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A Novel Method for Delamination Detection in Composites

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ABSTRACT: Delamination detection in the composite structure based on the vibration responses when excited at the lower modes has been suggested here. It has been observed that the nonlinear interaction between the delaminated layers produce higher harmonics of the exciting frequency. These higher harmonics have observed to be useful for the detection and location of the delamination without comparing the vibration data from the healthy state of the composite structure. The paper presents the observation based on the finite element analysis of a composite plate with and without delamination and then on the experiments on the composite plates with and without delamination.

KEYWORDS: Composite structures, Finite Element Modeling, Delamination, Nonlinear interaction, Vibration response.

1 INTRODUCTION

Delamination detection in the composite structures is one of the active research areas since decades. Number of research has been carried out to meet this objective. The most commonly used method in the literature is based on the vibration analysis [1-23]. These vibration based studies include (a) change in modal parameters (natural frequencies and mode shapes) [1-4] or the vibration responses by comparing the data with the healthy state condition [1, 2, 6], (b) mapping the deflection shape of the surface of the composite structure either through the embedded sensors [19-20] or scanning the complete surface by the laser vibrometer [17-18]. The changes in the modal parameters may not be significant if the delamination size is small and the data from the healthy state may not be available for many existing composite structures. The array of the embedded sensors may also not be readily available in many cases. Moreover, the deflection mapping of the surface needs the structure to be excited at very high natural frequency in order of more than 10 kHz[15] which is also not a practical approach using the normal piezo-electrical shakers generally used in the vibration testing.

Considering these limitations, a simple method which may be relatively easy to implement in practice and not requiring data from the healthy state condition is needed to meet the objective. Hence it is assumed that the excitation at a few lower modes by the conventional shaker is always possible and then scanning the complete composite surface through the laser vibrometer may not impose any practical limitations. With this assumption, the excitation of a composite plate with and without a delamination at a few lower modes and then the velocity responses measurements at number of points has been considered in the present study. Initially, the finite element (FE) model of a composite plate with and without delamination has been developed to simulate this experiment. The plate was then excited at a few lower modes so that the amplified steady state responses can be observed. The nonlinear interaction between the delaminated layers for the plate with delamination was also considered during the vibration response estimation. The breathing (opening and closing) of a crack in a structure during vibration always produce the higher harmonics of the exciting frequency [24], hence the similar responses are expected for the delaminated composite structure. In fact, it has been observed that the nonlinear interaction between the delaminated layers produce higher harmonics of the exciting frequency. These higher harmonics are then observed to be useful for the detection and location of the delamination without comparing the vibration data from the healthy state of the composite structure. The paper presents the observation based on the finite element analysis of a composite plate with and without delamination and then experimental validation on the composite plates with and without delamination.

2 COMPOSITE PLATES

The experimental composite plate made of E-glass fibre and epoxy resins has been considered for the present study. It has a total of 8 layers of equal thickness which are arranged as [0^o /90^o/0^o /90^o/90^o /0^o /90^o/0^o] as shown in Figure 1. The size of the test plate is 400 mm x 400 mm and total thickness 3.5mm. One test sample of the composite plate has the delamination of 40 mm x 40 mm size between 3rd and 4thlayersfromthe top surface and its centre located at the coordinate of (275mm, 275mm) from the one corner of the plate. These test plates are shown in Figure 2. The material properties of the plate are the density, $1185\,kg/m^3$, the elasticity constants, $E_1 = 55$ GPa, $E_2 = E_3 = 9.5$ GPa, $G_{12} = G_{13} = 5.5$ GPa, $G_{23} = 3.21$ GPa, and the Poisson ratios, $\nu_{12} = \nu_{13} = 0.33$, $\nu_{23} = 0.48$

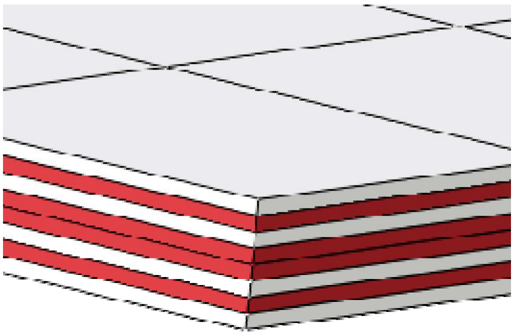


Fig. 1. Arrangement of 8 layers in the composite plate

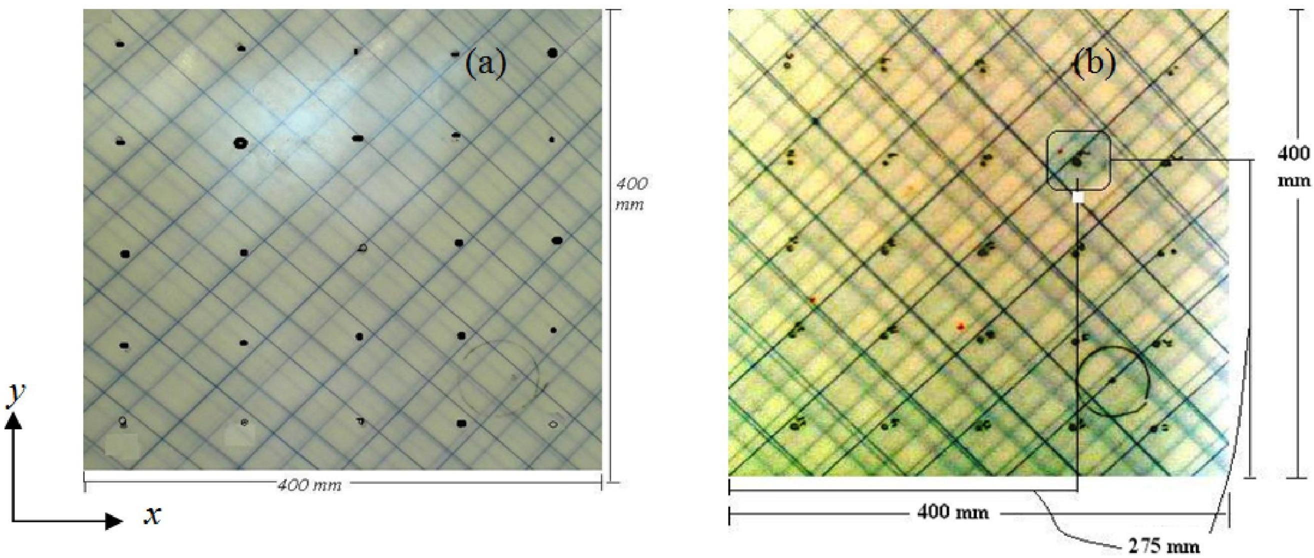


Fig. 2. Typical test plates of E-glass fibre, (a) no delamination, (b) delamination at coordinate location (275mm, 275mm)

3 FINITE ELEMENT (FE) MODELLING

The FE models for both the plates (with and without delamination) have been constructed in the ABAQUS 6.10 FE code. The element C3D8I has been used for this modeling. An element size of 5mm x 5mm has been used for each layers resulting in 51200 elements for a plate. A typical FE model is shown in Figure 3. However for the delaminated plate, the delamination region was modeled by creating duplicate nodes at the delamination interface which is also marked in Figure 3. The measurement locations chosen for the velocity response in the FE simulation are also shown in Figure 3. The free boundary condition was assumed for all 4 edges. The modal analysis for both the FE models (healthy and delamination cases) has been carried out. The calculated frequencies are also listed in Table 1.

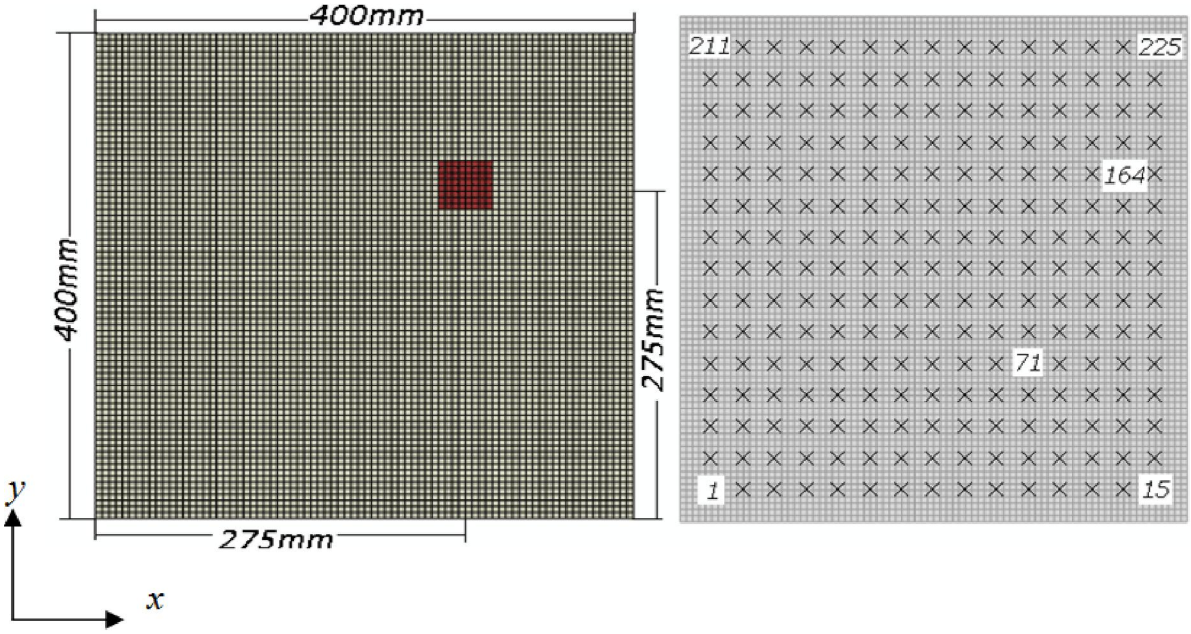


Fig. 3. (a) An FE model of the E-glass fibre plate (also showing delamination region), (b) Measurement locations (marked as x) in FE simulation

Table 1. Calculated natural frequencies

Modes	Healthy Plate	Delaminated Plate
1	50.03 Hz	49.96 Hz
2	101.42 Hz	100.97 Hz
3	134.61 Hz	134.21 Hz
4	143.55 Hz	143.26 Hz
5	166.83 Hz	166.80 Hz
6	265.87 Hz	265.55 Hz

4 RESPONSE ESTIMATION

The velocity responses have been estimated using the explicitly dynamics analysis in the ABAQUS 6.10 FE code for both healthy and delaminated plates when excited at few lower modes. The non-linear interaction between the delaminated layers has also been simulated during the response estimation for the delaminated plates. Typical velocity amplitude spectra when excited at Mode 3 and 4 are shown in Figure 4. It has been observed that the modes other than the excited mode are also present in the spectra for both the healthy and delaminated plates, probably due to anisotropic material properties of the composite material. In addition, the prominent higher harmonics of the exciting frequency has also been observed as expected due to the nonlinear interaction between the delaminated layers for the delaminated plate compared to the healthy plate. The exciting frequency (1X) and its higher harmonics (2X, 3X, …) are marked as ‘**O**’ in Figure 4.

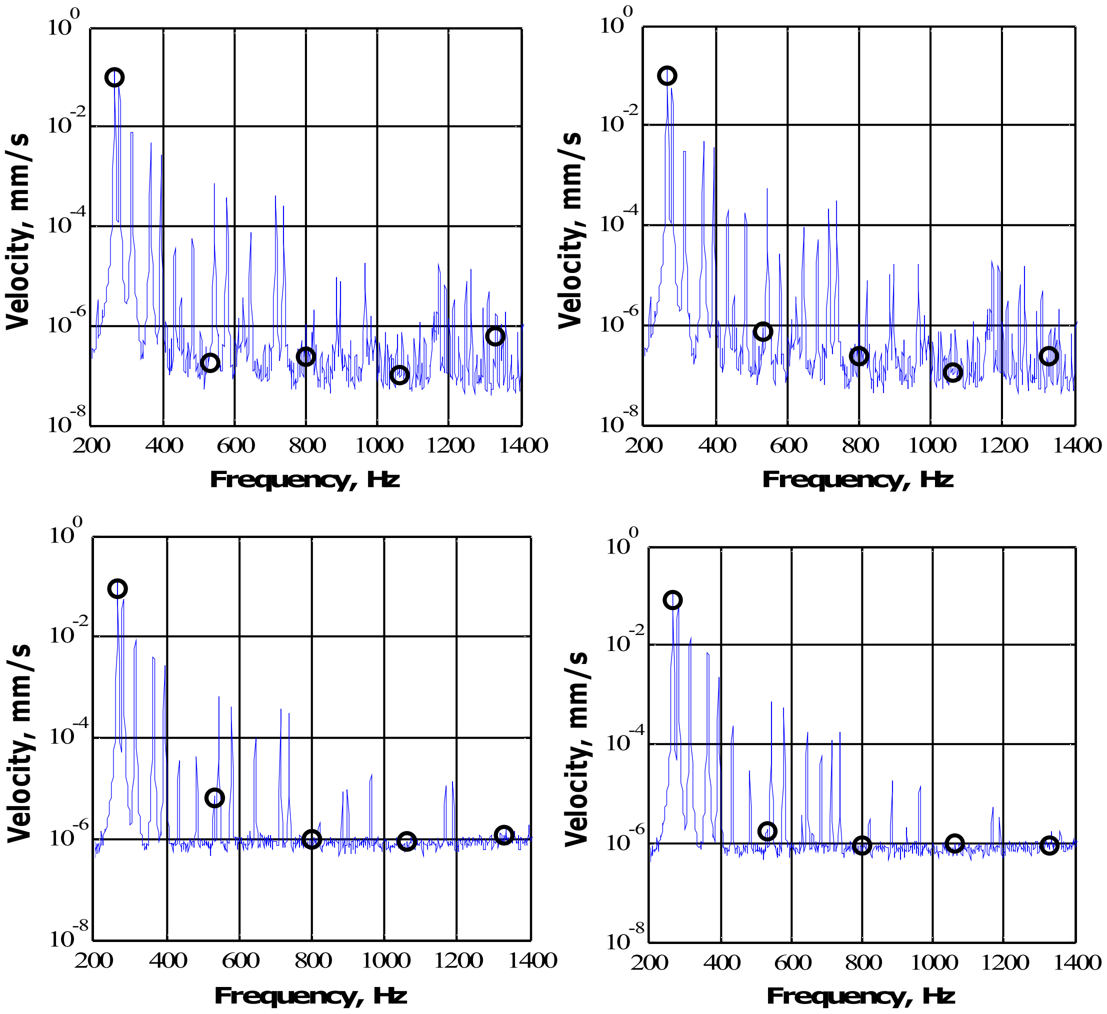


Fig. 4. Typical FE simulated amplitude velocity response spectra at location at nodes71, 164forthehealthy (a-b) and delaminated plates (c-d) when excited at Mode 6 respectively

5 DELAMINATION DETECTION

Having known the presence of prominent higher harmonic components of the exciting frequency in the spectra due to the nonlinear interaction between the delaminated layers in the composite structure, a simple approach has been devised for this purpose of the delamination detection. The term "Normalized Summation of higher Harmonics (NSH)" at each mode has been defined which is computed as

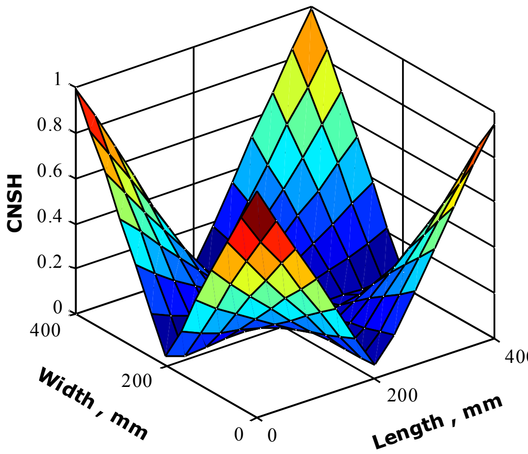
Summation of harmonics (SH) when excited at Mode *i* at location *j*,

$$SH_{ij} = \sum_{n=2}^{h} (v_{ij})_n \qquad (1)$$

where *n* is the harmonics of the exciting frequency from 2, 3,..., *h*, $(v_{ij})_n$ is the velocity amplitude of the harmonic, *n* at the exciting mode, *i* at the measured location, *j* and then this SH_{ij} is normalized by the maximum value from all the measured location to get the normalized SH (NSH). The component 1X which is the amplitude of the exciting mode has not been included in the equation (1) because the operation deflection shape (ODS) at 1X generally represents the mode shape of the exciting mode. However, the amplitude of the higher harmonics definitely related to the size and location of the delamination. Finally the contribution from few lower modes has been defined as "Cumulative NSH (CNSH)" at each measured location which has been computed as

$$CNSH_j = \sum_{i=1}^{q} NSH_{ij} \qquad (2)$$

where q is the number of modes used for this computation. Here the first 5 modes have been used. The plots of the CNSH of the plate with and without delamination are shown in Figure 5 which provides excellent indication for the location of the delamination.



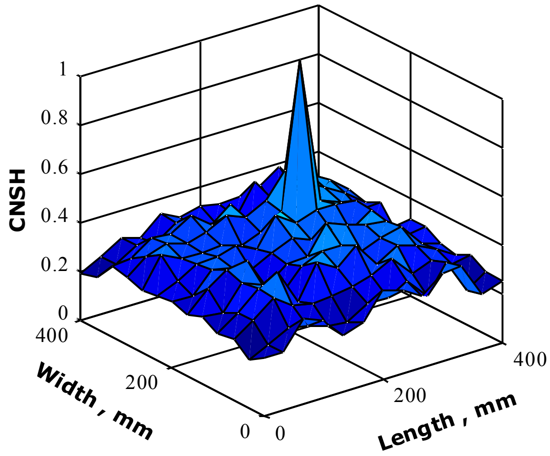
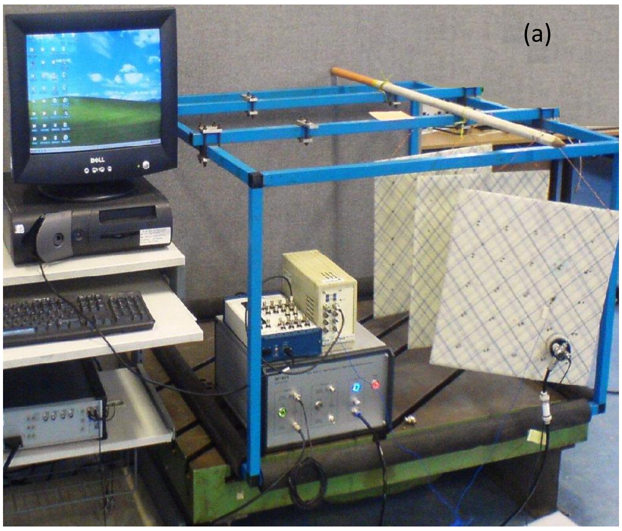


Fig. 5. Typical CNSH plots using Modes 1 to 6 in the FE simulations, (a) Healthy plate, (b) Delaminated plate

6 Experiments

The schematic of the experimental setup is shown in Figure 6(a). It consists of a composite plate shown in Figure 2 which was hanged by the soft elastic rope from the top 2 corners of the top edge to realize the free boundary condition for all the 4 edges of the plate. A 234 gram 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) at different locations. Typical mounting of the shaker and few accelerometers are shown in Figure 6(b). The portable shaker is connected with a vaccum pump in the shaker amplifier unit as shown in Figure 6(a) and the vaccum pressure generated by the pump has then been used to attach the shaker to the plate. A total of 25 response measurement locations were used for the experiments, these locations are also marked in Figure 7. Location 19 is the centre of the delamonation in the delaminated plate.



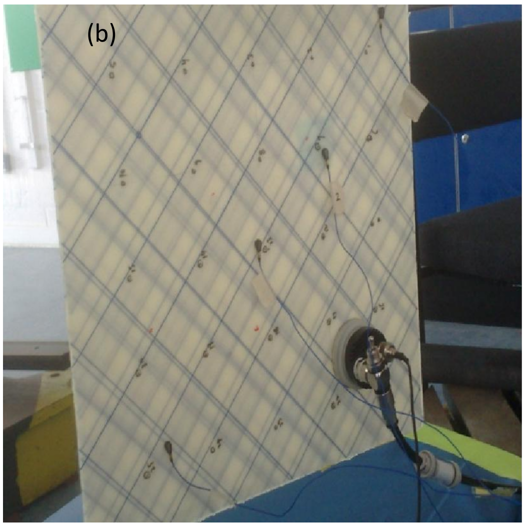


Fig. 6. (a) The experimental test setup, (b) Shaker mounting

The modal tests were conducted for both plates (healthy and delaminated) using the impulse-response modal test has been carried out using the instrumented hammer (Model 086C03, M/s PCB) to find out the natural frequencies. The modal tests were conducted when the shaker was mounted on the plate as shown in Figure 6(b).The measured data for both the tests were collected to the computer through an 8-channels 16-bit data acquisition card for the further analysis. 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 2.Theidentified natural frequencies for the delaminated plate are generally nearly close to the healthy plate as expected due to the small size of the delamination in the delaminated plate. However the experimental frequencies are slightly lower than the FE computed frequencies (Table 1) due to the mass of the shaker in the experimental cases except for Mode 1. Further investigation has been done to understand the reason for little higher value for Mode 1 in the experimental cases. The study by Lin HY et al. [21] has also observed the similar behavior and it was concluded that the experimental setup for the free boundary condition generally affect Mode 1 because the plate may not be realizing the free boundary condition. Hence, this could be the possible reason for the higher value at Mode 1 in the present experimental cases.

Table 2. Experimentally identified natural frequencies

Modes	Healthy Plate	Delaminated Plate
1	58.03 Hz	57.46 Hz
2	92.85 Hz	92.45 Hz
3	130.27 Hz	133.22 Hz
4	137.44 Hz	140.40 Hz
5	153.27 Hz	155.01 Hz
6	211.12 Hz	211.25 Hz
7	263.55 Hz	262.37 Hz
8	344.89 Hz	354.21 Hz

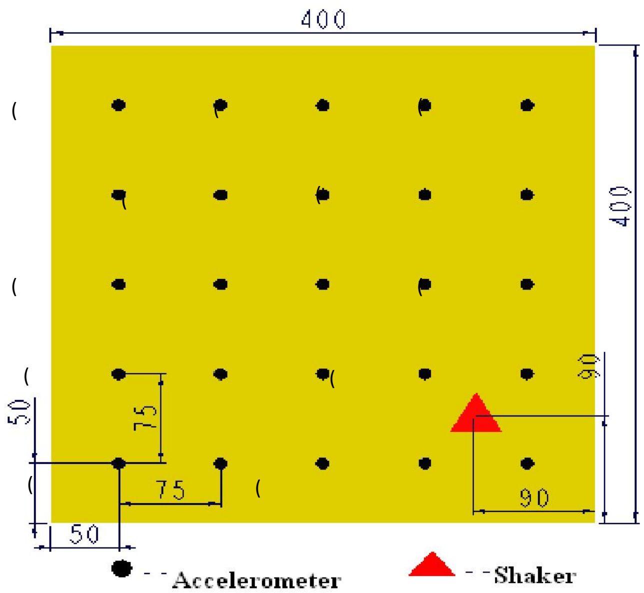


Fig. 7. Measurement locations (25 points in 5 x 5 equidistant grids) on the plate

Vibration experiments have also been conducted on the healthy and delaminated composite plates shown in Figure 6. 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 in absence of the laser vibrometer. The data were collected to the computer at the sampling frequency of 20 kHz for the further analysis. The acceleration signals were then analyzed to compute the velocity amplitude spectra for both the 2 cases. Few typical acceleration spectra for the healthy plate and the delaminated plate are shown in Figure 8 when excited at mode 6 at locations 9 and 20 (marked in Figure 7). 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. Once again, 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 nonlinear interactions between the delaminated layers in the plate 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 plate with delamination. The plots of the CNSH of the plate with and without delamination for the experimental cases are also shown in Figure 9 which, once again, provides excellent indication for the location of the delamination. Hence the experimental observations are consistent with the FE simulated results.

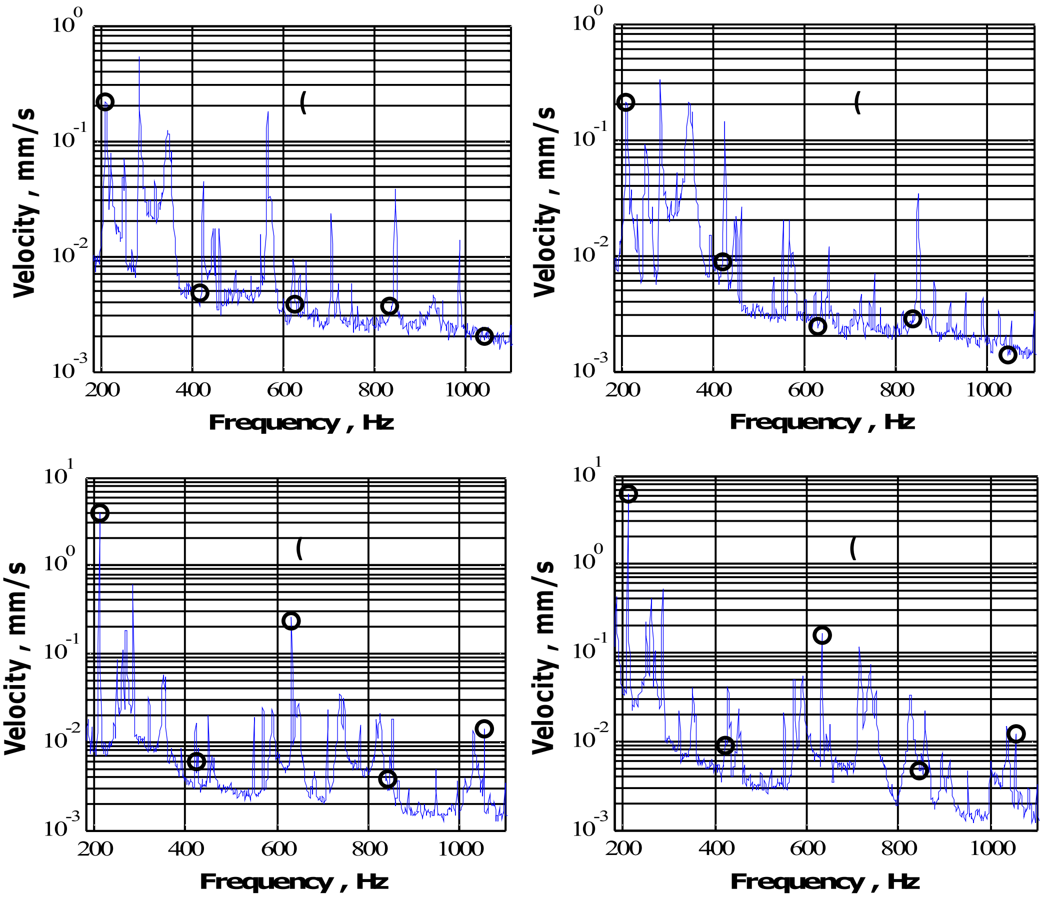


Fig. 8. Typical measured amplitude acceleration response spectra at locations 9, 20 for the healthy (a-b) and delaminated plates (c-d) when excited at Mode 6 respectively

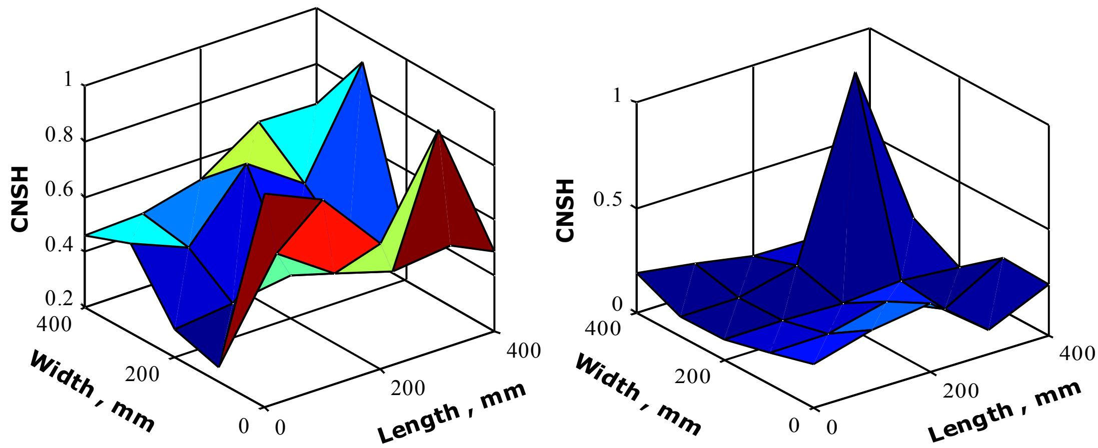


Fig. 9. Typical CNSH plots using Modes 1 to 6 for the experimental examples, (a) Healthy plate, (b) Delaminated plate

7 Conclusion

The nonlinear interaction between the delaminated layers in the composite plate during vibration has been considered here for the delamination detection. Initially, a typical composite plate made E-glass epoxy with and without delamination has been used in the FE simulation for the development of the detection method. As expected, the nonlinear interaction between the delaminated layers when excited at a few lower modes produced the prominent higher harmonics components of the exciting frequency. Then the normalized contribution of higher harmonic components at each mode has been defined as the "Normalized Summation of Harmonics (NSH)" and then it's cumulative for a few lower modes as CNSH. The delamination location has clearly been identified by the proposed CNSH method for the simulated examples. The method has then further been validated by the experiments conducted on the composite plates same as used in the FE simulations with and without delamination. Hence the proposed CNSH can be deemed as a good indicator for the delamination detection. 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.

References

[1] S. H. Diaz Valdes, and C. Soutis, "Delamination detection in composite laminates from variations of their modal characteristics," *Journal of Sound and Vibration*, vol. 228, no. 18, pp. 1-9, 1999.

[2] A. Paolozzi and I. Peroni, "Detection of Debonding Damage in a Composite Plate through Natural Frequency Variations," *Journal of Reinforced Plastics and Composites,* vol. 9, no. 4, pp. 369-389, 1990.

[3] H. Y. Kim and W. B. Hwang, "Effect of debonding on natural frequency response functions of honeycomb sandwich beams," *Composite Structures*, vol. 55, no. 1, pp. 51-62, 2002.

[4] P. Qiao, K. Lu, W. Lestari, and J. Wang, "Curvature mode shape-based damage detection in composite laminated plates," *Composite Structures*, vol. 80, no. 3, pp. 409-428, 2007.

[5] P. Kudela and W. Ostachowicz, "A Multilayer Delaminated Composite Beam and Plate Elements: Reflections of Lamb Waves at Delamination," *Mechanics of Advanced Materials and Structures*, vol. 16, no. 3, pp. 174-187, 2009.

[6] H. Y. Kim and W. B. Hwang, "Effect of debonding on natural frequency response functions of honeycomb sandwich beams," *Composite Structures*, vol. 55, no. 1, pp. 51-62, 2002.

[7] C. N. Della and D. Shu, "Vibration of beams with two overlapping delaminations in pre-buckled states," Composites Part B, vol. 38, no. 2, pp. 109-118, 2007.

[8] Z. Su and L. Ye, "Lamb wave-based quantitative identification of delamination in CF/EP composite structures using artificial neural algorithm," *Composite Structures*, vol. 66, no. 4, pp. 627-637, 2004.

[10] Z. Su, L. Ye, and Y. Lu, "Guided Lamb waves for identification of damage in composite structures: a review," *Journal of Sound and Vibration,* vol. 295, no. 3–5, pp. 753–780, 2006.

[11] H. Luo and S. Hanagud, "Dynamics of Delaminated Beams," *International Journal of Solids and Structures*, vol. 37, no. 10, pp. 1501-1519, 2000.

[12] N. Akhter, H.C. Jung, H. Chang, and K. Kim, "Location of delamination in laminated composite plates by pulsed laser holography," *Optics and Lasers in Engineering*, vol. 47, no. 5, pp. 584-588, 2009.

[13] T. Akira, T. Yuuki, and S. Yoshinobu, “Delamination monitoring of graphite/epoxy laminated composite plate of electric resistance change method,” *Composites Science and Technology*, vol. 62, no. 9, pp. 1151-1160, 2002.

[14] A. N. Amr and W. W. El-Dakhakhni, “Non-destructive evaluation of laminated composite plates using dielectrometry sensors,” *Smart Materials and Structures*, vol. 18, no. 5, 055014(8pp), 2009.

[15] H. Sohn, G. Park, J. R. Wait, N. P. Limback, and C. R. Farrar, “Wavelet-based active sensing for delamination detection in composite structures,” *Smart Materials Structures*, vol. 13, no. 1, pp. 153–160, 2004.

[16] H. W. Park, H. Sohn, K. H. Law, and C. R. Farrar, “Time reversal active sensing for health monitoring of a composite plate,” *Journal of Sound and Vibration*, vol. 302, no. 1-2, pp. 50-66, 2007.

[17] A. Ghoshal, A. Chattopadhyay, M. J. Schulz, R. Thornburgh, and K. Waldron, “Experimental investigation of damage detection in composite material structures using a laser vibrometer and piezoelectric actuators,” *Journal of Intelligent Material Systems and Structures*, , vol. 14, no. 8, pp. 521-537, 2003.

[18] S. Wildy, B. Cazzolato, and A. Kotousov, “Detection of Delamination Damage in a Composite Laminate Beam Utilizing the Principle of Strain Compatibility,” *Key Engineering Materials*, vol. 417-418, pp. 269-272, 2010.

[19] N. Akhter, H. C. Jung, H. Chang, and K. Kim, “Location of delamination in laminated composite plates by pulsed laser holography,” *Optics and Lasers in Engineering*, vol. 47, no. 5, pp. 584-588, 2009.

[20] A. N. Amr and W. W. El-Dakhakhni, “Non-destructive evaluation of laminated composite plates using dielectrometry sensors,” *Smart Materials and Structures*, vol. 18, no. 5, 055014(8pp), 2009.

[21] Lin HY, Huang JH, and Ma CC., “Vibration analysis of angle-ply laminated composite plates with an embedded piezoceramic layer,” *IEEE Trans Ultrason Ferroelectr Freq Control*., vol. 50, no. 9, pp. 1084-99, Sep 2003.

[22] U. Polimeo, M. Meo, and D. P. Almond, “Smart Nonlinear Acoustic Based Structural Health Monitoring System,” *Advances in Science and Technology*, vol. 56, pp. 426-434, 2008.

[23] M. Meo, U. Polimeo, and G. Zumpano, “Detecting Damage in Composite Material using Nonlinear Elastic Wave Spectroscopy Methods,” *Applied Composite Materials*, vol. 15, pp. 115-126, 2008.

[24] J. K. Sinha and M. I. Friswell, “Simulation of the Dynamic Response of a Cracked Beam,” *Computers and Structures*, vol. 80, no. 18, pp. 1473-1476, 2002.