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Guided wave propagation in a honeycomb composite sandwich structure in presence of a high density core

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ABSTRACT

A coordinated theoretical, numerical and experimental study is carried out in an effort to interpret the characteristics of propagating guided Lamb wave modes in presence of a high-density (HD) core region in a honeycomb composite sandwich structure (HCSS). Initially, a two-dimensional (2D) semi-analytical model based on the global matrix method is used to study the response and dispersion characteristics of the HCSS with a soft core. Due to the complex structural characteristics, the study of guided wave (GW) propagation in HCSS with HD-core region inherently poses many challenges. Therefore, a numerical simulation of GW propagation in the HCSS with and without the HD-core region is carried out, using surface-bonded piezoelectric wafer transducer (PWT) network. From the numerical results, it is observed that the presence of HD-core significantly decreases both the group velocity and the amplitude of the received GW signal. Laboratory experiments are then conducted in order to verify the theoretical and numerical results. A good agreement between the theoretical, numerical and experimental results is observed in all the cases studied. An extensive parametric study is also carried out for a range of HD-core sizes and densities in order to study the effect due to the change in size and density of the HD zone on the characteristics of propagating GW modes. It is found that the amplitudes and group velocities of the GW modes decrease with the increase in HD-core width and density.

1. Introduction

Honeycomb composite sandwich materials have been extensively used in marine, aerospace and automotive industries due to their high strength-to-weight ratios, effective acoustic insulation and high energy absorption capabilities [1]. High strength/weight ratio makes it suitable for constructing major structural components, such as blades, fuselage, and wings, whereas, the high energy-absorption characteristic makes it suitable for the impact protection and mitigation related domains. This novel material is in great demand due to its various field applications. Due to some practical over and above structural reasons, the application of such HCSS often involves the use of different cores with variable stiffness in the same sandwich component [2]. The high-density core regions are frequently used in those sandwich structures where it is required to introduce electrical and electronic devices, fasteners, backing plates, stiffeners for attachment or rigging purpose, etc. The various core inserts (backing plates, stiffeners, etc.) substitutes a part of the original core in sandwich structures [3–5].

Unfortunately, composite structures are susceptible to hidden damage in the form of disbond and delamination, which can appear due to manufacturing defects, aging, repeated loadings, low velocity impact, etc. A number of studies [6–11, etc.] have been carried out that focuses on the detection and mitigation of such type of hidden damage at an early stage before they grow and lead to the catastrophic failure of the structure. The ultrasonic GW based nondestructive evaluation (NDE) technique for the inspection of large areas has proved to be efficient in localizing and characterizing these defects. The major referred advantages of GW inspection technique is the dependency of wave structure on the frequency and phase velocity, and its capacity to propagate over a long distance with penetration capability into the hidden layers [12]. It is also referred that the GW mode tuning plays a significant role in NDE and structural health monitoring (SHM) of composite structures employing piezoelectric transducers [13,14]. The current methodologies involve deployment of surface mounted broadband transducers or built-in piezoelectric wafer transducers (PWTs) for detection of disbonds in sandwich structures (8, 10, 15, 16, etc.). However, to the authors' knowledge, no studies are reported to understand the effects of HD-core on GW propagation in HCSS using built-in PWTs. It is envisaged that the present study will help to analyze and differentiate the actual effects of disbonds

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on the signals during the ultrasonic guided wave based NDE of HCSS in presence of a HD core.

Owing to the complex nature of sandwich structures, an understanding of the GW propagation mechanism in these structures with different frequencies inherently imposes many challenges [17]. The GW propagation in a sandwich structure can be characterized as leaky GWs, owing to the spectacular acoustic impedance difference between the skin and core in the honeycomb sandwich structures and the high core/skin thickness ratio at sufficiently higher wave frequencies [15,16]. It is demonstrated that a substantial amount of wave attenuation occurred due to the energy dissipation mechanism of GWs inside the honeycomb core. Qi et al. [18] compared the ultrasonic GW transmission energy for the healthy specimen and the debonded specimen in order to identify the skin-core debonding in the honeycomb composite by using the leaky surface wave propagation employing clusters of sensor. However, the information was not provided for the quantitative assessment of debonding. An increase in amplitude of the received output signal was further noticed due to the GW propagation through the debonded area of honeycomb sandwich structure [8,10,19].

Theoretical studies are also carried out in order to study the dispersion behavior and elastic response of the propagating GWs in HCSS owing to transient surface loading. In an early attempt, an analytical model was developed by Nilsson [20] to study the wave propagation in a three-layered sandwich structure with different boundary conditions. The governing equations are derived by employing the general field equations (2D) to the core, and the thin plate/beam theory (one-dimensional) to the skin (laminates). Other higher order theories are also developed to study the dynamic response of sandwich beams [21–24]. Nonetheless, these theoretical models utilized several priori kinematic assumptions. A more efficient 2D semi-analytical model (based on the Thomson–Haskell method) is developed by Castaings and Hosten [25] in order to predict the dispersion curves and the through-thickness displacement, stresses and energy flow distributions, of the propagating GW modes in sandwich plates made of viscoelastic, anisotropic material layers. A complete description of the dispersion relation with no restrictions on the frequency and wavelength is presented by Liu and Bhattacharya [26]. In order to accomplish this, the wave equation is transformed to a Hamiltonian system and then a transfer matrix approach is employed for the solution of the Hamiltonian system.

Nevertheless, these works are only limited to frequency and wave-number domain. Hay et al. [8] has presented a theoretical analysis of leaky Lamb waves in the composite skin. The sensitivity analysis of various Lamb wave modes for the composite skin-core debonding is studied by frequency sweeping. Recently, Banerjee and Pol [27] developed a robust 2D semi-analytical model based on the global matrix method for rapid calculations of the elastodynamic field in a laterally unbounded HCSS plate subjected to time-dependent transient surface excitation. The model has shown the potential to accurately predict the modal features of output GW signal in the HCSS.

On the other hand, a very limited number of studies are reported in literature that deals with variable core density in HCSS. Bozhevolnaya et al. [28] have studied the sandwich beams and panels with symmetric faces and variable core stiffness. A closed-form estimate of the stress–strain fields induced by local effects and its accuracy were verified experimentally in the case of a sandwich beam under three-point bending. The significant rise of the bending stresses in the faces at the vicinity of the core junctions is observed. Typical sandwich beam configurations with glass fiber-reinforced plastic face sheets and core junctions between polymer foams of different densities and rigid aluminum were tested under quasi-static and fatigue loading conditions by Johannes and Thomsen [29].

This study is motivated by the need to develop detailed understanding on GW propagation mechanism in presence of HD core for NDE of HCSS using built-in PWT network. Initially, the baseline theoretical response of the HCSS plate is obtained in an effort to understand the dispersion behavior of the GW signals, and to guide numerical and experimental studies for modal tuning purpose at relatively higher frequencies. A three-dimensional (3D) finite element (FE) modeling is then carried out to simulate the effect of HD-core on GW propagation in the HCSS. Toward this, a commercially available FE code ABAQUS/6.10 is used to simulate the GW propagation and reception by the surface-bonded PWTs. The electro-mechanical coupling behavior of the PWTs is achieved by directly applying the electrical voltages. Experimental studies are then conducted to verify the numerical simulation within the network of PWTs. In order to study the size and density effects of the HD-core region on the propagating GW modes, extensive parametric studies have been carried out for a range of HD-core sizes and densities.

2. Laboratory experiment

In order to conduct the laboratory experiments, a rectangular HCSS sample plate is considered and PWTs are mounted at certain locations to study the GW propagation in the presence and absence of HD core. An efficient NI-instrumental setup is employed in order to generate and receive the GW signals through the PWTs. Detailed description of the HCSS sample plate and the experimental setup is given in the following sections.

2.1. Sample-plate

The sandwich plate (600 mm × 450 mm × 13.5 mm) used in this study consists of two 0.74 mm thin graphite/epoxy fiber reinforced composite (GFRC) skins at the top and bottom of a 12 mm thick aluminum honeycomb core. Both the GFRC skins are made up of seven individual layers, in which five 0.05 mm thin unidirectional (UD) twill (diagonal ply orientation) composite layers are present in-between two 0.17 mm 0°/90° cross-ply (CP) layers. The honeycomb core is made up of HEXCEL-Al5056, which is in a hexagonal shape with cell size of 1/16 in. The bond between skin and core is achieved by means of a foaming adhesive, HEXCEL-212Na. During manufacture of the sample plate, a HEXCEL-AL5052 HD-core section (100 mm × 125 mm × 12 mm) with cell size of 3/16 in. is introduced in-between the soft-core region at a particular location as shown in Fig. 1. The detailed material properties of the HCSS sample plate are presented in Table 1.

2.2. Experimental setup

In order to validate theoretical and numerical results, laboratory experiments are carried out on the HCSS sample plate using square type (20 mm × 20 mm × 0.4 mm) PWTs (e.g. Fig. 1). The PWTs are bonded to the plate using a commercially available cyanoacrylate based adhesive, and they serve as transmitters as well as receivers. An NI-instrument [10] is deployed to operate the PWTs and to collect their output signals. The NI-instrument is a PXI system, which consists of an embedded arbitrary function generator (FGEN), an 8-channel oscilloscope (SCOPE), a multiplexer switch and the instrument is connected to a desktop monitor as shown in Fig. 1(a). A five-cycle sine pulse modulated with a Hanning window pulse is transmitted into the sample plate by means of the FGEN soft front panel, and the SCOPE soft front panel is