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## **DELAMINATION DETECTION OF COMPOSITE LAMINATES USING NATURAL FREQUENCY VIBRATION METHOD**

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### **ABSTRACT**

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 testing, 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 here. 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 testing 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.

### **KEY WORDS**

Laminated composite material, Free vibration, Delamination.

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## 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.
$\nu$	Poisson's ratio.
$\rho$	Mass of unit area.
$\omega$	Angular frequency of free vibration.

## INTRODUCTION

The applications of composite materials have become common in different industries. These materials have higher stiffness and strength to weight ratio [1]. Although composite materials offer many advantages in the designing and manufacturing of structures .The application of 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 [2].

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 [3].

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 [4]. 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. Diaz and Zak [5, 6] investigated the effect of delamination on the natural frequencies of laminated composite beams. Zhang et al. [7] 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 [8] 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 [9] 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 [10] 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 [11]. In the present study, the lateral load is replaced by *D'* Alembert load ( $-\rho \frac{\partial^2 w}{\partial t^2}$ ) based on static analysis. Where  $\rho$  is the mass of unit area,  $w$  is the 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 laminates, shown in Figure.1, can be written as presented in Eq.2:

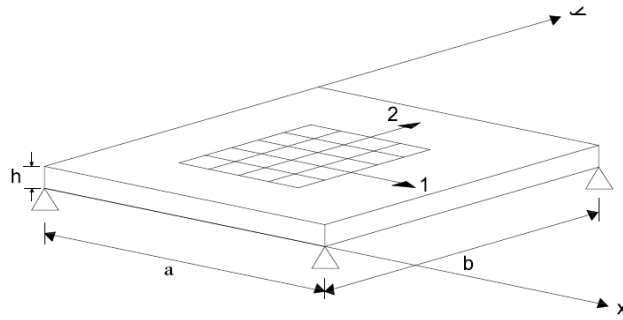
$$M^4 D_{1111} + 2M^2 N^2 D_{1122} + 4M^2 N^2 D_{1212} + N^4 D_{2222} - \rho \omega^2 = 0 \quad (2)$$

where:

$\omega$  is angular frequency of free vibration

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

m and n = 1,2,3,....



**Fig. 1** Simply supported orthotropic laminate.

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

$$D_{1111} = \frac{h^3 E_{11}}{12(1 - \nu_{12}\nu_{21})},$$

$$D_{2222} = \frac{h^3 E_{22}}{12(1 - \nu_{12}\nu_{21})},$$

$$D_{1122} = \frac{h^3 \nu_{12} E_{22}}{12(1 - \nu_{12}\nu_{21})},$$

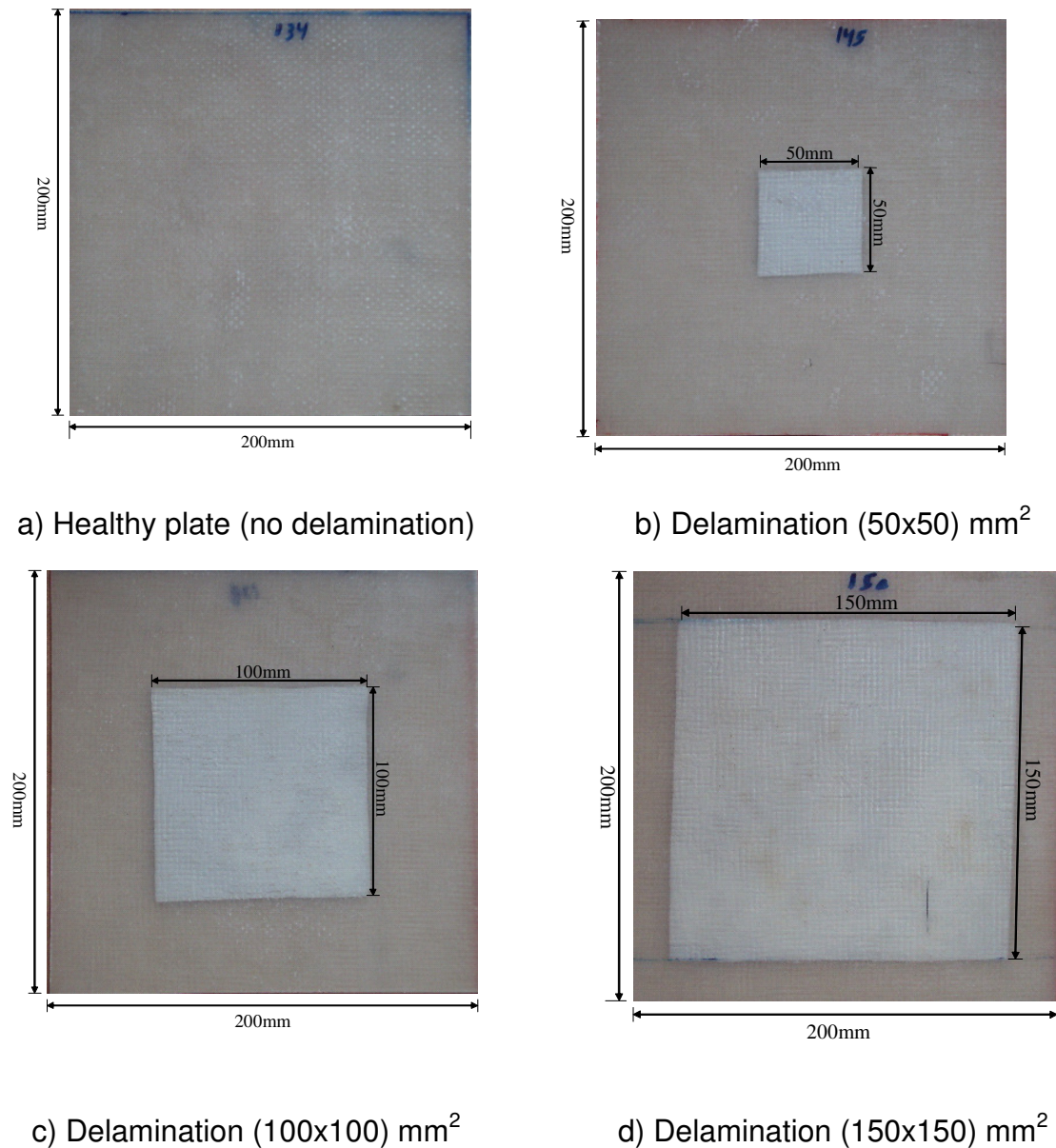
$$D_{1212} = \frac{h^3}{12} (G_{12}).$$

(3)

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 ( $\rho = 3.75 \text{ kg/m}^2$ ) composite of E glass fibre and epoxy matrix with hardener (Epilam 2017). After the curing process at room temperature, four test specimens of size ( 200X200X2.5) mm are cut from a plate of 8 plies laminate by using cutting machine, with different area of mid plane artificial delaminations (50X50, 100X100, 150X150) mm. All the test specimens are finished by abrading the edges on a fine sand paper as shown in Figure 2.



**Fig. 2** Test specimens.

## 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 fibre 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  $\nu_{12}$ . A specimen cut at angle 45° to the longitudinal direction to find the shear modulus  $G_{12}$ . The measured experimental values of the elastic moduli ( $E_{11}$ ,  $E_{22}$ ,  $\nu_{12}$ ,  $G_{12}$ ) are shown below:

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

$$\begin{aligned} \nu_{12} = \nu_{21} &= 0.256 \\ G_{12} &= 2.8 \text{ GPa} \end{aligned} \quad (4)$$

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

$$\begin{aligned} D_{1111} = D_{2222} &= 25.14 \text{ N.m} \\ D_{1122} &= 2.51 \text{ N.m} \\ D_{1212} &= 3.64 \text{ N.m} \end{aligned} \quad (5)$$

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 eight-layer (0/90) woven E glass fibre /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 (200X200X2.5) mm without delamination (healthy plate), and twelve square plates of the same dimension with different area of delamination (50X50, 100X100, 150X150) mm. 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 5mm, 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.

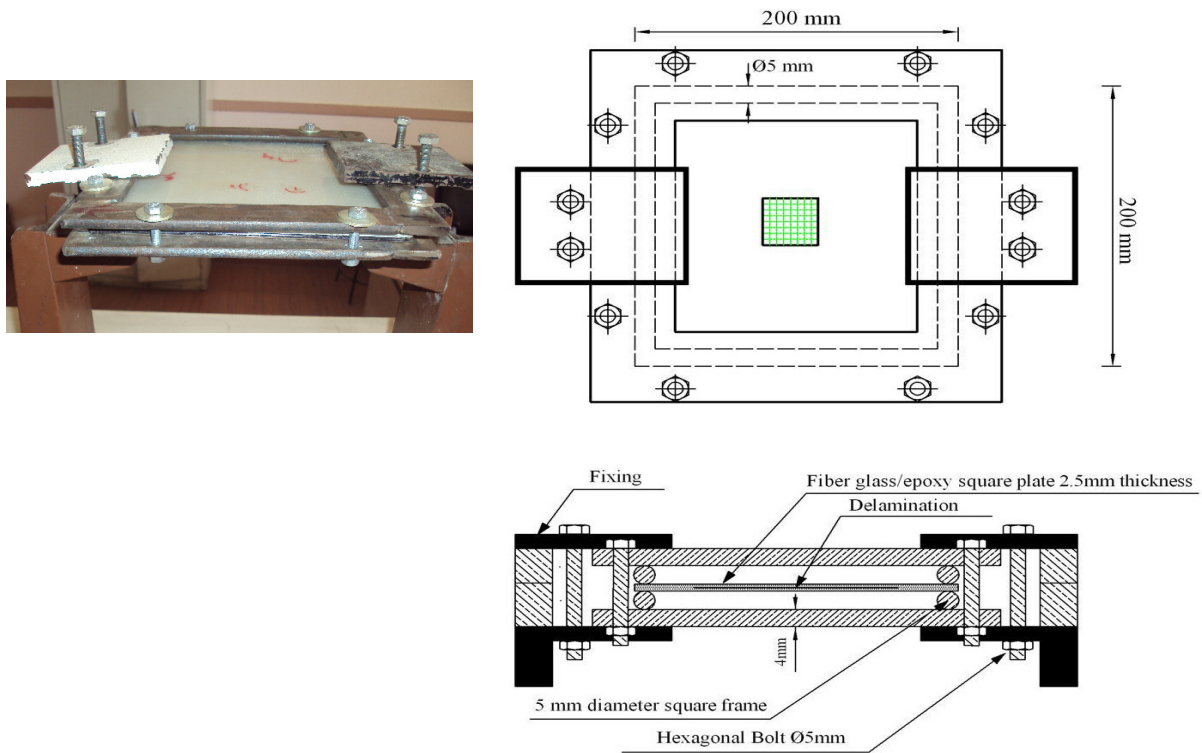
## RESULTS AND DISCUSSIONS

Modal analysis is conducted on non destructive testing (vibration testing) 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.

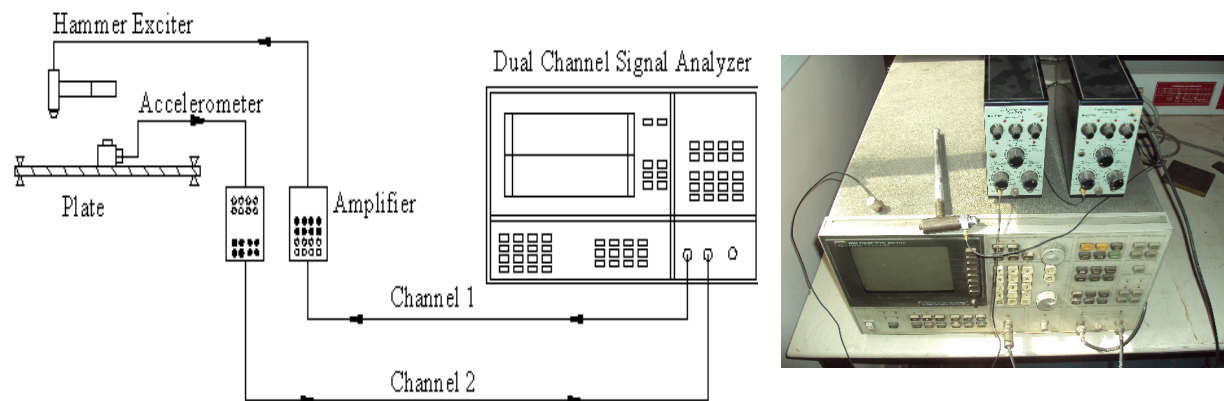
In the present experimental work, we have studied the effect of increasing delamination area on natural frequencies of square laminated cross-ply (0/90) woven E glass plates, which are simply supported around its four edges. The experimental measured first four modes of vibration for different delamination area are given in Table1.



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



**Fig. 3** Simply supported fixture apparatus of square laminate specimen.



**Fig. 4** Vibration test system.

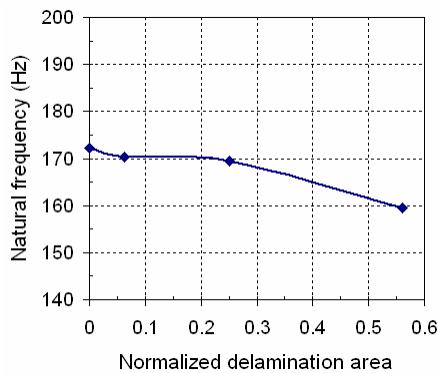
**Table 1** Experimental measured natural frequencies (Hz) of square laminate plates with different mid plane delamination area.

Modes	Healthy plate	Mid plane delaminated area		
		(50x50)mm <sup>2</sup>	(100x100)mm <sup>2</sup>	(150x150)mm <sup>2</sup>
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

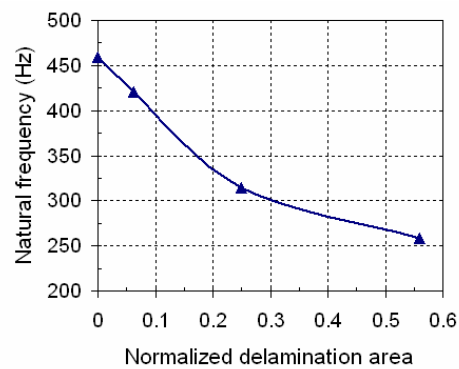
**Table 2** Comparison between theoretical and experimental natural frequency results in Hz for healthy plate.

Mode	Theoretical	Experimental	Percentage error
First	169.44 Hz	172.2 Hz	1.6%
Second	455.86 Hz	459.5 Hz	0.79%
Third	455.86 Hz	466.3 Hz	2.3%
Fourth	677.79 Hz	686.4 Hz	1.25%

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

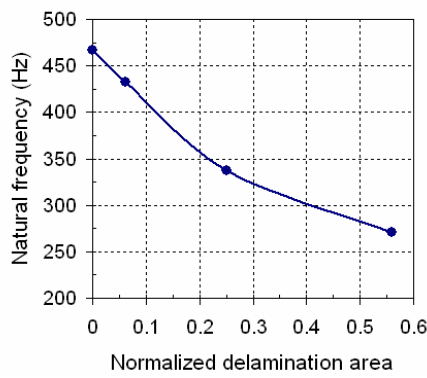


a) First mode

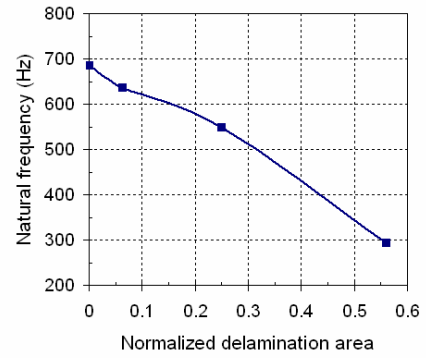


b) Second mode

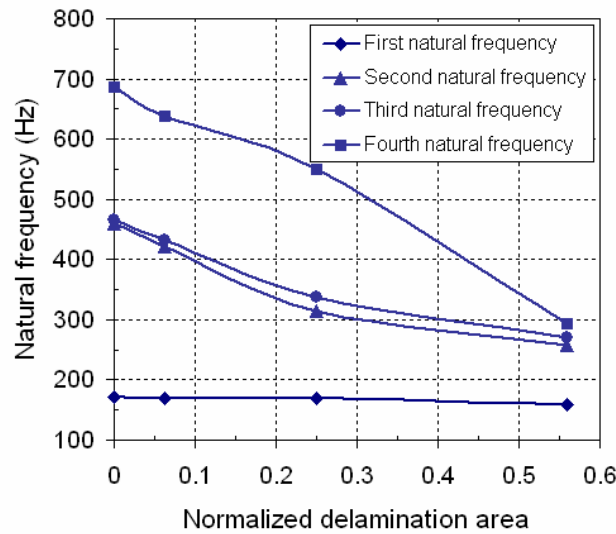




c) Third mode



d) Fourth mode

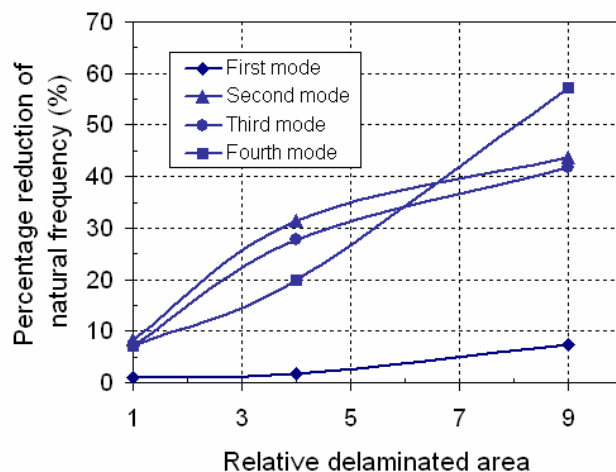


**Fig. 5** Variation of natural frequencies with normalized delamination area for the first four modes of vibration.

It can be seen that, as expected, for all modes the larger delamination area, the more significant the 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 of natural frequencies reduction (%) due to different delamination area in first four modes of simply supported square laminated plate.

Mode	Mid plane delaminated area		
	(50x50)mm <sup>2</sup>	(100x100)mm <sup>2</sup>	(150x150)mm <sup>2</sup>
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



**Fig. 6** Percentage reduction of first four natural frequencies with relative delaminated area (50x50) mm<sup>2</sup>.

For instance, the natural frequency of first mode has small reduction for delamination of area (100x100) mm<sup>2</sup> (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 area. Therefore, it is indispensable to analyze the delamination effects in 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.

## CONCLUSIONS

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:

1. A good correlation between theoretical and experimental analysis is observed (error less than 2.3%).
2. Delamination in a laminated plate reduces its natural frequencies and reduction increase with delamination area.
3. The effect of the delamination area on first mode is very small.
4. The higher natural frequency modes are significantly influenced by the delamination area.
5. 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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