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A spectral element for wave propagation in honeycomb sandwich construction considering core flexibility

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ABSTRACT

Spectral elements are found to be extremely resourceful to study the wave propagation characteristics of structures at high frequencies. Most of the aerospace structures use honeycomb sandwich constructions. The existing spectral elements use single layer theories for a sandwich construction wherein the two face sheets vibrate together and this model is sufficient for low frequency excitations. At high frequencies, the two face sheets vibrate independently. The Extended Higher order SAndwich Plate theory (EHSaPT) is suitable for representing the independent motion of the face sheets. A 1D spectral element based on EHSaPT is developed in this work. The wave number and the wave speed characteristics are obtained using the developed spectral element. It is shown that the developed spectral element is capable of representing independent wave motions of the face sheets. The propagation speeds of a high frequency modulated pulse in the face sheets and the core of a honeycomb sandwich are demonstrated. Responses of a typical honeycomb sandwich beam to high frequency shock loads are obtained using the developed spectral element and the response match very well with the finite element results. It is shown that the developed spectral element is able to represent the flexibility of the core resulting into independent wave motions in the face sheets, for which a finite element method needs huge degrees of freedom.

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1. Introduction

Sandwich structures are widely used in the aerospace industry due to their high specific strength and stiffness which provides stronger and stiffer structure for the same weight (low specific density) [1,2]. Usually sandwich structure is comprised of a core placed between two stiff face sheets. Such aerospace structures are subjected to high frequency shock loads and therefore have to be designed to withstand these loads. The behaviour of these structures to the high frequency excitation can be well understood through their wave propagation characteristics.

Many works are reported in literature, as regard to wave propagation aspect in sandwich structures. Ref. [3] used a transfer matrix method and Ref. [4] shows that the stiffness modulation can be used as a tool to suppress energy transportation by wave propagation. Here, propagation of waves of purely shear deformation in a sandwich plate is compared with the elasticity theory and concluded that a simplified theory can be reliably used to assess the dispersion properties of a sandwich plate in the frequency range of practical interest Ref. [4].

Alternatively, the analysis of sandwich structures is carried out by considering the displacement kinematics. There are exhaustive number of displacement based theories in the current literature. Displacement based theories are further classified into Equivalent Single Layer (ESL) theories and layer-wise theories. The most common ESL theories used are the Euler–Bernoulli Theory (EBT) and the First order Shear Deformation Theory (FSDT), where the core is assumed to be incompressible. Other ESL based theories which take into account of cross-sectional warping exists in the literature and a detailed survey of the refined theories are presented in [5,6]. ESL theories are useful when the sandwich core is very stiff in the direction normal to the panel and it is statically loaded. Also, the ESL theories are sufficient to obtain the wave propagation characteristics at low frequencies where both the face sheets vibrate together. At higher frequencies the two face sheets vibrate independently and the core undergoes stress normal to the face sheet. On the other hand in the layer-wise theories, each layer is analysed using independent kinematic assumptions and the continuity between the adjacent layer is imposed either through the displacement or stresses/strains. Layer-wise theories are

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specifically useful when the sandwich core is not very stiff in the direction normal to the panel.

A mixed model for sandwich beam with compressible core, considering the transverse normal and transverse shear stress as suggested in [7], known popularly as the Higher order Sandwich Panel Theory (HSaPT) is suitable for such cases. Free vibration studies are made based on this theory and is presented in [8]. Here, neglecting the in-plane stresses, a constant shear stress distribution through the thickness of the core is a good approximation for static problems and quasi-static loading cases. Experimentally it is shown in [9], the compliant core absorbs energy and undergoes significant transverse deformation and HSaPT can be used in the case of compliant core as compared to the ESL theories mentioned above. But in dynamic problems, especially high transient loading cases the axial acceleration and the core density is not negligible. When the axial inertial terms are included the constant shear stress distribution through the height of the core is not valid and an Extended Higher order SAndwich Panel Theory (EHSaPT) is proposed in [10], by taking into account the axial rigidity of the core. Here, only the spatial part is considered and the variational method is applied to obtain the governing differential equations and the boundary conditions. Thus, in their work, the results for static responses are presented and compared with that of the elasticity solutions; demonstrating the superior accuracy of this theory. Later, the same theory is used to study wrinkling behaviour in sandwich panels and is presented in [11]. The results are compared with the elasticity solutions and experiments, where close match is observed. Ref. [12] used the same theory by considering both the static and dynamic parts of the equations. Here, the blast loading case is presented demonstrating the cavitation like phenomena in sandwich beams and good comparison of dynamic response with elasticity solutions is made.

It is known that the response to the low frequency transient can be determined using the finite element method and usage of the finite element method for high frequency response estimation increases the system size and requires large number of equations to be solved. For such problems, spectral elements [13,14] have several advantages over the finite element method and found to be useful. Here, the exact interpolation functions to the field variables are derived by considering the dynamic equations of motion; theoretically leading to a single element for any length of the sandwich beam. Another advantage of the spectral element is that the analysis is carried out in the frequency domain and can be utilised in the study of frequency dependent characteristics, with ease.

Spectral elements for isotropic beams based on ESL theories like the Euler–Bernoulli Theory and on the First order Shear deformation theory are well discussed in [13]. Based on the same theories, detailed dispersion studies, solutions to vibration problems and structural health monitoring aspects in composites is presented in [14]. Many applications on the usage of spectral element like identification of structural boundaries and modelling of smart structures is clearly brought out in [15]. Similarly, the spectral finite element model for analysis of flexural-shear coupled wave propagation in delaminated multilayer composite beam is presented in [16]. Work on the sandwich beam in the spectral element domain is presented in [17]. Although this work presents a good comparison of predicted accelerances with the measured data from impulse hammer experiments, for frequencies up to 2 kHz; the sandwich core compressibility and the complete spectrum of higher order dispersion modes are not addressed.

The spectral elements in the existing literature use the Fourier transform to solve the equations of motion. Fourier transforms assumes that the time signal is periodic in time domain and introduce periodicity in the frequency domain to remove the integral representation of the forward transform. Signal wrap-around is observed in the time domain responses as a consequence of using the discrete inverse Fourier transform along with the induced periodicity in the frequency domain. This wrap-around can be avoided by either increasing the time window or adding sufficient damping to the response. Sometimes, a combination of both may be required. A Timoshenko beam spectral element is developed using the Laplace transforms and is presented in [18]. Here, the numerical Laplace transforms is implemented using the fast Fourier transforms, retaining the excellent frequency domain analysis provided by the Fourier transforms based spectral elements.

The above spectral elements use ESL theories where the two face sheets vibrate together. As finite element models become complex by introducing additional degrees of freedom, a spectral element formulation is more suited. Therefore in this work, a spectral element based on the EHSaPT using numerical Laplace transforms is developed. The developed spectral element of the EHSaPT has 9 degrees of freedom (*DOFs*) per node, thus comprising 18 *DOFs* per element. As the theory accounts for separate displacement fields for the top face sheet, core and the bottom face sheet, the detailed local behaviour can be studied, where the difference in the responses between the top face sheet and the bottom face sheet is more pronounced.

Using this spectral element the wave propagation characteristics of honeycomb sandwich construction are determined. Responses of a typical honeycomb sandwich structure subjected to high frequency shock excitation are obtained and validated through the finite element results. Ability of the developed spectral element in reporting independent wave motions in the face sheets is demonstrated.

2. Spectral element formulation

This section presents the spectral element formulation based on EHSaPT [10,11] for a sandwich wide beam as shown in Fig. 1.

2.1. Displacement field

The displacement of the top and bottom face sheets are assumed to satisfy the assumptions made in the Euler–Bernoulli beam theory. The axial and transverse displacements of the core are represented by a quadratic and cubic expansion respectively as considered in [7]. The displacement fields for the top and bottom face sheets are given as,

For top face sheet, $c \leqslant z \leqslant c + f_t$,

$$u^t(x,z,t) = u_0^t(x,t) - \left(z - c - \frac{f_t}{2}\right)\frac{\partial w^t(x,t)}{\partial x}, \tag{1a}$$

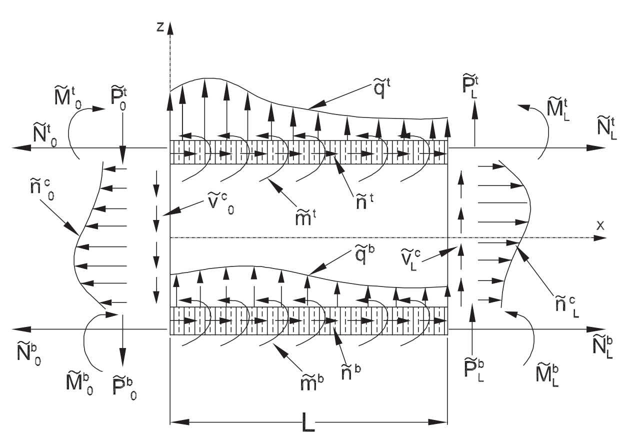

Fig. 1. Sandwich beam configuration.

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