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Detection of delamination in composite beams using frequency deviations due to concentrated mass loading

Chen Yang, S. Olutunde Oyadiji *

School of Mechanical, Aerospace and Civil Engineering, The University of Manchester, M13 9PL, UK

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ABSTRACT

Modern composite structures are usually designed to withstand mass loading. The effects of delamination due to concentrated mass loading with respect to modal frequency variations in composite beams have been investigated in the present work numerically and experimentally. A noticeable delamination-induced modal frequency deviation has been observed when a concentrated mass loading is imposed at pre-defined sections of the delaminated composite beams compared to the intact (reference) composite beams. For delaminations of only 10% of the length of a composite beam, modal frequency deviations of about 20% were observed numerically and experimentally. Further investigations of different delamination configurations show that the modal frequency deviations are dependent on the longitudinal location as well as the interlayer positions of the defects. Higher frequency deviations are observed when delamination approaches the clamped boundary of a composite beam. The results suggest that the frequency curve deviations have a local or global characteristic depending on whether the delamination occurs at the near surface or the mid-plane of the composite beam, respectively. Consequently, the frequency curves can be employed as NDT tool for delamination identification and localisation.

1. Introduction

The use of fibre reinforced polymers (FRPs) in mechanical and civil engineering has increased dramatically in the last few decades. Besides the high stiffness to mass ratio in FRPs, the flexibility in the combination of fibre and matrix materials offers performance enhancement in design. The above advantages enable FRPs to be used as weight bearing components in modern engineering structures. However, the performance of the composite can be affected by certain types of defects such as matrix cracks and delaminations in service duration [1]. Delamination, which is one of the most important and unique failure modes in FRPs, has received increasing attention in the drive to understand its causes and induced effects through material analysis [2,3].

From the perspective of structural dynamics, one of the well-known delamination-induced effects is the modal frequency shifting due to the modal stiffness reduction [4]. Therefore, the study of frequency variation due to defects has shown the need for design tolerance estimation as well as structural health monitoring [5]. The effects of frequency decreasing and modal damping increasing due to interlaminate delamination in graphite/epoxy composites have been experimentally investigated by Lai and Young [6]. As suggested by the authors, impulse response testing can be used as a simple approach in vibration analysis for composite structures in intact and damage states. In addition to the delamination parameters such as the length and the location, the influences of modal frequency shift with respect to the different boundary conditions have been reported by Gadelrab [7]. The above studies have been extended to higher frequency vibration conditions and the frequency variation at low and high vibration modes has been compared in [8].

The frequency variation between intact and damage state also enables the study the potential damage in composite laminate structures, such as delamination, using various inverse algorithms. The use of modern signal processing methods, such as surrogate-assisted optimization, artificial neutral network (ANN) and empirical mode decomposition (EMD) in for delaminated beams has been reported in literature [9]. Recently, the relationships between the notch size and width with respect to the variation of the frequency response function envelopes have been analysed in [9–11]. Yang et al. [12] studied the frequency and damping variations in damaged laminate structures for symmetrical and anti-symmetrical flexural modes. Although it has been demonstrated

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* Corresponding author. Tel.: +44 161 275 4348; fax: +44 161 275 3844.
E-mail address: s.o.oyadiji@manchester.ac.uk (S.O. Oyadiji).

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that several modal parameters are influenced by the delamination in composites structures, frequency measurement has a higher degree of robustness than the other parameters, such as mode shapes and damping ratio in real application, as suggested in [13–15]. In addition, the frequency measurement can be achieved by few sensor points which is more cost-effective compared to parameters such as displacement mode shapes.

From the previous studies, the modal parameter variation due to delamination is generally studied for the condition without additional mass loading. Since composites laminate structures may be subjected to mass loading in applications. The understanding of the dynamic characteristics of composites laminate structures under such loading condition, especially in damaged states is important for design safety. Zhong and Oyadiji [16,17] investigated the effect of frequency variation for a cracked beam under concentrated mass loading imposed at different locations. An abnormal frequency variation has been found around the crack locations. This defect-dependent frequency variation has also been observed experimentally recently in a plate and a cylinder with pre-defined notch defect by Zhang et al. [18,19]. The focus of the current work is on the investigation of the variation of the dynamic characteristics of delaminated composite structures using concentrated mass loading.

In this paper, the effect of delamination at various axial locations and layer interfaces with respect to modal frequency variations under mass loading is studied using glass/epoxy beam samples. As the mass loading can be imposed at various locations, the dynamic responses of delaminated composite beams with mass loading at several axial locations are analysed. To simplify the study, the locations of the mass loading have been constrained to the centre lines of the beams. Therefore, only the flexural modes are investigated. Six defected samples and one intact sample are manufactured to study the effect using experimental modal testing. Finite element models are employed to study the frequency deviations due to delamination and mass loading under noise-free condition. Experimental modal testing is performed for each simulated cases to prove the integrity of the results. The deviations of the modal frequencies of intact and damaged composite beam samples are derived to quantify the effects of delamination for different defect configurations.

2. Material and method

2.1. Sample preparation and testing

The tested beams are made by the six-layer (0/+45/−45/−45/+45/0) glass fibre lamina with epoxy resin through the vacuum infusion technique. The delamination is fabricated in two steps. First, a single layer of Teflon sheet is placed at the pre-defined location and interlaminates position during layup to form a weak bond after curing. Second, a thin (0.05 mm) metal shim is used to separate the two layers at the defined delaminated section to form the delamination. The dimensions as well as the delamination cases are given in Fig. 1. The finished samples are 550 × 100 × 4 (mm) in each dimensions. The effective working length is 500 mm with 25 mm are clamped at the supports. Delamination at three different axial locations are included. For defect at each axial location, one near surface (between top and bottom layers) case and one mid-plane delamination case are studied separately.

Fig. 2(a)–(d) present the tensile and twist tests according to the standard [20,21]. Uniaxial tensile tests along primary and secondary directions are performed to obtain the Elastic modules along the primary (E_{11}) and the secondary directions (E_{22}). The Poisson ratio v_{12} is deduced from the ratio of elongation in uniaxial tension test between primary and secondary direction. The Poisson ratio v_{13} is assumed to be equal to v_{12} based on the transversely isotropic material assumption. The shear module G_{12} is tested from two-point plate twist test shown in Fig. 2(d). In addition, shear modules G_{13} and G_{23} is assumed to be equal to G_{12}. The Poisson ratio v_{23} is estimated from shear module G_{23}. The input material properties in finite element modelling are presented in Table 1.

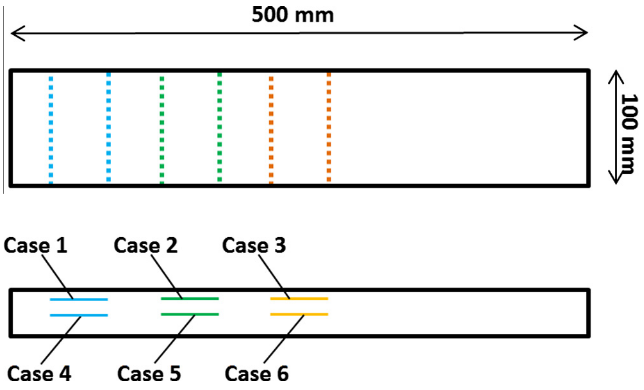

Fig. 1. Drawing of sample showing geometrical dimensions and locations of the delaminations for the six cases.

2.2. Finite element modelling

The finite element software package ABAQUS v6.13 has been used to generate the original modal frequency data for analysis. The material property of the composite beam in the numerical modelling is given in the above table. Fig. 3(a) and (b) present the mesh condition of the simulated sample with a pre-defined delamination at central location. The simulated structure contains 40 × 8 × 6 elements along the length, width and thickness directions. The element shows an aspect ratio equal to one. To reduce the locking effect in linear element for bending modes, the three dimension solid quadratic hexahedral elements (C3D20R) are employed in the analysis. Delamination is simulated using parallel unconnected surface at pre-defined section and is equivalent to a zero-volume void. The concentrated mass loading is modelled as a 1D point-like element with a constant mass magnitude around 0.1 kg. For each delamination case, 21 points of concentrated mass loading along the central line with same adjacent distance are analysed. The models are created by input file to maintain accurate positions of delamination and concentrated mass loading.

2.3. Experimental modal testing

Fig. 4 shows the experimental setup and data acquisition system. The effective length, width and thickness of the samples are the same as given in Fig. 1. For local mass at each location, impulse response method using an impact hammer (PCB 086C03) is employed in vibration testing to minimise external contact effect of the exciter on the structure. A mass of 0.1 kg is used to simulate the point-mass loading in the experiment. In order to reduce the effect of other mass loading, a low mass (0.5 g) accelerometer (PCB 352C22) is fixed to the central line of the structure to measure the bending modes of the response. The mounting of both the mass and the accelerometer are achieved by using adhesive petro wax (PCB 080A109).

The experimental data acquisition is achieved by using LMS Test.Lab system. Frequency span is set up to 0–500 Hz through the entire test and frequency resolution in Fast Fourier Transform (FFT) has been set to 0.3 Hz. The frequency response function is measured using H2 estimator in the LMS Test.Lab system. Frequency responses functions are measured at a total of 21 points along the length direction with uniform interspacing. The modal