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WAVELET MODELING OF STRESS WAVE PROPAGATION IN COMPOSITE JOINTS

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Abstract. *The spectral wavelet finite element method is used to study the transient dynamics and wave propagation through glued lap joints of composite materials. The calculation model assumes that the glued elements are considered as shear deformable plates with five degrees of freedom. This approach allows describing mechanical displacements both in the mid-plane of the composite system and outside it. The partial differential equations that describe the wave motion characteristics of the bonded elements are derived using the Hamilton principle. The adhesive layer is assumed to be a set of linearly distributed shear and transverse normal elastic elements. The analysis showed that the control equations in partial derivatives are interconnected due to the presence of an adhesive layer, which negatively affects the simplicity of the solution. The paper proposes a modification of the spectral finite element method, which is used to solve differential equations. The modified technique approximates the spatial dimension using Daubechies scaling functions, reducing the partial differential equations to differential equations that are functions of only one spatial dimension. Calculation techniques are presented to describe the complex mechanism of wave propagation through adhesive joints in composite structures.*

Key words: *wavelet, wave propagation, mechanical displacement, spectral finite element method, adhesive joints.*

Introduction.

Adhesive bonding of structural composite components has several advantages over traditional mechanical fastening methods. These include higher fatigue strength and longer service life, low weight, the ability to join thin and dissimilar components, good sealing, low manufacturing cost, and good vibration and damping properties compared to other mechanical joining methods. However, while adhesive bonding may offer significant advantages over mechanical fasteners, it has not yet demonstrated sufficient integrity under extreme conditions. Current requirements for the certification of composite systems require proof that each adhesive joint will not separate and cause failure of the structure when the critical design load is reached [1]. Currently, these requirements are met by assembling with mechanical fasteners in combination with adhesives. These circumstances prevent the full cost and weight savings of composites as a structural material from being realized.

Efficient computational tools capable of analyzing adhesive joints enable a wide range of designs to be quickly designed and certified and are thus cost-effective. Numerical methods offer a fairly wide range of models that describe lap joints and compare the capabilities and limitations for solving specific problems. In particular, finite element techniques have been used to solve problems related to adhesive joints [2]. It should be noted that almost all of these methods are limited to performing static analysis. Some other studies have focused on low-frequency dynamic/vibration analysis of adhesive joints [3]. However, there is a lack of efficient computational tools to analyze the propagation of high-frequency dynamic stress wave resulting from transient mechanical loading.

This paper is devoted to a modification of the spectral wavelet finite element model for studying transient wave propagation through bonded composite plates. The analytical equations of motion governing the coupled structure were derived from first-order shear deformation theory using a dynamic version of the virtual work principle. The improved model considers the adhesive layer modeled as a line of continuously distributed tension/compression and shear springs. The transformation of the governing partial differential equations from the time domain to the frequency-wave number domain is performed using compactly supported Daubechies wavelets. As subsequent calculation steps, a dynamic stiffness matrix was obtained that relates the nodal forces and displacements in the transformed domain.

Wavelet approximation and spectral finite element formulation

The spectral wavelet transform technique involves transforming field variables (sets of mechanical displacements) into the frequency-wave domain. Compactly supported Daubechies scaling functions are used for approximation in time and one spatial dimension. The Daubechies scaling functions with compact support have only a finite number of nonzero filter coefficients. The limited set of characteristic coefficients allows us to reduce the processing of finite elements in this method to fixing the boundary conditions of the first and second kind on a set of local volumes for the connections of composite structures. The transformed governing partial differential equation for a boundary condition of a fixed order can be written as follows

$$A_{ik}\frac{d^2u}{dx^2} - i\beta B_{ik}\frac{dv}{dx} + k_x(u_{ik} - h_2\varphi_x) + I_{ik}\left(\gamma^2 u_{ik} - \varphi_x\right) = 0. \qquad (1)$$

The terms β and γ appearing in the equations are the eigenvalues obtained by separating the equations after time- and space-dimensional wavelet approximations. The ordinary differential equations for this technique are similar to the Fourier transforms for the spectral finite element method. For the case of no mechanical discontinuity and the presence of continuous mechanical shifts A_{ik} and B_{ik} at fixed moments I_{ik} of deforming forces, only one spectral element can be used to represent the region of the bonded composite lap joint plate. There are four nodes associated with the element, and each node has 5 degrees of freedom, which are denoted as u_{ik} and φ_{ik}.

Following the procedure for formulating the spectral element, the relationship between the nodal forces F^e and displacements u^e can be obtained as

$$\{F^e\} = [K]\cdot\{u^e\}, \qquad (2)$$

where [K] is the dynamic stiffness matrix of the spectral element.

The order of the matrix is equal to the total number of degrees of freedom in the element. When the nodal forces are known, the nodal displacements can be obtained from the above relation (1). At this point, the formulation of the spectral wavelet transforms for finite differences applied to the double-beam system can be complemented by a set of characteristic equations. The above technique can be extended to consider multiple high power bonded elements depending on the type of bonded composite structure system. The numerical results indicate that the wavelet transform technique can be effectively used to study the transient dynamics in local volumes of individual composite elements.

In the present study, one lap joint, which has received much attention due to the increasing use of composites in structural applications, was investigated. Wavelet analysis was performed entirely for the high and low frequency region to obtain the dynamic stiffness matrix of the lap joint structure.

Summary and conclusions.

An effective use of the finite difference method involves representing the bonded composite materials as beams. The laying sequence of the laminated composite material was taken as $[0]_{10}$. The order of the Daubechies scaling function used is N = 22. The developed finite difference spectral wavelet transform model is used to analyze the time-domain wave propagation of composite single lap joints. Since the formulation is based on plate wave equations, the model can be reduced to the analysis of problems associated with adhesive joints consisting of bonded materials in cylindrical bending as well as beams. The formulation of the plate was based on the first-order shear deformation theory for accuracy at relatively high frequencies (compared to the classical laminated theory). The adhesive layer was modeled as a line of continuously distributed tension/compression and shear springs. A dynamic stiffness matrix was obtained, relating the nodal forces and displacements. The results of numerical calculations indicate the presence of an influence of the length and thickness of the bond line on the propagating waves.

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