Experimental Vibration Study on the Healthy and Delaminated Composite Plates

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Abstract. Vibration based damage, in particular delamination detection, in the composite structures is an active research area. The present study is also on the dynamics of the composite plates with and without delamination based on the experimental study. The test plate made of E-glass fibre and epoxy resins has been used here. A piezo-electric shaker has been used to excite the composite plate and the acceleration responses were measured using the number of accelerometers. The dynamics of the delaminated composite plates were then compared with a healthy composite plate when the vibration experiments have been conducted at the lower modes. The paper will discuss the observations made on the measured vibration responses from both the healthy and the delaminated plates and the possibility of the delamination detection from the experimental vibration data.

1. Introduction
Internal delamination, if present, in a composite structure generally propagates with time due to the service loads which can reduce its load carrying capacity with the passage of time and may leads to failure. Vibration based delamination detection in the composite structures is an active research area. Number of studies [1-18] has been conducted by the researchers to meet this objective. These studies include the mathematical modelling of the composite plate with a delamination [1-9], detection based on the change in the modal parameters and/or mapping the deflection of the composite plate either through the embedded sensors [17-18] or scanning the complete surface through laser vibrometer [10-11] when the composite structure excited at very high natural frequencies in the order of more than 10 kHz. It is because the delamination in a composite structure show prominent local mode in the delamination region at the much higher modes. However the use of the embedded sensors or the excitation at the frequency higher than 10 kHz may not be always practical and possible. The study on the change in the modal parameters is generally based on the theoretical study and a few experimental examples limited to the modal analysis [7-8]. This approach may not be useful when the damage or delamination size is small.

Hence to understand the dynamics of a delaminated composite plate compared to a healthy plate, the vibration experiments have been conducted at the lower modes. The test plate made of E-glass fibre and epoxy resins has been used here. A piezo-electric shaker has been used to excite the plate and the acceleration responses were measured using the number of accelerometers. The paper will discuss the observations made on the measured vibration responses from both the healthy and the delaminated plates and the possibility of the delamination detection from the experimental vibration data when the plates are excited at few lower modes.
2. Composite plates

The test plate made of E-glass fibre and epoxy resins has been used here. It has a total of 8 layers of equal thickness which are arranged as [0°/90°/0°/90°/0°/90°/0°/90°] as shown in Figure 1. The size of the test plate is 400 mm x 400 mm and total thickness 3.5mm. A total of 3 plates have been used, one without delamination (healthy) and the other two; one with delamination of 40 mm x 40 mm size between 3rd and 4th layers from the top surface and its centre located at the coordinate of (275mm, 275mm) from the reference x and y axes, and the other similar to the last one but with delamination in the centre of the plate. First two plates are shown in Figure 2.

![Figure 1 Arrangement of 8 layers in the test plates](image1)

![Figure 2 Typical test plates of E-glass fibre, (a) no delamination, (b) delamination at coordinate location (275mm, 275mm)](image2)

3. Experimental Set-up

The schematic of the experimental setup and the mounting of the portable shaker are shown in Figure 3. A piezo-electric shaker (Model PS-X03, M/s ISI-SYS) has been used to excite the plate and the acceleration responses were measured using the number of accelerometers (Model 352C22, M/s PCB). The plate was hanged to realise the free boundary condition for all the 4 edges of the plate.
4. Modal Testing

The modal tests were conducted for both plates using the sweep-sine excitation in the frequency band of 0 to 500Hz initially and then the impulse-response modal test [19] has been carried out using the instrumented hammer (Model 086C03, M/s PCB) to find out the natural frequencies. The measured data for both the tests were collected to the computer through an 8-channels 16-bit data acquisition card for further analysis. The measurement locations using the accelerometer (Model 352C22, M/s PCB) for all the three plates (healthy, in-centre and off-centre delamination) are shown in Figure 4. The natural frequencies were then identified using the frequency response functions (FRFs) computed from the measured force and acceleration data. The experimentally identified modes are listed in Table 1. It is expected that the delaminated plates should show slightly lower natural frequencies compared to the healthy plate, but it is not consistent for all modes. The possible reason could be the small deviation in the manufacturing process because these samples have been specially manufactured for the present study. The other possibility could be small difference in the position of the shaker mounting on the different plates.

| Modes | Healthy Plate | Faulty Plate (in-centre delamination) | Faulty Plate (off- centre delamination) |
|-------|---------------|---------------------------------------|----------------------------------------|
| 1     | 58.03 Hz      | 55.56 Hz                              | 57.46 Hz                               |
| 2     | 92.85 Hz      | 94.05 Hz                              | 92.45 Hz                               |
| 3     | 130.27 Hz     | 130.65 Hz                             | 133.22 Hz                              |
| 4     | 137.44 Hz     | 138.11 Hz                             | 140.40 Hz                              |
| 5     | 153.27 Hz     | 156.77 Hz                             | 155.01 Hz                              |
| 6     | 211.12 Hz     | 204.34 Hz                             | 211.25 Hz                              |
| 7     | 263.55 Hz     | 266.06 Hz                             | 262.37 Hz                              |
| 8     | 344.89 Hz     | 362.45 Hz                             | 354.21 Hz                              |
Figure 4 Measurement locations (25 points in 5 x 5 equidistant grids) on the plate

Figure 5 Typical amplitude acceleration spectra for the healthy plate when excited at Mode 6 (a-b) and 7 (c-d) at locations 9, 20 respectively
5. Response Measurement
Vibration experiments have also been conducted on the healthy and delaminated composite plates shown in Figure 3. Composite plates were excited through the shaker at the first 8 modes. The steady state acceleration responses were then collected from 25 locations on the plates using the number of accelerometers (Model 352C22, M/s PCB). The measurement locations are shown in Figure 4. The data were collected to the PC at the sampling frequency of 20 kHz for the further analysis. The acceleration signals were then analysed to compute the amplitude spectra for all the 3 cases. Few typical acceleration spectra for the healthy plate and the plates with in-centre and off-centre delamination are shown in Figures 5-7 when excited at modes 6 and 7 at locations 9 and 20 (marked in Figure 4). The ‘1X’ in the spectra indicates the exciting frequency and the components 2X, 3X, … represent the higher harmonics of the exciting frequency in the spectra. It has been observed from the spectra that due to anisotropic nature of the composite plate, the modes other than the exciting mode also contribute to the overall response. In addition to this effect, the non-linear interactions between the delaminated layers in the plates with delamination also introduce the higher harmonics of the exciting frequency. Although the presence of such higher harmonics has also been observed in the healthy composite plate, probably again due to anisotropic property of the composite material, but the effect was not prominent compared to the plates with delamination.

Figure 6 Typical amplitude acceleration spectra for the off-centre delaminated plate when excited at Mode 6 (a-b) and 7 (c-d) at locations 9, 20 respectively
6. Delamination detection

Having observed the difference in the spectra between the healthy and delaminated plates, the acceleration response data has further been analyzed so that the delamination detection process becomes simple. The number of different statistical parameters like Crest Factor, Skewness, Kurtosis, etc. has been studies on the measured responses; however it was difficult to observe any good indicator for the delamination detection. The RMS (root mean square) value for the measured responses was also computed and encouraging observations have been made, hence this parameter has further been investigated. The measured acceleration responses generally have different overall amplitude (peak to peak) at different locations which make it difficult to compare the RMS values at different locations. Hence to unify the computation of the RMS at different measured locations, all the measured acceleration responses were normalised to ±1 amplitude and then the normalised RMS for the 25 measured locations of each plate at each mode of excitation have been computed first and then their average RMS value for each mode. Table 2 gives the averaged normalised RMS values for 25 locations at each mode for one healthy and two faulty plates. It has been observed that the averaged normalised RMS value at each mode for the healthy plates up to mode 8 shows small increase, however the increase in the averaged normalised RMS value for the acceleration responses observed to be more for the delaminated plates. Hence this parameter is good health indicator for the delamination detection.
Since it is not always practical to measure the acceleration response at the number of points on the large structure using accelerometers, the laser vibrometer is preferred option since this can easily and quickly scan the complete area at the desired number of points. Hence the acceleration data has been converted to velocity data and then again the averaged normalised RMS has been computed for each mode. The averaged normalised RMS values for the velocity responses measured at 25 locations at each mode for the healthy and two delaminated plates are listed in Table 3. It has been observed that the average of 8 modes RMS value is significantly higher for the delaminated plates compared to the healthy plate. The averaged normalised RMS value for the velocity responses at each mode remains constant at around 0.33, however it is more for the delaminated plates except at a few lower modes. Possibly at these lower modes in case of the delaminated plates, the non-linear interaction between the delaminated layers may not be prominent due to small size delamination considered here and resulting in lower RMS value like the healthy one, but the average of first 8 modes definitely show the potential for detecting the presence of delamination in quicker manner.

Table 3 Averaged normalised RMS values for the measured velocity responses at each mode

| Mode # | Healthy | Faulty (Off centre) | Faulty (In centre) |
|--------|---------|---------------------|--------------------|
| 1      | 0.3319  | 0.2888              | 0.2972             |
| 2      | 0.3421  | 0.3123              | 0.2784             |
| 3      | 0.3473  | 0.4085              | 0.2654             |
| 4      | 0.3128  | 0.4877              | 0.3595             |
| 5      | 0.3009  | 0.3175              | 0.3369             |
| 6      | 0.2962  | 0.4567              | 0.6194             |
| 7      | 0.3628  | 0.6225              | 0.5720             |
| 8      | 0.3836  | 0.6188              | 0.5819             |
| Average| 0.3347  | 0.4391              | 0.4138             |

7. Delamination Location

Once the presence of the delamination is detected and it is also important to know the location of delamination. Hence a simple approach has been devised for this purpose. The amplitude spectra have further been investigated. It has been observed that the delaminated plates show prominent higher harmonics of the exciting frequencies as shown in Figures 6-7, hence the harmonics of the exciting frequency has been analysed. Since the averaged normalised RMS value for modes 1 to 3 for the delaminated plates are nearly same as the healthy plate, hence the mode 4 onwards has been considered here for all the three plates. Following 2 approaches has been investigated.
(i) Operational Deflection Shape (ODS) at 1X component at each mode
(ii) Normalised Summation of higher Harmonics (NSH) at each mode which is computed as

\[ \text{Summation of harmonics when excited at Mode } i \text{ at location } j, \quad SH_{ij} = \sum_{n=2}^{h} (v_{ij})_n \]

where \( n \) is the harmonics of the exciting frequency from 2, 3, ..., \( h \), \( (v_{ij})_n \) is the velocity amplitude of the \( n \)th harmonic of the exciting mode, \( i \) at the measured location, \( j \) and then this \( SH_{ij} \) is normalised by the maximum value from all the measured location to get the normalised SH (NSH). The cumulative NSH (CNSH) at each measured location has also been computed for all the modes as

\[ CNSH_{ij} = \sum_{i=p}^{q} NSH_{ij} \]

where \( p \) and \( q \) are the modes used for this computation. Here the starting mode, \( p = 4 \) and end mode, \( q = 8 \) has been used. It is observed that the approach (i) is giving the deflection shape at each mode is equivalent to the mode shape as expected. However the plots of the NSH and its CNSH provide excellent indication for the location of the delamination. Typical NSH plots at different modes and its CNSH plot are shown in Figures 8-10 for the healthy composite plate. It has been observed that the NSH plot at each mode is also capable to show the delamination location, but the CNSH indicator provides much better delamination location.

Figure 8 NSH plots for (a) Mode 6 (a), (b) Mode 7, (c) Mode 8 and (d) CNSH plot for Mode 4 to 8 for the healthy composite plate
Figure 9 NSH plots for Modes 4-6 (a-c) and the CNSH plot (d) for Modes 4-8 for the off-centre delaminated composite plate

Figure 10 NSH plots for Modes 4-6 (a-c) and the CNSH plot (d) for Modes 4-8 for the in-centre delaminated composite plate
8. Concluding Remarks
The dynamics of the three composite plates – one healthy (no delamination) and other two plates having delamination at centre and off-centre have been study when excited experimentally at few lower modes. It has been observed that the measured acceleration spectra show the appearance of other modes when excited at a mode due to anisotropic property of the composite. In addition to this observation, the plates with delamination also show some higher harmonics of the excited frequency due to the non-linear interaction between the delaminated layers. It has also been observed that the averaged normalised RMS value at each mode show increasing trend for the delaminated plates compared to the healthy composite plate. It is also observed that the averaged normalised RMS value for the velocity responses for all the modes more than 0.4 indicates the presence of the delamination. Further analysis of the measured signals also shows that the NSH (normalised summation of higher harmonics) of the exciting frequency at each mode and its Cumulative NSH (CNSH) for few lower modes indicate the location of delamination clearly for the experimental cases. Hence the averaged normalised RMS and the CNSH for few modes can be deemed as the good indicators for the delamination detection and its location respectively. Since the development of method uses the velocity responses at just few lower modes so it is practically feasible for real structure using the conventional shaker and the laser vibrometer for this purpose. It is also important to note that the conclusion is just based on the experimental observations made on the E-glass fibre and epoxy resins composite plates only, hence this needs further validation on different types of the composite material.

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