered woven fiber glass/epoxy are determined using 3 mm electrical strain gages. Unidirectional tensile tests are performed on specimens cut in longitudinal and transverse directions to obtain E_{11}, E_{22} and v_{12}. A specimens cut at angle 45° to the longitudinal direction to find the shear modulus.The measured experimental values of the elastic moduli (E_{11}, E_{22}, v_{12}, G_{12}) are shown below:

$$E_{11} = E_{22} = 19 \text{ GPa}$$

$$v_{12} = v_{21} = 0.256$$

$$G_{12} = 2.8 \text{ GPa} \qquad \text{...(4)}$$

Considering the above measured mechanical properties, the flexural rigidities (3) are obtained as:

$$D_{1111} = D_{2222} = 25.14 \text{ Nm}$$

$$D_{1122} = 2.51 \text{ Nm}$$

$$D_{1212} = 3.64 \text{ Nm} \qquad \text{...(5)}$$

The introducing of the flexural rigidities (5) into Equation (2), leads to the values of the theoretical natural frequencies presented in Table 2.

VIBRATION TEST

Vibration tests are conducted on 8-layers (0/90) woven *E* glass fiber/epoxy composite plates, with and without artificial delaminations to detect the effect of delamination area on plate natural frequencies. Sixteen specimens were prepared; four square plates of dimension ($200 \times 200 \times 2.5$)mm^3 without delamination (healthy plate), and twelve square plates of the same dimension with different area of delamination (50×50, 100×100, 150×150)mm^2. The natural frequencies are measured for all specimens with four edges simply supported boundary condition. Locally manufactured, two square frames with side element diameter of 5 mm, Figure 3, are used to simulate four edges simply supporting conditions. An impact hammer was used to hit the plate five times at the marked point and the data averaged for each test. Ten repeated tests were conducted for each plate. The force was measured using a force transducer with charge amplifier (B&K type 2626).This output is captured by one accelerometer which mounted at different places to measure dynamic response and is amplified using a conditioning amplifier (B&K type 2626) and then read using the high resolution signal analyzer (B&K type 3562A), giving the Frequency Response Function (FRF) as shown in Figure 4.

RESULTS AND DISCUSSIONS

Modal analysis is conducted on non destructive testing (vibration test) to extract natural frequencies for the healthy plates and the delaminated plates. Generally, a plate with delamination will experience reduction in natural frequencies due to the loss of stiffness. The extent of the stiffness loss depends on delamination characteristics.

Figure 3: Simply Supported Fixture Apparatus of Square Laminate Specimen

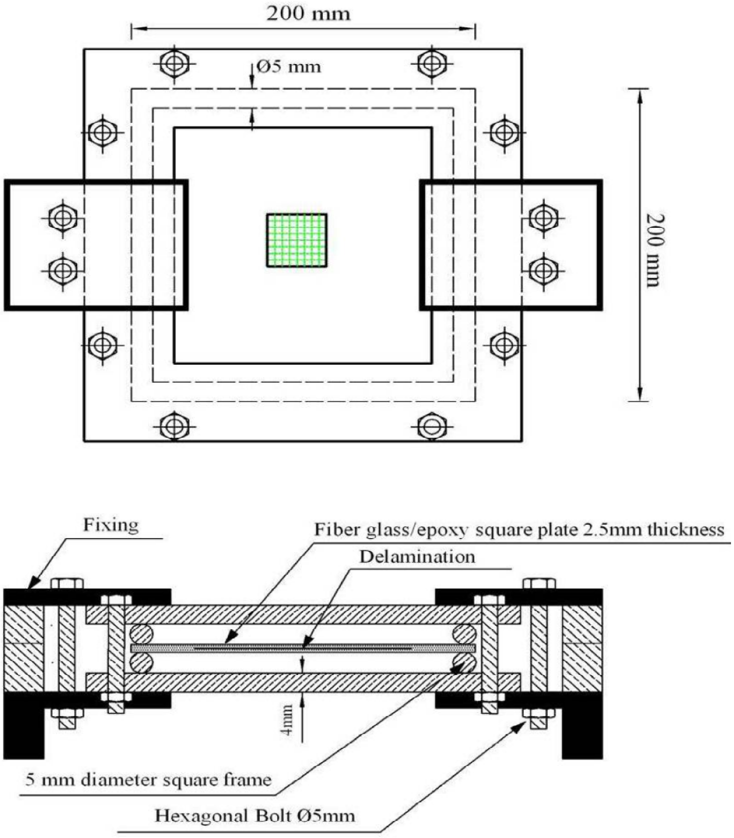
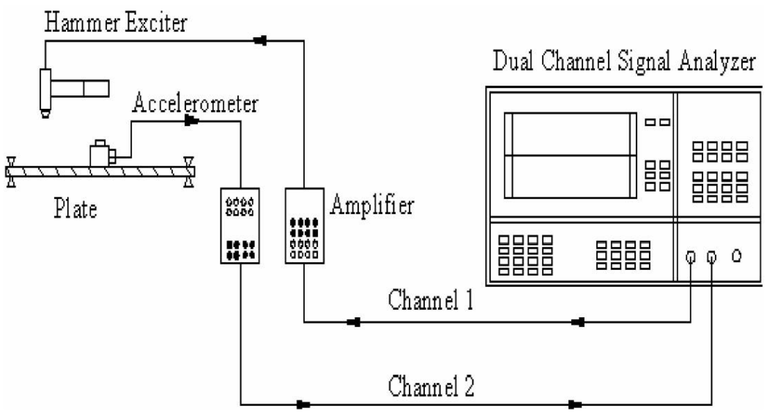


Figure 4: Vibration Test System



In the present experimental work, we have studied the effect of increasing delamination area on natural frequencies of square laminated cross-ply (0/90) woven *E* glass plates, which are simply supported around its four edges. The experimental measured first four modes of vibration for different delamination area are given in Table 1.

Table 1: Experimental Measured Natural Frequencies (Hz) of Square Laminate Plates with Different Central Mid Plane Delamination Area

Mode	Healthy Plate	Mid Plane Delaminated Area		
		(50 × 50 mm^2)	(100 × 100 mm^2)	(150 × 150 mm^2)
First	172.2 Hz	170.3 Hz	169.2 Hz	159.4 Hz
Second	459.5 Hz	420.8 Hz	314.5 Hz	258.2 Hz
Third	466.3 Hz	432.5 Hz	337.4 Hz	271.2 Hz
Fourth	686.4 Hz	637.3 Hz	549.2 Hz	293.3 Hz

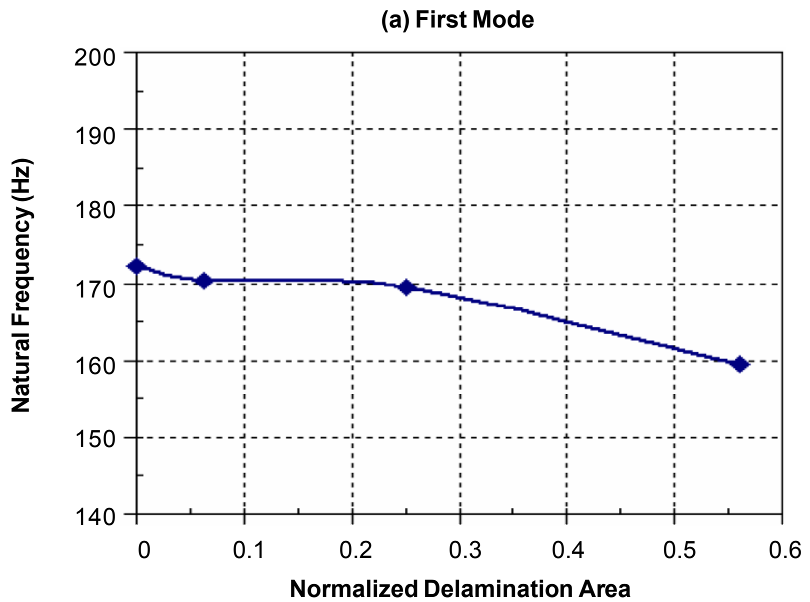
The experimental measured values of natural frequency for healthy plate are compared with those obtained theoretically, using Alembert principle in Table 2.

Through the next Figure 5, we can clearly observe that, the delamination results in the decrease in natural frequency, more predominantly for higher modes.

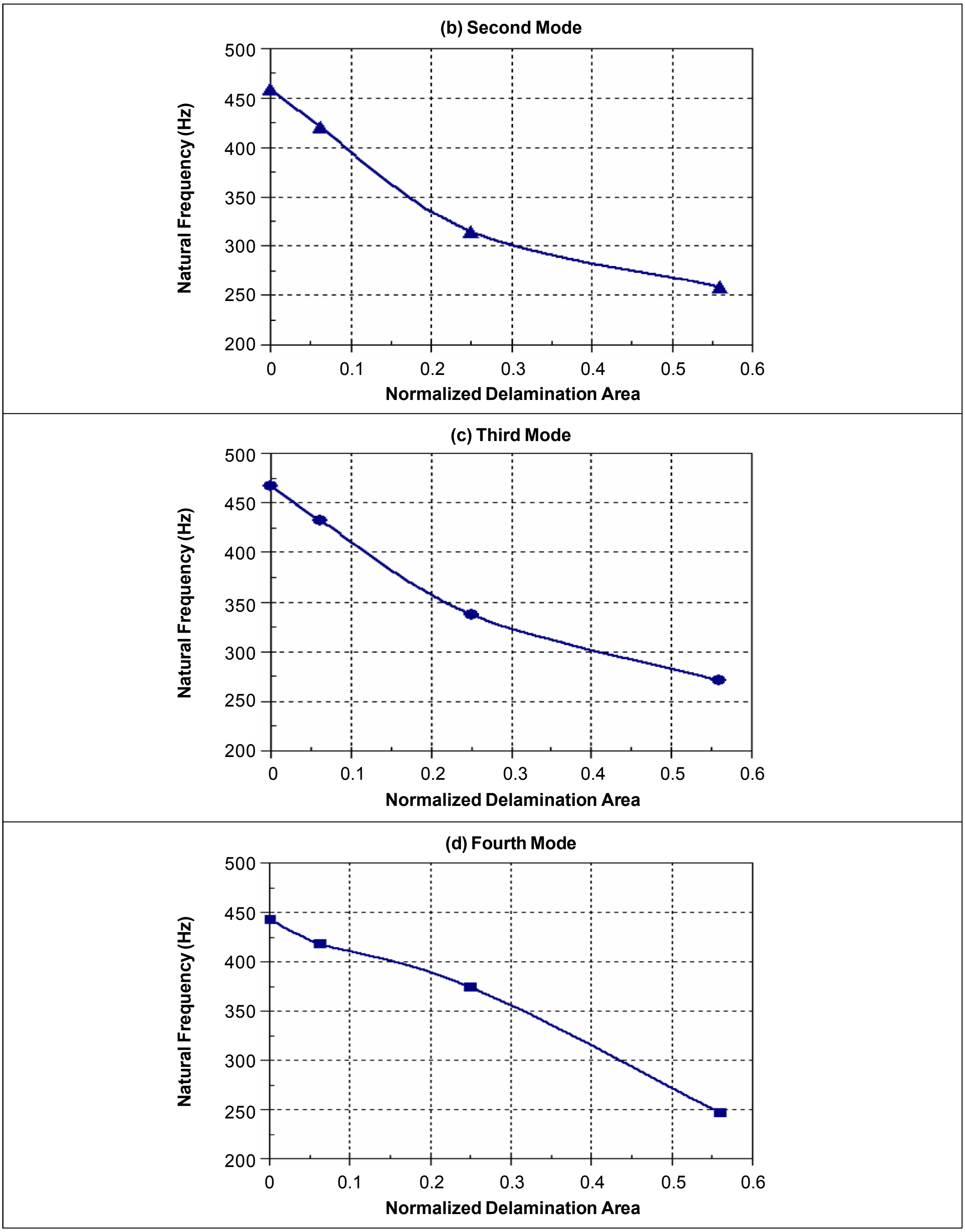
Table 2: Comparison Between Theoretical and Experimental Natural Frequency Results in Hz for Healthy Plate

Mode	Theoretical	Experimental	Percentage Error
First	169.44 Hz	172.2 Hz	1.60%
Second	455.86 Hz	459.5 Hz	0.79%
Third	455.86 Hz	466.3 Hz	2.30%
Fourth	677.79 Hz	686.4 Hz	1.25%

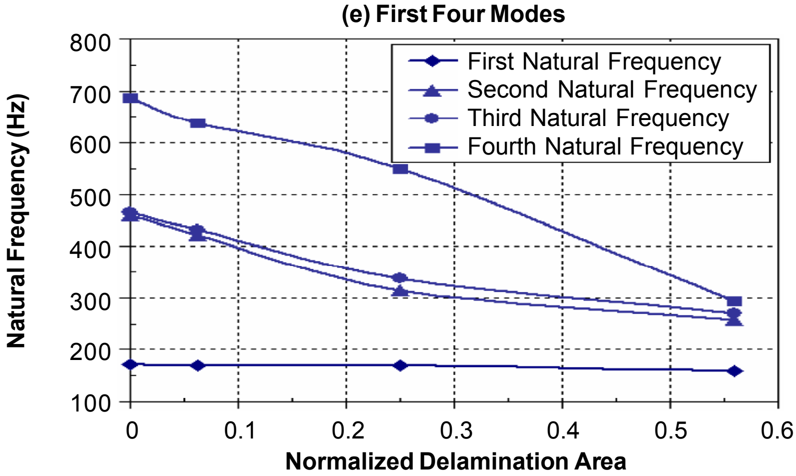
Figue 5: Variation of Natural Frequencies with Normalized Delamination Area for the First Four Modes of Vibration



Figue 5 (Cont.)


(b) Second Mode
Natural Frequency (Hz)
500
450
400
350
300
250
200
0
0.1
0.2
0.3
0.4
0.5
0.6
Normalized Delamination Area
(c) Third Mode
Natural Frequency (Hz)
500
450
400
350
300
250
200
0
0.1
0.2
0.3
0.4
0.5
0.6
Normalized Delamination Area
(d) Fourth Mode
Natural Frequency (Hz)
500
450
400
350
300
250
200
0
0.1
0.2
0.3
0.4
0.5
0.6
Normalized Delamination Area

Figue 5 (Cont.)

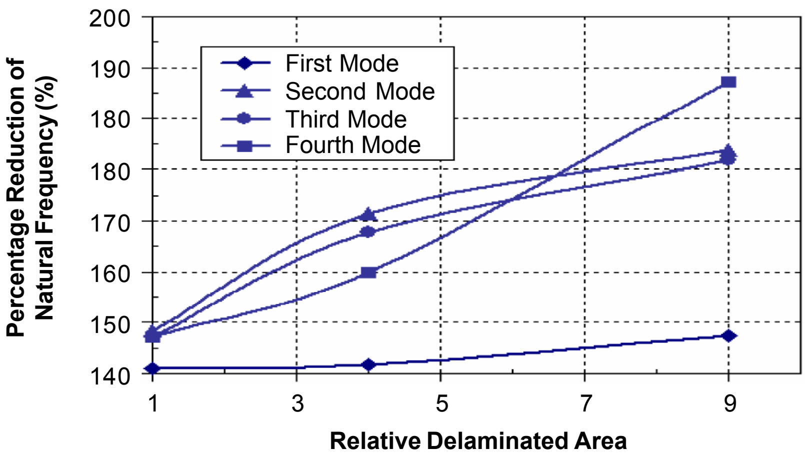


It can be seen that, as expected, for all modes the larger delamination area, the more significant decrease in natural frequency, also It can be deduced that different modes have different sensitivities to the delamination areas as shown in Table 3 and Figure 6.

Table 3: Percentage Reduction of Natural Frequencies Reduction (%) Due to Different Delamination Area in First Four Modes of Simply Supported Square Laminated Plate

Mode	Mid Plane Delaminated Area		
	(50×50 mm²)	(100×100 mm²)	(150×150 mm²)
First	1.10	1.74	7.43
Second	8.42	31.55	43.80
Third	7.24	27.64	41.84
Fourth	7.15	19.98	57.26

Figure 6: Percentage Reduction of First Four Natural Frequencies with Relative Delaminated Area (50×50 mm²)



For instance, the natural frequency of first mode has small reduction for delamination area (100 × 100)mm^2 (1.74%) whereas the reduction of the higher mode is significant (19.98%) relative to healthy plate.

The delamination-induced changes of the first natural frequencies are small, which indicate that, the delamination-induced frequency change is insignificant for first mode especially for small delamination area. Therefore, it is indispensable to analyze the delamination effects based on higher modes rather than first mode. Hence, it is not reasonable to detect the delamination by vibration test depending, only on first mode of natural frequency.

CONCLUSION

Free vibration testing of square composite plates with different areas of artificial delamination is studied. The influence of the delamination area on the measured first four natural frequency modes is investigated. Based on obtained theoretical and experimental results, the following conclusions can be drawn:

- A good correlation between theoretical and experimental analysis is observed (error less than 2.3%).
- Delamination in a laminated plate reduces its natural frequencies and reduction increase when delamination area increase.
- The effect of the delamination area on first mode is very small.
- The higher natural frequency modes are significantly influenced by the delamination area.
- The influence of delamination on natural frequency varies with vibration modes, and this phenomenon may be useful to determine the area of delamination. However, this is basically impracticable, because, the experimental equipment can hardly extract modes higher than five for composite plates.

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APPENDIX

Nomenclature	
a, b, h	Plate length, width, and thickness
$D_{\alpha\beta\gamma\delta}$	Flexural rigidities
E	Young's modules
FRF	Frequency response function
G	Shear modules
M, N	$\frac{m\pi}{a}, \frac{n\pi}{b}$
NDT	Non-destructive test
t	Time variable
w	Plate lateral deflection
$\alpha, \beta, \gamma, \delta = 1, 2$	Two dimensional tensorial indices
v	Poisson's ratio
ρ	Mass of unit area
ω	Angular frequency of free vibration