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A probabilistic approach for quantitative identification of multiple delaminations in laminated composite beams using guided waves

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ABSTRACT

In this study a probabilistic approach is proposed to identify multiple delaminations in laminated composite beams using guided waves. The proposed method is a model-based approach, which provides a quantitative identification of the delaminations. This study puts forward a practical damage identification method, and hence, it can identify multiple delaminations using guided wave signal measured at a single measurement point on the laminated composite beams. The proposed method first determines the number of delaminations using Bayesian model class selection method. The Bayesian statistical framework is then employed to not only identify the delamination locations, lengths and through-thickness locations, but also quantify the associated uncertainties, which provides valuable information for engineers in making decision on necessary remedial work. In addition the proposed method employs the time-domain spectral finite element method and Bayesian updating with Subset simulation to further improve the computational efficiency. The proposed probabilistic approach is verified and demonstrated using data obtained from numerical simulations, which consider both measurement noise and modeling error, and experimental data. The results show that the proposed method can accurately determine the number of delaminations, and the identified delamination locations, lengths and through-thickness locations are closed to the true values.

1. Introduction

1.1. Composite and non-destructive evaluation techniques

Laminated composite materials have been extensively used in many engineering applications, such as aerospace, mechanical and automotive engineering, due to their high strength, anti-corrosion and lightweight characteristics. Common defects occur in the laminated composite materials are fibre breaking, matrix cracking and delamination [1]. In particular the delamination could cause significant reduction in the stiffness and strength of structures and leads to structural failure. Detecting and identifying the delamination before structural failure are essential in improving the safety, durability and serviceability of the structures made by laminated composite materials.

Delamination is a separation of adjacent sub-surface laminae without any obvious visual evidence on the surface, and hence, non-destructive evaluation (NDE) techniques are required for detecting the delamination. Conventional NDE techniques, such as ultrasonic C-scan and A-scan, are point-to-point inspecting methods. They are time consuming and not able to inspect inaccessible locations of the structures. Low frequency vibration techniques [2] are efficient in inspecting large area of structures, however, they are insensitive to local defects, such as delamination.

1.2. Damage detection using guided waves

Guided wave has been widely recognized as one of the promising techniques for detecting the local defects [3,4]. It is elastic stress wave, whose propagation characteristics depend on structural boundaries. Guided wave can be used to inspect large area of structural components due to its long propagation distances. Because guided waves are excited at high frequency, i.e. in the order of kilohertz, their wavelengths are small, and hence, they are sensitive to the local and incipient defects, e.g. delamination.

Recently, guided wave based damage detection techniques have been widely employed in identifying the defects in one-dimensional (1D), e.g. beams [5] and rods [6], and two-dimensional (2D) waveguides, e.g. plates [7–10] and shells [11]. For 2D waveguides, a number of damage detection techniques have been developed in the literature such as pre-stack reverse-time migration technique [12], tomography [13] and diffraction

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tomography [14,15]. With the use of a transducer network, guided wave and scattered waves could be actuated and measured at different directions from the defect, respectively. This provides sufficient information for characterising the defects in 2D waveguides, e.g. defect location, size and shape. For 1D waveguides, most of the methods focused on determining the defect location based on the time-of-flight information of the reflected wave from the defect [16,17]. There was relatively less work focused on the defect characterisation, especially for delamination in the laminated composite beams.

Model-based approach has been employed to characterise the defects based on the measured guided wave signals in 1D waveguides. This approach treats defect parameters, such as defect location and size, as variables, by which the damage identification is achieved by minimising the discrepancy between the modeled and the measured guided wave signals. A number of model-based approaches have been developed for characterising different types of defects, such as step damages [18–20] and cracks [21–23] in aluminium rods and beams. However, there were limited studies focused on delamination in laminated composite beams [24].

Recently the Bayesian statistical framework [25] has been applied to provide a quantitative identification of the defect in 1D waveguides [18] and this method was verified using experimentally measured guided wave signals [19]. It incooperated a spectral finite element (SFE) model in the Bayesian statistical framework to provide a computational efficient and quantitative identification of the defect. One of the advantages of the Bayesian statistical framework is that it not only provides a characterisation of the defect, i.e. identifying the defect location and size, but also quantifies the uncertainties associated with the defect identification results. This provides valuable information on making decision about the remedial work necessary to repair the structural damage.

1.3. Challenges in multiple delamination identification

In practical situation, the number of defects is unknown before the damage detection, and hence, the identification of multiple defects is a challenging issue for 1D waveguides, especially for a situation that the number of transducers is limited. For non-model based approach, it is difficult to determine the number of defects based on the information of the scattered waves as a number of scattered waves can be induced by multiple wave reflections between the defects. For multiple delaminations, the problem is more complicated. At each delamination region, the waveguide is divided into two individual sub-waveguides, and hence, reflection happens when the wave entering and leaving each of the delamination.

Although the model-based approach is able to provide quantitative identification of one defect, it has a difficulty in identifying multiple defects. In the situation that the number of defects is unknown, the model considered more number of defects always has better fitting between the modeled and measured guided wave signals. Therefore, damage detection method based solely on the fitting between the modeled and the measured guided wave signals can be very misleading given the existence of modeling error and measurement noise in the measured data.

The aim of this study is to address the challenges in quantitative identification of multiple delaminations in laminated composite beams. The proposed method is developed based on the Bayesian statistical framework. The quantitative identification of the delaminations is achieved by solving a Bayesian updating problem, and hence, it could provide quantitative information of the delaminations, such as number of delaminations, delamination locations, lengths and through-thickness locations, and also the uncertainties associated with the damage identification results. To overcome the aforementioned challenge in identifying the multiple delaminations in laminated composite beams, the proposed method employs the Bayesian model class selection [26,27] to provide a robust determination of the number of delaminations. In addition the proposed method employs the formulation of Bayesian updating with structural reliability method (BUS) [28], and hence, the Bayesian updating problem can be solved by a computational efficient and robust algorithm, i.e., Subset simulation [29–31]. In this study both numerical calculated and experimentally measured guided wave signals are used to verify and demonstrate the capability of the proposed method.

The paper is organised as follows. In Section 2 the details of the Bayesian approach for multiple delaminations identification are presented first. This section describes the Bayesian model class selection, Bayesian model updating, BUS formulation and Subset simulation for improving the computational efficiency and robustness of the proposed multiple delaminations identification method. Section 3 describes the SFE method and modeling of the delaminations. Section 4 presents the results of the numerical case studies to verify the proposed multiple delaminations identification method. The numerical case studies consider different situations, such as different number of delaminations, delamination locations, lengths and through-thickness locations, to assess the performance of proposed method. Experimental verification is provided in Section 5 to demonstrate the practicability of the proposed method. Finally conclusions are drawn in Section 6.

2. Bayesian approach for multiple delaminations identification

The proposed Bayesian approach is developed based on the Bayesian model class selection and Bayesian model updating, which are used to determine the number of delaminations and provide quantitative identification of the delaminations. In the Bayesian approach, a laminated composite beam with length L and different number of delaminations are considered. A schematic diagram of the laminated composite beam with multiple delamination is shown in Fig. 1. In this study we assume there are N_M delaminations existed in the laminated composite beam and they are represented by different model classes $\bar{\mathbf{M}} = \{M_j : j = 1, 2, \ldots, N_M\}$. M_j is the model class representing the laminated composite beam with j delaminations. The delamination parameters l_j and d_j are used to describe the location and length of j-th delamination. For the through-thickness location, k_j is used to describe the delamination located between the k-th and $(k+1)$-th layers of the laminated composite beam.

The selection of the 'optimal' model class solely based on the fitting between measured and simulated data is impractical. In order to address this problem, this study used the Bayesian model class selection method in selecting the "optimal" model class to identify the number of delaminations. In addition the delamination parameters and their associated uncertainties are identified by the Baye-

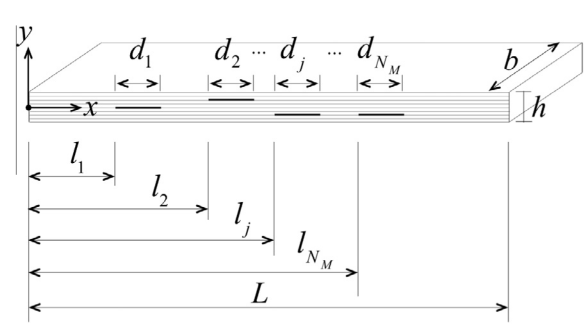

Fig. 1. Schematic diagram of the laminated composite beam with multiple delaminations.