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Characterization of the guided wave propagation in simplified foam, honeycomb and hollow sphere structures

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ABSTRACT

In recent years, researches about the capability of ultrasonic guided waves for detection of damages in cellular lightweight structures have been done. Besides the experimental studies, numerical approaches utilizing the finite element method are used to investigate the propagation and the interaction of guided waves in such complex material systems. To reduce the computational efforts, simplified models based on a homogenization technique are often used. The complicated heterogeneous cellular mid-core is simplified to a simple orthotropic layer modeled with eight-node 3D brick elements. However, it has been reported that this approach has specific limitations. The compact design of the simple homogeneous layer does not interact with the ultrasonic guided waves in a similar way as the real extended cellular structures do. These limitations are more obvious for the specific range of frequencies where the wavelength are smaller than the characteristic length scale of the cellular structure and the ultrasonic guided waves are more influenced by the microstructure. Therefore, a new kind of simplification approach based on geometrical parametric study is suggested in this paper. In this new kind, instead of material homogenization the main aim is to simplify the structural geometry. The proposed method has been used to simplify different cellular structures. The results of ultrasonic guided wave propagation are compared with the complex geometrical models. In order to prove the proposed approach, the wave propagation in a simplified hollow sphere sandwich plate is compared with experimental results. In addition, an application example of the proposed simplification approach for structural health monitoring in a hollow sphere structure is provided. Moreover, the experimental results for structural health monitoring gained by laser scanning vibrometry are presented and it is shown that the wave field interacts with damages. Finally, a computer tomography of the plate is also made in order to visualize debondings between the core material and the cover plates.

1. Introduction

Structural health monitoring (SHM) of composite structures using ultrasonic guided waves (GW) generated and received by a mesh of piezoelectric patches (PZT) is a developing technology which aims to reduce the maintenance cost and to increase the safety of structures [1,2]. SHM based on GW is an interesting technique for many industries because of the high sensitivity to detect damages, the possibility of an online monitoring and the low cost of the required equipment [1]. Sandwich plates with cellular core materials among the lightweight composite structures are modern materials which can also be subjected for SHM applications using GW. Due to the high specific stiffness, the ability to absorb high amounts of energy at relatively low stress levels, the potential for noise control, vibration damping and thermal insulation [3] the cellular materials are suitable for a wide field of multi-functional applications, e.g. in automotive [4], aviation [5,6] and space industries [7,8]. In addition to SHM applications, the fundamental knowledge of GW behavior in the cellular sandwich structures was addressed in some recent studies.

Mustapha et al. [9] used the low frequency fundamental anti-symmetric wave mode (A_0) to detect debonding in sandwich CF/EP composite structures with a honeycomb core using the finite element analysis. The honeycomb structure has been modeled with eight-node 3D brick elements with the homogenized orthotropic material properties. The flight of damage-reflected waves has been used to detect the damage location. Finally, the numerical results from the simplified finite element model have been validated experimentally. In another study, piezoelectric discs bonded

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on the glass fiber plate of a foam sandwich panel have been used to generate anti-symmetric low-frequency GW for SHM [10]. The damage identification procedures has been optimized using finite element analysis and experimental tests. A non-contact laser doppler vibrometer (LDV) has been performed to scan the foam structure panel while exciting with surface-bonded piezoelectric actuator [11]. The LDV scan shows a fringe pattern of the reflected waves, which confirms the capability of the GW to detect damages in such structures. The wave propagation in lightweight plates with truss-like cores has also been investigated in [12]. It has been shown that the vibrational behavior can be reduced to equivalent plate models in the low frequency region where global plate waves dominate. An application example of a regional train floor section has been tested to validate the theoretical dispersion characteristics. Furthermore, continuous mode conversation of the GW propagation in CFRP composites has been studied in [13] using numerical and experimental approaches.

1.1. Homogenization based simplification

As mentioned before, using the simplified models based on material homogenization is one of the common approaches to reduce the computational costs for simulating the GW propagation in complicated cellular structures. In [14] an open cell structure with specific properties has been considered and it has been shown that the calculation run-time for the homogenized model is 1.4 times faster. In these simplified models used in the recent studies, the complicated cellular mid-core of the sandwich panel has been replaced by a simple homogeneous layer with orthotropic mechanical properties utilizing eight-node 3D brick elements [15], cf. Fig. 1.

The homogenous material should be capable of storing the same strain energy as the considered heterogeneous material under any arbitrary load [15]. To achieve the orthotropic material properties a standard homogenization technique based on a representative volume element (RVE) approach in combination with the FEM is used [16]. A RVE, also known as unit cell, can be considered as a model which captures the main features of the microstructure. Special boundary conditions have to be applied in order to determine all elements of the RVE Hooke's matrix [15]. It has been demonstrated that this method can be used for several kinds of heterogeneous materials. The results have shown good agreement with several other homogenization methods [17].

However, it has been shown in several studies that this kind of simplification based on homogenization has specific limitations to simulate GW propagation in cellular structures. A 3D finite element has been used by Song et al. [1] to study the GW propagation in honeycomb sandwich panels. The results have been compared with a simplified model, where the heterogeneous core layer has been replaced by homogenized elements with cubic geometry. It has been reported that the agreement of the results calculated with the extended honeycomb model in comparison to the simplified model depends on the frequency of the loading signal. In another study by Hosseini and Gabbert the wave propagation in a honeycomb sandwich plate has been compared with a simplified model [18]. It has been reported that the wavelength values obtained from the simplified model and the honeycomb sandwich panel model are not similar (with an average of 25% difference). While, the group velocity and energy transmission values from both models match (with an average of 5% difference). The GW propagation in foam sandwich structures have been compared with the simplified ones [14]. Gibson and Ashby [19,20] applied the developed models for representing the mechanics of metal foams. It has been reported that the group velocity and the energy transmission values correspond in the simplified and in the extended model, but the wavelength values do not match [14].

One can explain the limitations of the homogenized based simplification by the fact that the wave interacts with the microstructure, if for certain ranges of the loading frequency, the wavelength of the propagated GW is in the range of the characteristic length scale of the cellular structure. But, the interaction of the GW with the cellular microstructure cannot be simulated using the simplified model with the compact homogenous layer modeled by the 3D solid brick elements without any free space between the elements, cf. Fig. 1. One may still suggest the homogenized based simplification to simulate the GW propagation in heterogeneous composite structures with compact structure and random material distribution, such as particle reinforced composites. The GW propagation in particle reinforced composite plates has been studied and compared with a homogenized RVE based simplified model in [21]. A good agreement (with an average of 5% difference) between the GW propagation properties in the real structure model and the simplified model has been observed.

To overcome these limitations in the present paper a new geometrical simplification approach based on parametric studies for GW propagation in cellular structures is introduced. The main aim of this new proposed method is to simplify the structural geometry instead of material homogenization. The method is applied for different sandwich plates with cellular core layers including honeycomb, hollow sphere, open-cell and closed-cell foam structures. The GW propagation properties including the group velocity, the wavelength and the energy transmission are

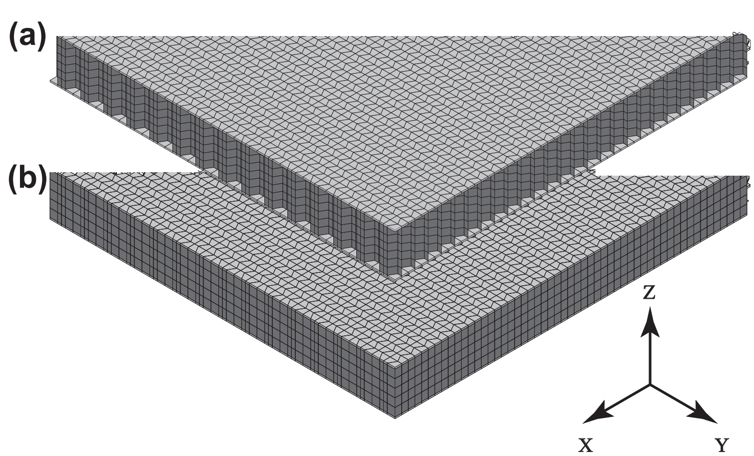

Fig. 1. (a) Real extended honeycomb sandwich panel and (b) simplified honeycomb model with eight-node 3D brick elements in the core.