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An integrated numerical model for investigating guided waves in impact-damaged composite laminates

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ABSTRACT

This paper presents a novel numerical technique that combines predictions of impact-induced damage and subsequent ultrasonic guided-wave propagation in composite laminates, with emphasis on the development and verification of the modelling framework. Delamination and matrix cracking are considered in the modelling technique, which is validated by experimental measurements on a carbon-fibre/epoxy plate using a drop-weight impact tower and a scanning laser vibrometer. Good agreement has been found between simulations and experiments regarding the impact response and global-local wavefields. Effects of these two damage modes, damage extent and multiple impacts on guided waves are studied using the modelling tool. Matrix cracking leads to lower wavefield scattering compared with delamination, particularly in un-damaged regions. The modelling strategy can provide valuable guidelines for optimising health-monitoring arrangements on composite structures that are susceptible to impacts, and the guided-wave model can also be integrated with other numerical models for predicting internal flaws in composite laminates.

1. Introduction

Owing to high specific stiffness and strength, fibre-reinforced plastic (FRP) composite laminates are increasingly being used in many industries, including aerospace, automotive, civil, electronics and marine. Excellent in-plane properties can be achieved by tailoring the fibre/matrix materials and stacking sequence of laminates. One of the major concerns when designing laminated structures is their relative weaker through-thickness properties. As a result, composite laminates are susceptible to interlaminar fracture (delamination) when exposed to an impact threat, e.g. dropped tools and hail. Typical damage modes due to low-velocity impact also include intralaminar failure, such as matrix cracking, fibre breakage and fibre/matrix debonding [1]. Low-velocity impact damage significantly degrades the residual strength and fatigue life of a laminated structure [2,3], with the degradation severity increasing with impact energy [4]. Therefore, a number of non-destructive testing (NDT) technologies have been developed to evaluate the structural integrity of composite laminates, including acoustic emission [5], eddy current effect [6], electrical resistance measurement [7], ultrasonic C-scan and tomographic imaging [8].

Ultrasonic guided waves have been widely used to evaluate the integrity of engineering structures, due to their ability to propagate over considerable distances and excellent sensitivity to the presence of defects in the propagation path. Given that composite laminates are generally thin plate-like structures, the resulting Lamb waves feature two simultaneously existing modes, namely the symmetric (S) and anti-symmetric (A) modes [9]. Guided waves are usually generated by an excitation source, typically a piezoelectric transducer coupled with the laminate. Once these waves have been generated, the structural integrity of the laminate can be evaluated by the transducer itself or other sensors coupled to the laminate. This procedure can take place during a maintenance inspection or while the structure is in service. Guided-wave propagation in composite laminates is a very complex phenomenon due to a number of factors, including (i) the anisotropic properties of individual laminae (plies), (ii) the fact that laminates are usually made of plies with different fibre orientations, and (iii) the dispersive nature of guided waves. Impact-induced damage further enhances the complexity, by scattering and reflecting guided waves. As a result, it becomes practically difficult to derive analytical solutions for the detailed guided-wave propagation behaviour of impact-damaged laminates. Hence, most of the research on guided-wave propagation in impacted laminates has been based on experiments and numerical modelling. Regarding experimental characterisation, low-velocity impact damage is normally

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introduced into a laminate through drop weight [10–12] or quasi-static indentation tests [13–15]. The location and size of damage and/or flaws can be ascertained by the phase shift and amplitude difference between the sensing signals acquired before and after impact [10,11,16]. Both of the sensing indicators increase with the damage size. The detection accuracy can be improved by increasing the number of signal acquisition points, as illustrated in [12] by a 2-dimensional scanning method. Another experimental approach for evaluating the health condition of an impact-damaged laminate is to examine the guided wavefield acquired by a scanning laser vibrometer (SLV). It provides more intuitive observations of guided-wave propagation, as well as its interaction with damage. The combination of time-domain and frequency-domain analyses of the guided wavefield aids more accurate prediction of the impact-induced damage [14,17].

Experimental characterisation of structural health monitoring (SHM) systems is costly and time-consuming, attributed to various configuration parameters, including the laminate material, the stacking sequence and the impact energy. It is also difficult to visualise wave propagation inside the laminates during experiments. Hence, several finite element (FE) models were proposed in [15,18–24] to investigate the influence of the dominant impact damage mechanism, i.e. delamination on guided waves. Delamination was assumed to have an idealised geometry and wave scattering due to delamination was examined in these models. On the other hand, Leckey et al. developed a 3D elasto-dynamic finite integration model that incorporated realistic impact-induced delamination geometries measured by X-ray computed tomography (CT) scanning [15], indicating that the realistic geometry of impact-induced delamination should be taken into account in order to improve the prediction quality of numerical models. In addition, the overall impact damage was represented by simply degrading material properties in the FE models proposed in [24,25].

Whilst numerical modelling techniques for predicting low-velocity impact damage are quite well advanced [26–28], modelling techniques that combine these simulations with the analysis of ultrasonic guided-wave propagation have not been so far put forward in the literature. Such an integrated modelling capability is imperative in the development of NDT and SHM systems for composites, since it completes the virtual characterisation process from impact to guided-wave propagation using numerical simulation, thus saving considerable time in comparison with experimental studies. Therefore, the objective of the present work is to develop an integrated numerical modelling methodology for characterising guided waves in composite laminates after undergoing low-velocity impact. The numerical strategy consists of a model that predicts impact-induced damage including delamination and matrix cracks, a guided-wave model that imports the predicted damage data and analyses guided-wave propagation in the damaged laminate, and a damage transfer code. Delamination and matrix cracking are both directly meshed in the guided-wave model. Section 2 first provides experimental characterisation of a quasi-isotropic carbon FRP plate. Section 3 presents detailed descriptions of the novel impact-ultrasonic modelling tool. Comparisons between experimental measurements and numerical results are then detailed in Section 4 to verify and validate the methodology. The modelling framework is employed in Section 5 to investigate the effects of these two damage modes, damage extent and multiple impacts on guided waves.

2. Experimental characterisation

2.1. Specimen preparation

A composite plate with the dimensions of 4 × 200 × 300 mm^3 (thickness × width × length) was manufactured from 32 plies of Hexcel® IM7/8552 pre-preg material, stacked following the sequence of $[45_2/0_2/90_2/-45_2]_{2S}$. The quasi-isotropic laminate was vacuum bagged and cured in an autoclave following the material manufacturer's recommended cycle (2 h at 180 °C with 180 psi pressure). Note that the in-plane dimensions of the plate are double that of the more commonly used ASTM D7136 standard [29] in order to give a panel size that is more realistic for guided-wave propagation. Fig. 1 shows the analytical dispersion curves created for the laminate using the software package DISPERSE® and the material properties given in Table 1.

2.2. Low-velocity impact

The plate was impacted at its centre using an Instron® Dynatup 9250 HV drop-weight impact tower, whose impactor had a 16 mm diameter hemispherical shape and a 6.3 kg weight. In order to accommodate the larger than standard plate, a new support fixture was designed and manufactured. Based on the scaling between the ASTM standard plate [29] and the plate tested in this study, the support frame dimensions were doubled to 250 × 150 mm^2, as compared in Fig. 2. The same four rubber-tipped clamps were used. The support fixture was made of steel, and the flatness tolerance of the top surface was kept within 0.1 mm to ensure that each opening edge provided uniform support to the plate during impact. The impact energy for this case was 12 J, so that damage introduced by the low-velocity impact test was dominated by delamination and matrix cracks. The projected delamination area in the plate was inspected by ultrasonic C-scan.

2.3. Scanning laser vibrometry

The laser vibrometry study was undertaken using a 3D scanning laser vibrometer (Polytec® PSV-500-3D-M). The test set-up is presented in Fig. 3. Through the use of three laser heads the system can resolve wave velocities in three principal directions, i.e. two in-plane and one out-of-plane. Ultrasonic excitation was achieved using a Mistras Group Ltd. *Nano30* piezoelectric transducer (8 mm diameter), placed at the middle of the left-hand short side of the plate on the impactor side. The transducer was fixed with silicon RTV adhesive (Loctite® 595) which also provided suitable acoustic coupling. The transducer was excited by a 140 kHz five-cycle sine

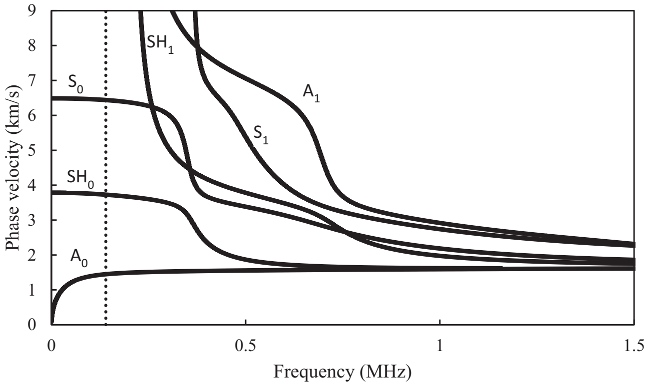

Fig. 1. Analytical dispersion curves of the quasi-isotropic IM7/8552 carbon FRP plate used in this study.

Table 1
IM7/8552 individual ply properties (1 indicates fibre direction) [28,30].

E_{11}	$E_{22} = E_{33}$	$G_{12} = G_{13}$	G_{23}	$\nu_{12} = \nu_{13}$	ν_{23}	ρ
161 GPa	11.4 GPa	5.17 GPa	3.98 GPa	0.32	0.436	1626.7 kg/m^3