MODELING DAMAGE IN CYLINDRICAL SHELLS USING ELASTIC WAVE-BASED TECHNIQUES

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1. Introduction

The characteristic of wave propagation in elastic media can be used to predict the size of damage in a structure or used in the ultrasonic inspection techniques and structural health monitoring. Any localized damage in a structure reduces its stiffness, which in turn reduces the natural frequencies and alters the vibration modes of the structure. During the past two decades, extensive researches have been conducted in the area of damage detection based on structural dynamic characteristics using different algorithms and useful databases [1]. However, the maintenance cost of the structures may increase because of the complicated fracture process of the CFRP laminates. A new technological innovation to reduce the maintenance cost is a health monitoring or management system. At present, optical fiber sensors are most promising among all [2, 3]. This is because optical fibers have enough flexibility, strength and heat-resistance to be embedded easily into composite laminates. A most potential candidate for the sensing device is an optical fiber Bragg grating (FBG) sensor [4].

Ultrasonic non-destructive evaluation (NDE) plays an increasingly important role in determining properties and detecting defects in composite materials, and the analysis of wave behavior is crucial to effectively using NDE techniques. There are a number of different types of waves used for damage detection, such as Rayleigh and Lamb wave. The basic information about ultrasonic guided waves was gathered in many textbooks [5-9]. The first introduction of Lamb waves as a means of damage detection was made by Worlton [10] in 1961. He noticed that distinguish characteristics of the various modes of Lamb waves can be useful in nondestructive testing applications. A literature review of the most salient work with regard to ultrasonic guided wave research was presented by Rose [11].

Damage modeling in composite structures has been attempted by various researchers in the past. The latest effort includes a generalised laminate model featuring both weak interfacial bonding and local delamination by Shu [12]; a plasticity model coupled with the damage and identification for carbon fibre composite laminates by Boutaous et al. [13] and a general FEM model by Yan et al. [14]. As far as the damage index is concerned, a good summary on vibration-based model-dependent damage identification and health monitoring approaches for composite structures can be found in Zou et al. [15]. Araujo dos Santos developed a damage identification technique based on frequency response functions (FRF) sensitivities for laminated structures [16].

There have been many works on wave propagation problems related to composite shells. Mirsky [17] and Nowinski [18] solved for axially symmetric waves in orthotropic shells. Chou and Achenbach [19] provided a three-dimensional solution for orthotropic shell as well. Yuan and Hsieh [20] proposed an analytical method for the investigation of free harmonic wave propagation in laminated shells. Nayfeh [21] discussed scattering of horizontally polarized elastic waves from multilayered anisotropic cylinders embedded in isotropic solids. The numerical description of the waves traveling into waveguides and slender structures has also raised many interests – an information about those problems are discussed in Refs [22].

The fundamental relations can be developed by applying Hamilton's principle, both in 3D or 2D formulations. To visualize the effect of anisotropy on wave propagation six representations of wave surfaces are used: velocity, phase slowness, phase wave surfaces, group velocity, group slowness and group wave surfaces.

The study involving the monitoring, detection and arrest of the growth of flaws, such as cracks, constitutes what is universally termed as Structural Health Monitoring. SHM has four levels: 1, confirming the presence of damage, 2, determination of the size, location and orientation of the damage, 3, assessing the severity of the damage, 4, controlling the growth of damage. For cylindrical shells such an analysis is mainly conducted in two ways: a) numerically with the use of a numerical-analytical method or a strip element method, b) experimentally using smart (piezoelectric) patches. In general, two typical modes of failure are investigated, i.e. intralaminar cracks arising due to a damage of an individual ply in a laminate or interlaminar cracks due to debonding of individual plies.

2. Cylindrical Panel with a Single Local Delamination

Now, let us consider a cylindrical panel made of glass woven roving having the following properties:

$E_{long}=E_{circumf}=13.14$ [GPa]
$G=9.68$ [GPa]
$\nu=0.25$
$\rho=1100$ [kg/cm^3]

The panel was made of 8 layers and had the following geometrical parameters: L=298 [mm], R=92 [mm], t=1.8 [mm]. An excitation signal took the form of sine wave function was modulated with the Hanning window and was applied at the left piezoelectric actuator in Fig.1; its frequency is equal to 100 [kHz]. The piezoelectric sensor (on the right side in Fig.1) was placed close to the local square delamination having the size 10 [mm] and being in the middle of the laminate.

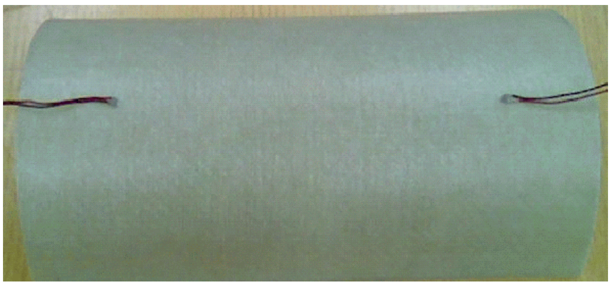

Fig. 1. General configuration of the cylindrical panel with the sensor and actuator.

The wave propagation in the panel with local delamination was analysed both numerically and experimentally. The excitation signal and the response signal were generated and collected by the analyser and then those signals were converted to digital ones with the use of MATLAB package.

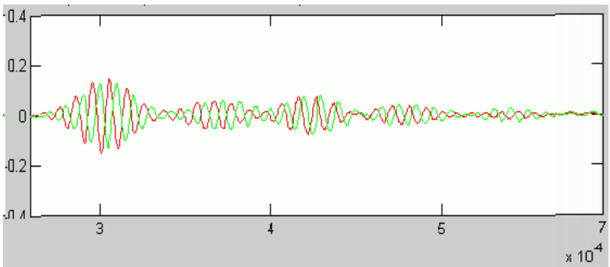

Fig. 2. Experimental wave propagation results (red line – without delamination, green line – with delamination)

Figure 2 demonstrates the response signals obtained experimentally for the perfect and imperfect (with the single delamination) cylindrical panel. As it may be seen there is a visible difference between response signals for perfect and imperfect shells.

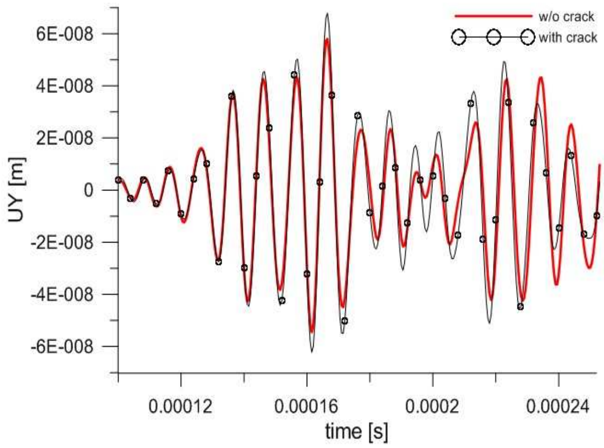

Fig. 3. Numerical wave propagation results.

However, the reasonable detection of the size and the location of delamination requires the careful analysis and optimal design of the location and number of piezoelectric sensors and actuator. It is especially visible by the numerical (finite element) analysis of wave propagation for perfect and imperfect shells – Fig. 3.

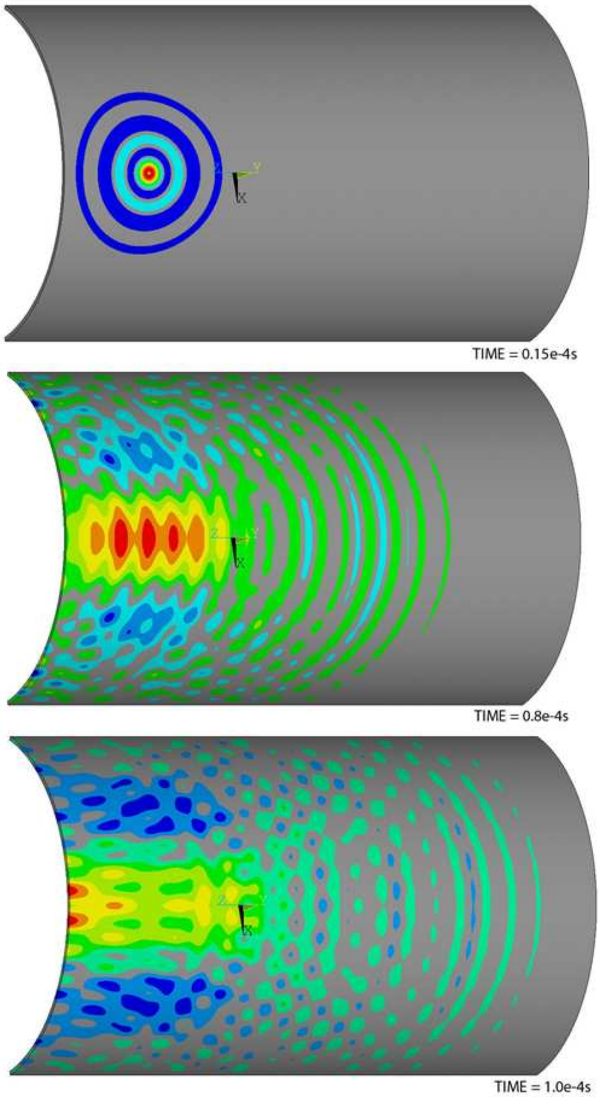

Fig. 4. Fronts of propagating waves for an intact composite panel

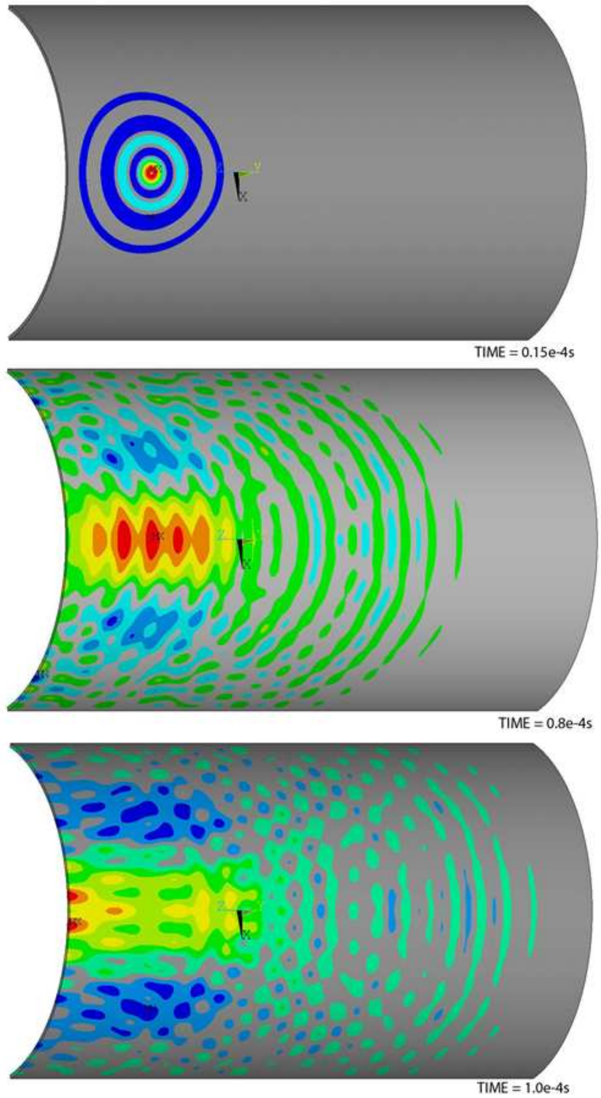

Fig. 5. Fronts of propagating waves for composite panel with a single local square delamination

It is worth to point out that the group velocity is higher in the circumferential than in the longitudinal direction. In addition, in the delaminated region the interference between generated and reflected waves is observed that affects the signal collected by the sensor. The comparison of displacements obtained by the numerical analysis is demonstrated in Figs 4 and 5. In general, there is almost the same distribution as observed experimentally (Fig.1) but in the qualitative sense only. In order to obtain better quantitative agreement between experimental and numerical analysis it is necessary to conduct further work dealing particularly with the optimal design of sensors number and locations.

3. The influence of ortothropy

In order to investigate the influence of ortothropy on the velocity of waves propagation, three cases of material properties was considered in numerical analysis. The Young's modulus ratio E_2/E_1 described the difference between each of material properties. We made an assumption that longitudinal Young's modulus was constant. The comparison of displacements obtained for cylindrical panels with different E_2/E_1 ratio at two time steps is demonstrated in Figs 6 and 7.

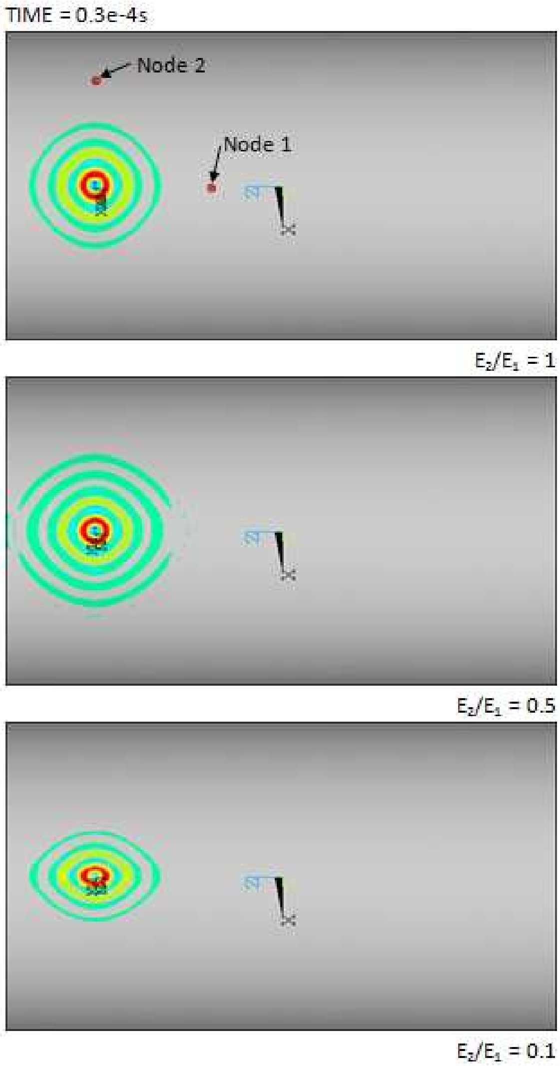

Fig. 6. Fronts of propagation waves for three cases of material properties defined by E_2/E_1 ratio (time = 0.3e-4).

It can be seen that decreasing of material stiffness in circumferential direction cause decreasing wave propagation. The response of wave propagation for two nodes marked on Figure 6 (Node 1 and Node 2) is demonstrated on Figs 8 and 9. The velocity of wave propagation for node 1 is the same for each material because of assumption of constant longitudinal Young's modulus. It can be also observed on Figs 6 and 7. Figure 9 demonstrates the difference in velocity for node 2.

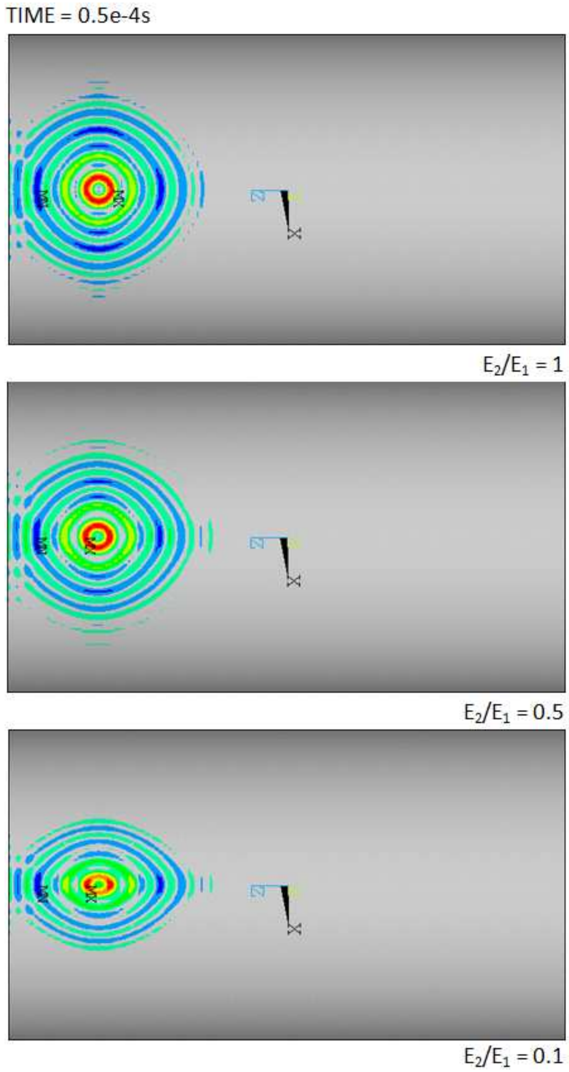

Fig. 7. Fronts of propagation waves for three cases of material properties defined by E_2/E_1 ratio (time = 0.5e-4).

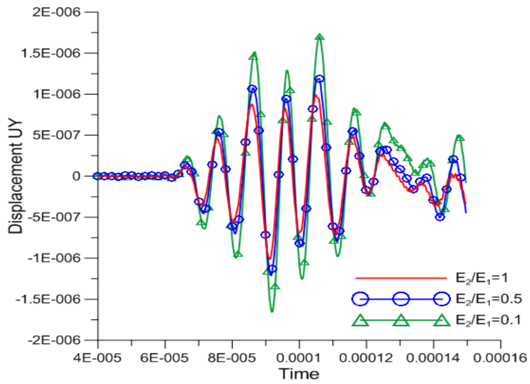

Fig. 8. Numerical wave propagation result for node 1.

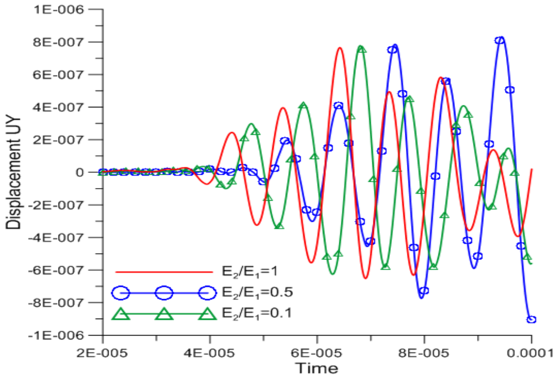

Fig. 9. Numerical wave propagation result for node2.

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