IOP Conf. Series: Materials Science and Engineering **402** (2018) 012143 doi:10.1088/1757-899X/402/1/012143

Dynamic analysis for delamination detection in carbon fiber composite beam

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Abstract. Delaminations in the composite structure are the main causes of structural failure. It not only degrades the strength and durability of the composites but also makes it prone to failure. It also affects the vibration properties like natural frequency and mode shapes. Hence understanding the features of an undamaged and delaminated composite in a dynamic environment is very essential. There are various non-destructive testing methods like ultrasonic inspection, thermography, X-Ray Diffraction and X-Ray Radiography etc for determination of the defects in the composite structure which is time consuming and costly. This paper investigates the presence of delamination in sub-layer of carbon fiber reinforced composite through modeling and simulation. Vibration tests were performed initially to determine the natural frequencies and the damping rate of both undamaged and delaminated composites. The separate models for undamaged and delaminated composites were designed using ANSYS and a good agreement was found between the experimental and the numerical approaches. It is observed that due to the presence of delamination, the natural frequency decreases and the rate of damping increases as compared to an undamaged composite structure. Different mode shapes were also obtained to show the differences between undamaged and delaminated composites beams.

1. Introduction

Composites pocesses attractive properties like high strength to weight ratios, lightweight, low cost, fatigue life etc. which leads to its extensive use in different sectors like aerospace[1], automotive, defense, sporting goods, electronics and electrical, marine, biomedical industries and others [2-3]. Besides having diverse application, damages such as delamination, debonding, barely visible impact damage [4], matrix cracking, fiber breakage, voids, porosity etc. are inevitable during their manufacturing and service life. These damages degrade the strength and durability of the composites thereby making it prone to failure. Hence it is very much essential to understand the different damage prediction as well as on-line damage detection techniques of composite with the advancement of different technologies.

Delamination is nothing but the separation between individual plies of the laminate which comes into picture during any kind of manufacturing processes or bird strike or low-velocity impact. It often leads to a reduction in stiffness and structural damage of composite structures. The transfer of stress between the plies is also prevented due to the presence of this delamination [5]. Due to delamination, stiffness is reduced due to which natural frequency is reduced which can even lead to resonance condition [6]. Sometimes it may affect the different vibration properties like mode shapes and natural frequency. Hence it is very much essential to understand the features of an undamaged and delaminated composite in a dynamic environment.

Various nondestructive tests (NDT) have been carried out for the diagnostic monitoring of composites like X-ray Radiography, Ultrasonic Testing, X-ray Diffraction, IR Thermography etc. W. Swiderski [7] has used X-ray tomography to determine the depth of delamination in the carbon fiber reinforced composite. Infrared thermography technique was used by W. Harizi et al. [8] to determine a defect in the glass fiber reinforced polymer during tensile loading. Image reconstruction method is used by Mengchum Pan et al. [9] in pulse eddy current thermography to increase the sensitivity to detect a crack in metal alloy and carbon fiber reinforcement. Zhinua Ning et al. [10] suggested that thermal resistance increases in unidirectional carbon fiber reinforced due to presence of delamination. Vladimir P. Vavilov [11] had used thermal/infrared test to determine the defect by impact in carbon fiber reinforcement. Junliang Dong et al. [12] used terahertz imaging and ultrasonic C-scans for determining the delamination in glass fiber reinforced composite. Heating assisted eddy current test was conducted by Koichi Muzikami et al. [13] to detect the delamination in carbon fiber reinforcement.

Several contributions have already been made by different authors [14] from time to time for experimental and numerical investigations for the behavior of damaged multilayer composite structures. Narra Sowjanya and Mulluri Haritha [15] studied structural and vibration investigation of delaminated composite beams where analysis was done by varying the delamination length. The delamination effect on the modal parameters of different laminates is being presented by Christian N. Della and Dongwei Shu [16]. Comparison of different NDT methods on detection of delaminations with varied diameters and depths in composites was studied by Liang Cheng and Gui Yun Tian[17]. Some researchers have also investigated the application of high-frequency waves in damage detection of laminated aero-structures [18].

The use of vibration characteristics in structural damage detection has been studied by several researchers [19]. However most of the papers are based on the stress and strain analysis part. Hypothesizes for an optimized mathematical model to deal with fracture study of composite structures is still a matter of great challenge for the research community. In this paper, the dynamic analysis of delaminated carbon fiber composite and composite without any damage has been studied. The natural frequencies and damping rate in the delaminated and undamaged composite beams have been found experimentally. Various Non-destructive Testing methods were carried out in order to find out the presence of delamination zone within the delaminated composite beam.

2. Material

The beam is made of a commercially available carbon/epoxy material with a $[0^o]_8$ stacking sequence. It is composed of eight layers each of 0.275mm thick. It has a mass of 0.336 kg and a density of 1.696 X 10^{-6} Kg/mm³. The specimen had a dimension of 300mm X 30 mm X 2.2mm. The different mechanical properties of carbon fibre composite taken are given below as:-

Young's modulus X direction (E_1) = 140GPa, Young's modulus Y direction (E_2) = 140Gpa, Young's modulus Z direction (E_3) = 4.8Gpa, Shear modulus XY (G_{12}) = 7.1Gpa, Shear modulus YZ (G_{13}) = 2.55Gpa, Shear modulus XZ (G_{23}) = 4.8Gpa, Poisson's ratio XY (γ_{12}) = 0.3, Poisson's ratio YZ (γ_{13}) = 0.41, Poisson's ratio XZ (γ_{23}) = 0.3. Geometry of the delaminated specimen is same as the undamaged specimen. Delamination is provided between layer 4 and 5 with the delaminated area ranging between 30mm to 105mm and 215mm to 255mm.

3. Theoretical method

The Euler's Bernoulli beam equations for undamaged carbon fiber beam are used to determine the modes of vibration as given below:

For mode 1: $$\omega_{nf1} = 1.875^2 \sqrt{\frac{Eh^2}{12\rho L^4}} \quad (1)$$

For mode 2: $$\omega_{nf2} = 4.694^2 \sqrt{\frac{Eh^2}{12\rho L^4}} \quad (2)$$

For mode 3: $$\omega_{nf3} = 7.855^2 \sqrt{\frac{Eh^2}{12\rho L^4}} \quad (3)$$

Where ω_{nf1}, ω_{nf2}, ω_{nf3} are the corresponding modes of natural frequency (rad/s) for mode 1, mode 2 and mode 3 respectively.

E = Young's Modulus of elasticity, h = Thickness of specimen, ρ = Density of the specimen

L = Length of the specimen, ω_{nf1}= 1/2π fn_1.

Using above equations natural frequencies for three mode shapes are obtained as given below:
For mode 1 fn_1 = 42.691Hz, for mode 2 fn_2 = 267.561Hz, for mode 3 fn_3 = 749.256Hz.

4. Tap Test

This setup involved use of a clamp (to fix the composite beam as a cantilever), accelerometer, connecting cables, accelerometer data reader and a laptop as shown in Figure.1. The one end of specimen was fixed as a cantilever beam on to the clamp, keeping a length of 275mm of the beam free to hang. An accelerometer was mounted at the end of the fixed end and free end to obtain natural frequency and damping factor respectively. The accelerometer data reader collects vibration acceleration data and shows it in the software. In this test, the cantilever beam was given a downward displacement of 20mm and released such that it vibrates freely and get damped on its own. The corresponding vibration data was taken from the software in the laptop. Readings were taken out using delaminated composite beam and undamaged composite beam.

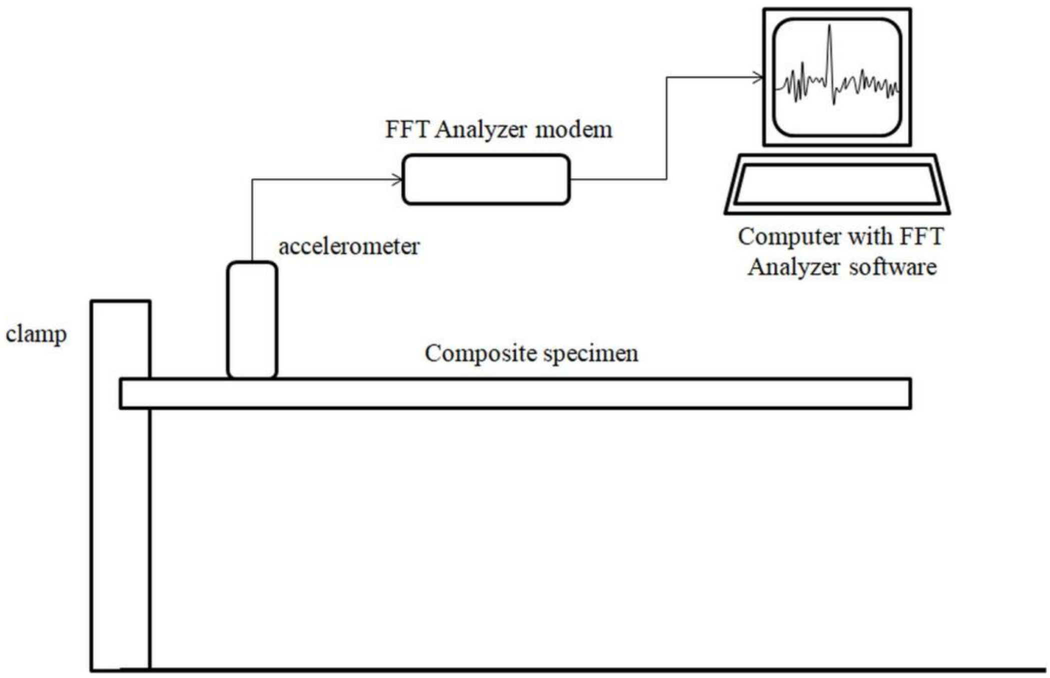


Figure 1. Setup for Tap Test

5. Numerical analysis

ANSYS is used to determine the natural frequency and mode shapes of both delaminated and undamaged carbon fiber reinforcement specimens. ANSYS Composite Pre-Post is used to model the specimens. A material property of carbon fiber reinforcement is given and then geometry is created for the undamaged specimen of dimension 275mm × 30mm. The geometry of the delaminated specimen is same as the undamaged specimen with the delaminated area ranging from 30mm to 105mm and 215mm to 255mm. Carbon fiber reinforced laminate is composed of 8 layers each of 0.275mm thick and delamination is provided between layer 4 and 5. Figure 2 shows the model of delaminated carbon fiber reinforcement. In order to obtain different modal parameters like natural frequencies and mode shapes, modal analysis is carried out.

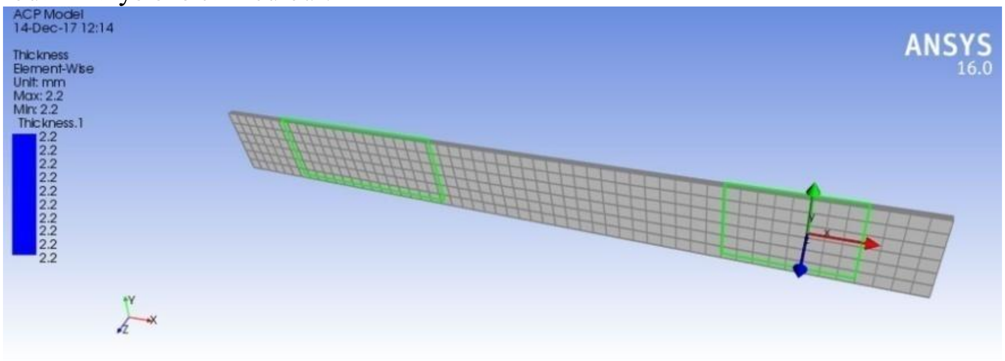


Figure 2. Carbon fiber reinforce specimen with delamination

6. RESULTS & ANALYSIS

The analysis of free vibration of delaminated and undamaged carbon fiber composite beam has been discussed. Figure 3 shows the variation of rate of damping in case of delaminated carbon fiber composite and undamaged carbon fiber composite. It is observed that due to the presence of delamination time required to damp the vibration is less in compared to the undamaged beam. However delaminated beam has good damping capacity due to the dissipation of energy caused due to frictional contact.

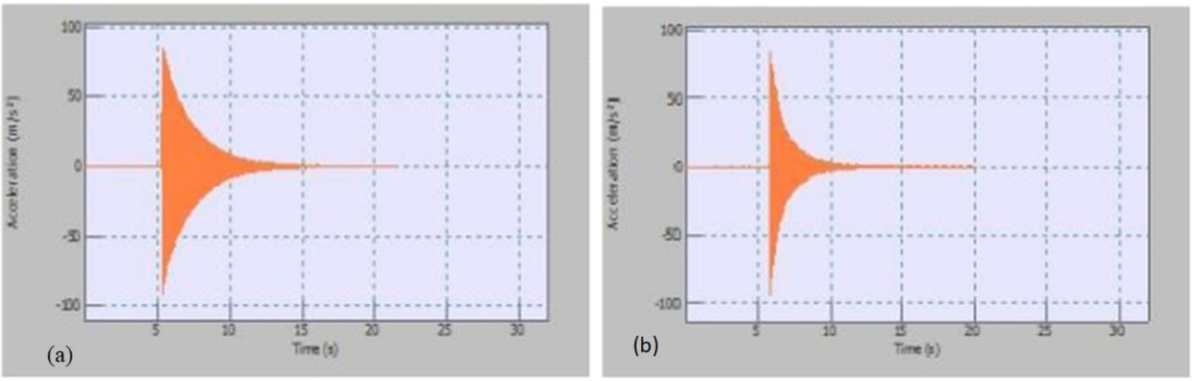


Figure 3. Time vs. Acceleration graph for Carbon Fiber Composite (a) without damage (b) with damage

Table 1 shows the comparison between mode shapes of undamaged and delaminated carbon fiber reinforced beam. It is observed that mode 1 is less sensitive to the presence of delamination in comparison to mode 2 and mode 3. From previous literature it was observed that more is the delamination closer to the surface, the variation in the mode shape was visible [20]. But as the delamination is present in the middle layer in our present study, the variation is very minute.

Table 2 shows the natural frequency of mode 1, mode 2, and mode 3 of the undamaged and delaminated beam as obtained from the theoretical, experimental and numerical methods. The above result clearly indicates that the natural frequency is less in the delaminated beam as compared to the undamaged beam. It is also observed that there exists some change in natural frequency for mode 2 and mode 3 respectively. Hence it can be inferred that the strength of delaminated beam is less due to lesser natural frequency.

Table 1. Comparison of Mode shapes of undamaged and delaminated carbon fiber reinforcement

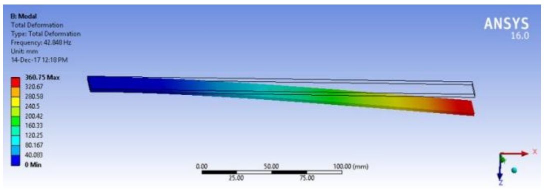
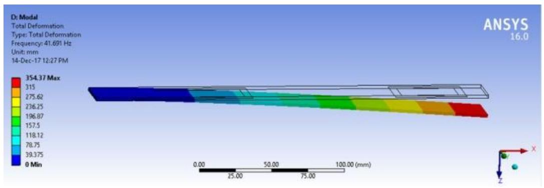
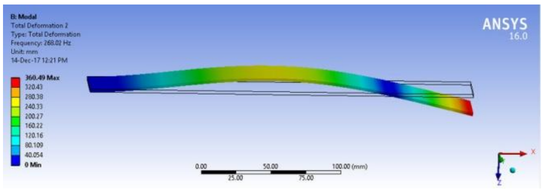
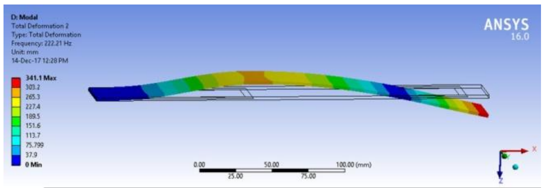
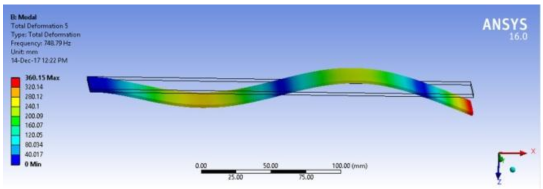
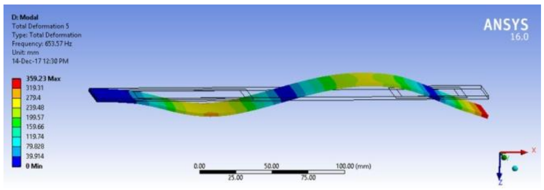
Mode Shapes	Undamaged composite beam	Delaminated composite beam
Mode 1		
Mode 2		
Mode 3		

Table 2. Comparison of Theoretical, Experimental and Numerical results

Modes	Undamaged			Delaminated	
	Theoretical	Experimental	Numerical (ANSYS)	Experimental	Numerical (ANSYS)
Mode 1	42.691 Hz	42.62 Hz	42.848 Hz	41.406 Hz	41.691 Hz
Mode 2	267.561 Hz	265.32Hz	268.02 Hz	262.89Hz	222.21 Hz
Mode 3	749.256 Hz	740.85Hz	748.79 Hz	715.90Hz	653.57 Hz

7. Conclusions

The following conclusions are obtained from the present study:

- Due to the presence of delamination, the natural frequency decreases and the rate of damping increases in a delaminated carbon fiber composite as compared to an undamaged composite structure.

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- As the natural frequency of the structure decreases due to the presence of delamination, the stiffness of the structure decreases and hence failure occurs earlier in the delaminated beam as compared to the other undamaged beam during loading.
- The presence of delamination in a composite material is mostly thought as a negative feature. But, there are also applications where the presence of delamination is an advantage because the vibrations in a delaminated composite structure get damped faster as compared to an undamaged composite structure. Hence, it can be used in the places where vibration damping is required without using any extra damping material.

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