

Defect detection by frequency analysis of flexural vibrations of free-free composite beam

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Abstract: This paper presents experimental investigations using a vibration method by impulse excitation of free flexural oscillations of composite beams. The purpose of the study is to establish the sensitivity of the method and technique used for defect detection and localization. To realize the objective, rectangular groove type defects were simulated at different distances and depths. The influence of the location and depth of the artificial cracks on the dynamic properties of the beams was investigated. The resonance frequencies were determined by frequency analysis. A decrease in the resonant frequencies of the flexural oscillations is observed. The experiments conducted show a change in the dynamic characteristics of the beam depending on the dimensions and location of the defects.

Keywords: IMPULSE EXCITATION, FREE FLEXURAL OSCILLATIONS, COMPOSITE BEAMS, RECTANGULAR GROOVE TYPE DEFECTS, FREQUENCY ANALYSIS

1. Introduction

The frequency method is one of the most common methods for detecting delamination and cracks in composite structures by determining the modal shapes and natural frequencies of the structures [1,2,3, 4]. Frequency analysis of composite materials with defects has been developed by researchers [7,8, 9,10] who concluded that the natural frequency of the beam changes in the presence of a defect. Experimental and simulation studies to determine the frequency characteristics and dynamic behavior of composites are published [10,11,12]. The effects of fiber orientation, fiber types, measurement methods, and matrix materials on the dynamic properties of composites were investigated in [6,12]. Frequency analysis of composite plates were conducted by [10,12,13].

From the literature studied, it is seen that a reliable indicator for the detection of defects or damage obtained in service is the change in resonant frequencies. However, unlike modal shape based methods, identification of the location of the damage is not easily achieved when using frequency measurements. Many authors have also studied different types of cracks [13,14]. Important factors influencing fracture behavior and mechanisms are fracture depth and length [2,15].

Pulsed free oscillation excitation is a popular technique for diagnosis of various materials. The earliest research on the subject analysed fundamental frequencies; however, due to measurement errors and noise, natural frequencies in such mode shapes are not sensitive to structural damage [4, 9]. Other approaches have been developed to detect and monitor cracks and damage in various structures – for example, crack growth detection by ultrasonic methods [16].

The presence of a defect leads to a local reduction in the stiffness of the structures, resulting in changes in the dynamic properties, alteration of the natural frequencies, modal shapes and an increase in the damping decrement.

In this work, the applicability of free-bending oscillation methods for the identification of rectangular channel type cracks is investigated. The parameter used to identify the cracks is the natural frequency. The influence of the location and depth of artificial cracks on the dynamic characteristics of composite beams is investigated.

2. Materials and Experimental Procedures

2.1 Materials

A sheet of epoxy fiberglass with a thickness of five millimeters was selected for the study. The plate was fabricated by hot pressing layers of glass fabric impregnated with thermosetting phenolic and epoxy resins. A sufficient number of beam-type specimens were cut from the composite slab with dimensions $L=0.25\text{m}$ length, $b=0.025\text{m}$ width and $h=0.005\text{m}$ thickness. The threads of the glass

fabric are parallel and respectively perpendicular to the x-axis /fig.1/.



Fig. 1. Specimen with an artificial rectangular channel type crack

To establish the sensitivity of the pulsed excitation vibration method for defect detection, rectangular groove type defects were simulated at different distances from the edge of the specimens (x_i), namely on $0.1L$ and $0.2L$. The dimensionless parameter is used when presenting the results x_i/L . The slits are transverse, arranged perpendicular to the stacked layers of glass fabric. The simulated rectangular channels have different depths $a=0.2h$ and $a=0.4h$. A schematic of the specimens with the artificial defects is given in Fig. 1. A sufficient number of specimens were made and examined to investigate the location of the artificial defects at a fixed defect depth.

2.2 Free Vibration Impact Test

According to the Euler-Bernoulli theory, in flexural transverse vibrations of a beam of constant cross section and thickness, there are innumerable many natural frequencies, which are determined by the dependence:

$$\omega_n = \frac{\pi^2 n^2}{l^2} \sqrt{\frac{E J_y(z)}{\rho A}}$$

Where A is the cross section of the beam, $J_{y(z)}$ is the moment of inertia, a characteristic of the cross section, ρ - the density of the material, E is the modulus of elasticity of the composite material. For $n=1,2,3,4\dots$ the natural frequencies depend on the initial conditions, i.e. the way the oscillations are excited, as well as on the boundary conditions. At $n=1$ the beam bends one half wave, at $n=2$ there are 2 half waves and so on. The forms of bending oscillations of a beam with free ends are shown in Fig. 2.

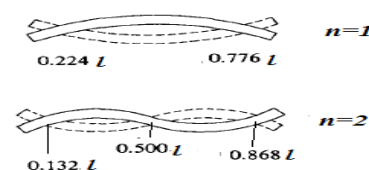


Fig. 2. Shapes of bending oscillations of a beam with free ends

For the fundamental frequency realization at first mode ($n=1$), the fixed points are at a distance of 0.224 from the ends of the beam. Initially, the fundamental resonant frequency ($n = 1$) was calculated by the relation:

$$f = \sqrt{\frac{\pi^2 J_y E}{4 \cdot \rho \cdot A \cdot l^4}}$$

The area of cross-section A is $1,25 \cdot 10^{-4} \text{ m}^2$. The moment of inertia is $J_y = 2,60417 \cdot 10^{-10} \text{ m}^4$. The density is $\rho = 1820 \text{ kg/m}^3$, and the modulus of elasticity E is $20 \cdot 10^9 \text{ Pa}$

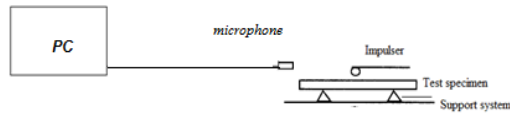


Fig.3. Schematic of experimental setup for the free vibration impact test

A pulse excitation in the middle of the specimen was used to excite transverse bending oscillations in the specimen using a rubber mallet. A Superlux ECM-999 type microphone located at the top of the specimen was used to record the mechanical oscillations. A computer, PC USB 16-bit two-channel sound card 20~20kHz, data logger -Real Time Acoustic Analyzer is used for registration, recording and subsequent signal processing.

The beam was suspended horizontally on elastic rubber strands at two points located at a distance of 0.224 of the length from each end, which are the nodal points for the first mode of flexural oscillations.

To realize "out of plane" bending, in which the direction of displacement is perpendicular to the large plane of the specimen, the diagram in fig. 4a. To excite in-plane oscillations, the scheme given in Figure 4b is used. The microphone is placed close to the specimen above the anti-node point. The specimen is lightly struck in the centre of the specimen. The test is recorded and repeated five times. Five readings of the resonant frequency shall be recorded and the average value taken.

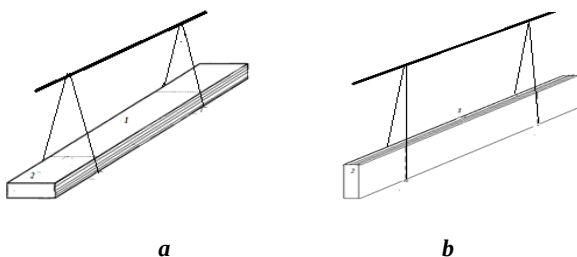


Fig.4. Schematic representation of the beam attachment under excitation of free flexural vibration. a: out of plane flexure; b: in-plane flexure; 1 - impulse point; 2 - microphone point

3. Results and discussion

The test procedure was repeated for different beams made of the same material and geometry, but with different notch locations. The signal obtained from the defective and nondefective beams are compared both in time and spectrum. The natural frequencies and their corresponding amplitudes for the excited first mode of the bending oscillations were obtained.

In Fig. 5 initial results are given for the study of beams bending oscillations out of plane for healthy beams and beams with a defect at distance $x=0.1 L$. It can be noticed that the presence of a defect leads to a decrease in the natural frequencies of the beams, but this change is negligible.

The offset of the resonant frequency in the presence of a defect is noted by the parameter Δf :

$$\Delta f = \frac{f_{1,0} - f_{1,d}}{f_{1,0}}$$

Where $f_{1,0}$ is the first natural frequency of a healthy beam under excitation of flexural oscillations, and $f_{1,d}$ is the natural frequency of a beam with a crack.

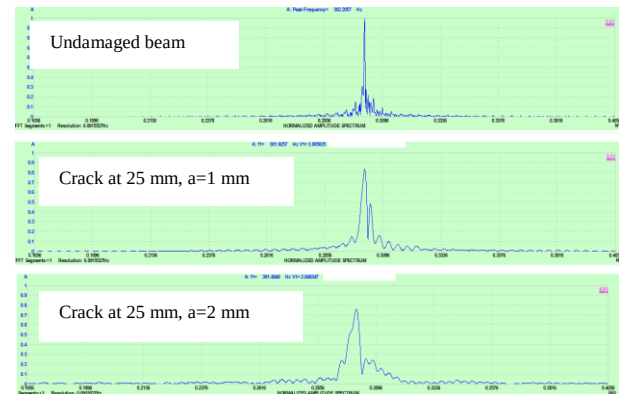
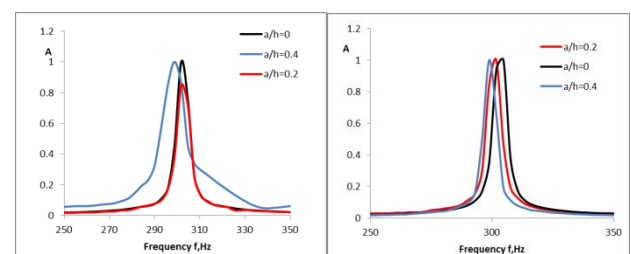


Fig.5. Initial results of the experimental modal analysis of a composite beam with a rectangular channel type crack located at a distance $x=0.1 L$ from the beam origin. /Out of plane vibrations/

From the results given in Table 1, columns 5, 6 and 7, 8 respectively, the effect of defects on the values of resonant frequencies of out of plane oscillations and in plane oscillations respectively is observed.

Table 1: Table 1. Results of the experiments for out of plane and in-plane flexure

N	Description	x/L	a/h	1 st mode Natural frequency, Hz	$\Delta f, \%$	1 st mode Natural frequency, Hz	$\Delta f, \%$
				Out of plane flexure		In plane flexure	
1	Undamaged beam	0	0	302.33	0	1443	0
2	defect 0,1 L to the left	0.1	0.2	301.67	-0.2	1440.8	-0.15
3	defect at 0,1 L to the left	0.1	0.4	301.45	-0.3	1447	-0.98
5	without defect	0	0	304.688	0	1426.7	0
6	defect 0,2 L to the left	0.2	0.2	301.44	-1.1	1422.5	-0.28
7	defect 0,2 L to the left	0.2	0.4	299.67	-1.7	1420.7	-0.41



Fast Fourier Transform of the vibration signals for undamaged beams a damaged with notches

Fig.6. $x=0.1L$ with depths $a=0.2h, a=0.4h$ Fig.7. $x=0.2L$ with depths $a=0.2h, a=0.4h$

For out of plane oscillations, as the distance to the defect increases, i.e., as the parameter x/L is varied by 0.1 and 0.2 for

crack depth $a=0.2h$, a relative decrease in natural frequency by 0.2% and 1.1%, respectively, is observed. When increasing the depth $a=0.4h$, the resonant frequency is reduced to 1.7%. The Fourier spectra of the signals from the investigated beams are given in Figure 6 and Figure 7.

Changes of resonance frequencies in in-plane vibrations in the presence of defects are less than 1% and therefore are not presented graphically. In the process, it was found that the suspension location of the specimens had no noticeable effect due to the large difference between the elastic moduli of the specimens and the suspension strands being on the order of $20 \cdot 10^3$.

3. Conclusion

In this work, the capabilities of the vibration method and the available technique implementation of the method for the identification of defects in epoxy fiberglass composite beams have been investigated and verified. The influence of the ratio of the location of the notches to the length of the beam, as well as the ratio of the splitting of the crack to the thickness of the beam has been investigated. The results show a variation of the dynamic characteristics of the composite beams depending on the dimensions and location of the defects.

Further research is to be carried out to quantify the defect location and the variation of resonance frequencies; and to investigate other types of defects; the anisotropy caused by the location of glass layers in composite beams.

The results obtained do not give any real possibilities for direct practical application of the methodology used. For practical application and realization it is necessary to investigate and systematize the influence of defects on the dynamic properties of beams under excitation of different modes of oscillations.

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References

1. N. Maia et al. Damage detection in structures: From mode shape to frequency response function methods. *MSSP* **17**(3): 489-498 (2003).
2. E. Manoach et al. Vibration based damage detection in composite beams under temperature variations using Poincaré maps. *IJMS*, **62**(1): 120-132(2012).
3. E. Manoach et al. Vibration Based Methods For Damage Detection In Structures. *MATEC Web Conf.* **83** (2016).
4. A. Mohan, S. Poobal. Crack detection using image processing: A critical review and analysis. *Alex. Eng. J.* **57**(2): 787-798(2018).
5. E. Moustafa. Dynamic Characteristics Study for Surface Composite of AMMNCs Matrix Fabricated by Friction Stir Process. *Materials (Basel)* **11**(7) (2018).
6. M. Aydın et al. Effect of Orientation Angles on Vibration Properties at Carbon Fiber Reinforced Polymeric Composites. *E-Journal of New World Sciences Academy* **13**(3): 180-189(2018).
7. S. Iliopoulos et al. Detection and evaluation of cracks in the concrete buffer of the Belgian Nuclear Waste container using combined NDT techniques. *Constr Build Mater.* **78**: 369-378(2015).
8. D. Ngo-Cong, et al. Free vibration analysis of laminated composite plates based on FSDT using one-dimensional IRBFN method. *Comput Struct* **89**(1): 1-13(2011).
9. G. Pereira et al. Crack Detection in Fibre Reinforced Plastic Structures Using Embedded Fibre Bragg Grating Sensors: Theory, Model Development and Experimental Validation. *PloS one* **10** (10): e0141495-e0141495(2015).
10. H. Hu et al. Damage detection of surface cracks in composite laminates using modal analysis and strain energy method. *Compos. Struct.* **74**(4): 399-405 (2006).
11. C. Della and D. Shu. Free vibration analysis of composite beams with overlapping delaminations. *Eur J Mech A Solids* **24**(3): 491-503 (2005).
12. E. Moustafa et al. Detecting Damage in Carbon Fibre Composites using Numerical Analysis and Vibration Measurements, *Lat. Am. J. Solids Struct.* **18**(3), e362. (2021)
13. C. Kyriazoglou et al. Vibration damping for crack detection in composite laminates. *Compos. - A: Appl. Sci. Manuf.* **35**(7): 945-953 (2004).
14. J. Yu et al. Studies on Crack Propagation of Carbon Fiber Reinforced Epoxy Resin Composite. *Adv. Mater. Res.* **79-82**: 1029-1033(2009).
15. F. Iezzi, et al. Experimental Validation of Damage Indices Based on Complex Modes for Damage Detection in Vibrating Structures. *Proceedings of the 13th International Conference on Damage Assessment of Structures, Singapore, Springer Singapore* (2020).
16. J. Wen et al. Damage detection of carbon fiber reinforced polymer composites via electrical resistance measurement. *Compos. B. Eng.* **42**(1): 77-86 (2011).