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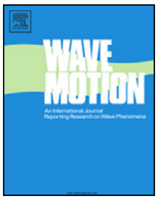

Leaky and non-leaky behaviours of guided waves in CF/EP sandwich structures

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HIGHLIGHTS

- The behaviour of guided waves in honeycomb and foam composite sandwich structures was studied.
- The thickness of the honeycomb core greatly affects the magnitude of the wave mode.
- The increase in excitation frequency results in mode conversion from guided waves to the Rayleigh wave.
- The A_0 appears to have both leaky and non-leaky behaviours.
- The S_0 mode appears always to have a leaky behaviour.

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ABSTRACT

The aim of this study is to investigate the leaky and non-leaky behaviours of guided waves, between the composite skin and the core in CF/EP sandwich structures, focusing on the fundamental symmetric like and anti-symmetric like guided wave modes and Rayleigh waves. In investigating the core effect on the guided wave propagation different types of cores are used, namely Nomex honeycomb (HRH 10 1/8-3) 10 and 20 mm in thickness and foam (Divinycell® PVC). The behaviour of the guided wave modes is characterised and the conversion mechanism to the Rayleigh wave is investigated. Further, leaky and non-leaky behaviours of guided waves upon interacting with debonded areas are explored, where the ability of guided waves to identify debonding of different sizes was assessed. Finite element analysis simulations are presented to support the experimental analysis, where propagation of ultrasonic waves and their interaction with debonded areas are quantitatively examined.

1. Introduction

Sandwich structures have been used successfully in a variety of applications such as spacecraft, aircraft, train and car structures, wind turbine blades, and marine superstructures. Sandwich structures are made of a lightweight core covered by thin stiff face-sheets (such as composite laminate). To ensure load transfer between the sandwich elements, the face-sheets and the core are joined by adhesive bonding films. Impact or cyclic loading on sandwich structures can introduce debonding between the skin and the core, substantially reducing the performance of the sandwich structure and possibly

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causing catastrophic failure in the structure [1]. However, damage detection in composite sandwich structures is particularly difficult because the skin–core configuration conceals damage. Various non-destructive testing (NDT)-based methods, such as the instrumented tap tester and air coupled transmission ultrasonic C-scanning, are currently in use for inspection and evaluation of sandwich structures.

Guided waves are sensitive to both the surface and embedded structural damage. They have proven proficiency, having been widely used to develop various damage identification algorithms for assessing delamination, de-bonding, holes, cracks/notches and corrosion in both composite and metallic plate-like structures [2–7]. Also significant is their potential to reduce inspection costs and to monitor complex geometries.

The wave propagation mechanism in composite sandwich structures is still not fully characterised. Many studies have focused on the propagation behaviour of guided waves through sandwich structures and the consequences as they interact with debonding and damage [8–14]. Castaings and Hosten [15] studied the propagation of guided waves in composite, sandwich-like structures and their use for traditional NDT using angle beam transducers. Osmont et al. [16] monitored the health condition of sandwich plates using piezoelectric sensors. Yang and Qiao [17] investigated wave propagation and scattering, also performing experiments on aluminium beams, carbon/epoxy composite laminates, and sandwich composite beams to validate the effectiveness of guided waves in damage detection. Luchinsky et al. [18] developed a detailed numerical model of a honeycomb sandwich structure including modelling of the impact. They also monitored wave propagation in the sandwich structure before and after the impact.

This study aimed to characterise the behaviour of the A_0 like and S_0 like guided wave modes in composite sandwich structures, and to investigate their conversion to the Rayleigh wave based on the change in the wavelength as the central frequencies of the wave signals are altered. The interaction of guided and Rayleigh waves with debonded areas was explored, and the leaky and non-leaky behaviours of guided waves were examined. Detailed finite element models (including the core geometry) were used to investigate the through-thickness motion of guided waves, as well as to validate most of the experimental results. Note that the A_0 like and S_0 like modes will be referred to as the A_0 and S_0, respectively, in the following discussion for the sake of simplicity.

2. Propagation characteristics of guided waves in sandwich structures

2.1. Guided and Rayleigh waves

For a plate with a thickness of one or more wavelengths, the Rayleigh wave excited in it has two normal modes i.e., the A_0 and the S_0 modes. Under these conditions, the phase and the group velocities of these modes are very close to the phase velocity of the Rayleigh wave. In addition, their displacements have shown a high similarity to those of the Rayleigh wave. It is also known that in the vicinity of the excitation source, the magnitude and the phase of the A_0 and S_0 modes are approximately equal when they are excited in the same manner. Moreover, when the displacements of the A_0 and S_0 modes are the same as to each other, it results in a zero phase difference between them and the superposition between them, and their total acoustic field resembles the Rayleigh wave acoustic field; hence these modes may be considered as an approximation of the quasi-Rayleigh wave. Therefore, Rayleigh waves are a high-frequency approximation of S_0 and A_0 guided waves. As the frequency becomes very high, the speeds of the S_0 and the A_0 wave coalesce, and both reach the same value, approaching that of the Rayleigh wave. Their displacement becomes localised and tends to the depth-wise distribution of the Rayleigh wave [19]. Furthermore, an increase in the thickness of the plate results in the similar change in the properties of the S_0 and A_0 modes, and they become the same as to each other (i.e. localised as previously described). Around 67% of the wave energy from an emitter on a homogeneous half-space propagates as Rayleigh waves [20]. A typical Rayleigh wave travels through a medium that is approximately one wavelength deep [21]. A wave with long wavelengths and low frequencies penetrates to a greater depth, whereas a short wavelength/high-frequency wave penetrates only a shallow volume close to the surface. Therefore, if a medium is layered, with different properties at different depths, different wavelengths (or frequencies) will propagate with different phase velocities [22].

2.2. Leaky guided waves

Since it was first observed in 1982, the phenomenon of leaky Lamb waves has been studied extensively, particularly in composite materials [23]. When a leaky wave propagates, it attenuates quickly because of the loss of energy to the substrate. Any debonding or crack at the interface can block the leaky energy transmission into the substrate and hence reduce the attenuation. A wave mode with a small attenuation coefficient can propagate a long distance in the layer/half-space structure, whereas a wave mode with a higher attenuation coefficient does not cover a large region, even though it is more sensitive to debonding. The mode and frequency selection are achieved based on weighing the importance of propagation distance versus sensitivity [11]. Non-leaky waves are suitable for surface damage detection because they concentrate energy on the top layer. However, the non-leaky wave is less sensitive to debonding of the skin substrate [11].

The use of guided waves for the detection of skin-to-core debonding or damage detection can be more effective if the correct wave mode and frequency are selected i.e. the phase speed of the guided wave should exceed the bulk wave speed in the structure. The guided-wave mode must have sufficient energy at the interface to allow energy leakage into the core.