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NUMERICAL INVESTIGATION OF ELASTIC WAVE PROPAGATION IN FUNCTIONALLY GRADED MATERIALS

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Functionally graded materials (FGMs) are a new class of advanced engineering materials being developed and implemented in industry, which eliminate the material property discontinuities by grading material composition and continuously varying the compositions or volume fractions. Due to rapidly growing research interests in these materials, ways to monitor their performance and gather information on their properties are also becoming a focus for researchers. In this study, a guided wave-based non-destructive evaluation technique for the testing and monitoring of damage in functionally graded beams is developed. Firstly, functionally graded materials and the types of damage that can occur in them are reviewed and identified. Then the characteristics of guided waves propagating in functionally graded materials (FGMs) is determined analytically and numerically to optimize their application in a structural health monitoring (SHM) and non-destructive evaluation (NDE) system for the detection of damage. In numerical modelling and simulation, a finite element model is devised to simulate guided wave propagating in functionally graded beams made of functionally graded carbon fiber-phenolic nanocomposites (FGCN). The numerical results offer insights into the complicated and often erratic nature of guided waves that propagate in functionally graded materials as well as their interaction with damage.

Keywords: Functionally graded materials (FGMs), Guided waves, Piezoelectric actuator/sensor, Structural health monitoring (SHM), Non-destructive evaluation (NDE); Finite element modelling.

1 INTRODUCTION

Functionally graded materials (FGMs) belong to a class of advanced materials in which the mechanical properties vary continuously along thickness. This class of advanced materials distinguish themselves from isotropic materials because of their gradients of composition, phase distribution, porosity, texture and related material properties such as hardness, density, resistance, thermal conductivity, Young's modulus, etc. (Gasik 2010). FGMs provide a solution to the demands on material properties in advanced engineering applications in which multi-functions cannot be achieved by monolithic or homogeneous materials (He *et al.* 2009). FGMs are quickly building popularity because their mechanical properties are highly desired in industries such as aerospace, construction, automotive, medical, electronics, etc. Since FGMs have a gradual transition from one material to the other and greatly lower the chance of shearing in the intersection, they have been proved more practical to use in high temperature applications. Guided waves, including Lamb, Rayleigh and Love waves, propagate along all structures that “guide” a wave along the length of the structure such as beams, pipes and plates (Wang, *et al.* 2011). Since these types of waves travel along the complete length of structures, their use in detecting anomalies on surfaces and in sub-surfaces of materials is adopted in SHM and NDE for both homogeneous and non-homogeneous media. They are also used as a method of measuring material properties of FGMs which include the elastic modulus and density (Cao *et al.* 2011). The wave characteristics for damage detection in materials are the mode, speed, phase and amplitude of the guided waves.

In this research, the overall aim is to analytically and numerically characterize the guided waves propagating in functionally graded carbon fiber-phenolic nanocomposites (FGCNs) and then apply these elastic waves to develop piezoelectric ceramic-based structural health monitoring systems. Therefore the research has been conducted via four stages: 1) analytical analysis; 2) numerical modelling and simulations; 3) validations between analytical analyses and numerical simulations; 4) development of non-destructive evaluation and structural health monitoring methods. The research findings provide guidelines for optimal design of such a structural health monitoring system for non-destructive evaluation of functionally graded materials (FGMs).

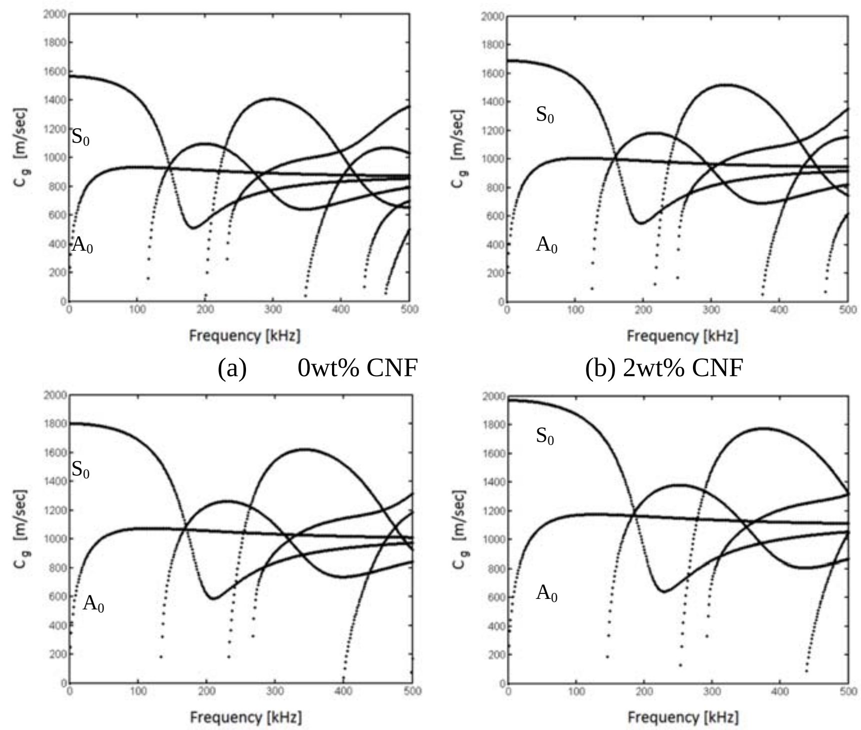
2 ANALYTICAL CHARACTERISATION OF ELASTIC WAVES IN FGMS

In this section, the characteristics of Lamb waves propagating in FGMs are investigated and dispersion curves are obtained for single- and multi-layered FGMs using a wave characterization tool - Graphical User Interface for Guided Acoustic Waves (GUIGUW) by Bocchini *et al.* (2010). The program employs the semi-analytical finite element method (SAFEM) to determine multimode Lamb waves. A series of 4-mm single-layer media made of phenolic resin matrix with 0wt% carbon nanofiber (CNF), 2wt% CNF, 4wt% CNF and 16wt% CNF were considered respectively. The material properties were determined experimentally (Ehsan *et al.* 2011) as listed in Table 1.

Table 1. Material properties of 0wt%, 2wt%, 4wt% and 16wt% CNF.

Material	**Young’s Modulus (GPa)**	**Density (kg/m³)**	**Poisson’s ratio**	**Thickness (mm)**
0wt% CNF	2.63	1180	0.3	4
2wt% CNF	3.09	1191.4	0.3	4
4wt% CNF	3.55	1202.8	0.3	4
16wt% CNF	4.49	1271.2	0.3	4

Group and phase velocities versus frequency of Lamb waves were determined in each of the single-layer media made of varying volume fractions of CNF using GUIGUW, as shown in Figure 1. From these analytically obtained dispersion curves, it can be seen that the dispersion effect changes with regard to the group velocity of the modes as well as the relevant frequency. Based on these results, an appropriate frequency to use for excitation of the S_0 and A_0 modes in single-layered carbon/phenolic nanocomposites should be between 10 kHz and 100 kHz.



(a) 0wt% CNF (b) 2wt% CNF

(c) 4wt% CNF (d) 16wt% CNF

Figure 1. Dispersion curves of single-layer 4-mm-thick media.

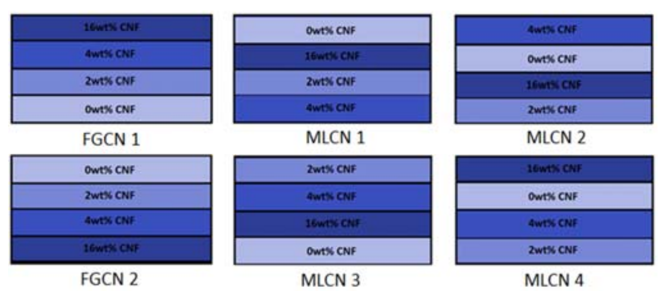
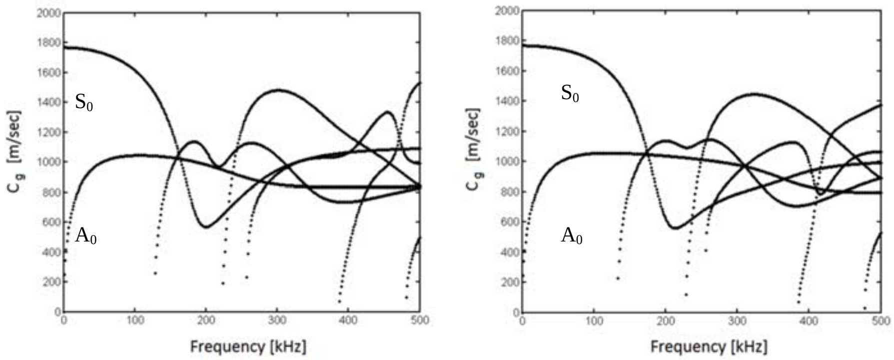


Figure 2. Graphical representation of multilayered phenolic resin media.

Secondly several multilayered phenolic resin media – FGCN and MLCN, made of functionally graded carbon fiber-phenolic nanocomposites with varying volume fractions of CNF each layer of 1 mm thickness, were investigated as shown in Figure 2. Figure 3 shows the dispersion curves of FGCN1-2 and MLCN1-4. It can be found that an appropriate frequency to use for excitation of the S_0 and A_0 modes in multi-layered carbon/phenolic nanocomposites should still be between 10 kHz and 100 kHz although there is a much more complex relationship between the dispersion curves in MLCN1-4 compared to those in FGCN1-2.



(a) FGCN1-2 (b) MLCN1-4

Figure 3. Dispersion curves of multilayered phenolic resin plates.

3 FINITE ELEMENT MODELLING AND SIMULATIONS OF GUIDED WAVES IN FGM BEAMS

In this section, a three-dimensional (3D) finite element analysis (FEA) is employed to model Lamb wave propagation and the interaction between elastic waves and damages via monitoring the characteristics of both S_0 and A_0 modes propagating in FGM beams (Yang *et al.* 2006; Wang and Yang 2014). The 3-D model of the FGM beam without and with damage was 470 mm long, 4 mm thick and 20 mm wide as shown in Figure 4.

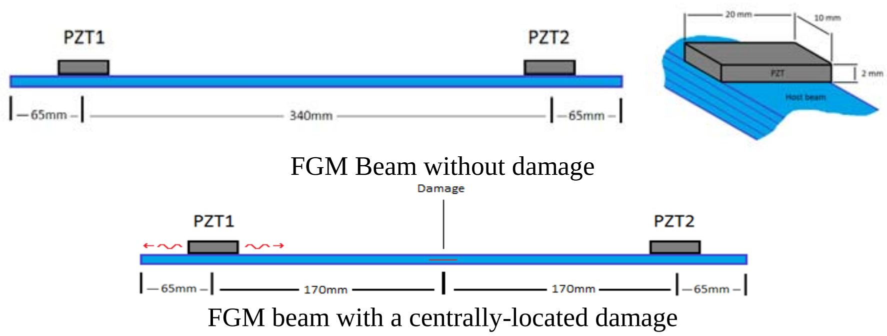
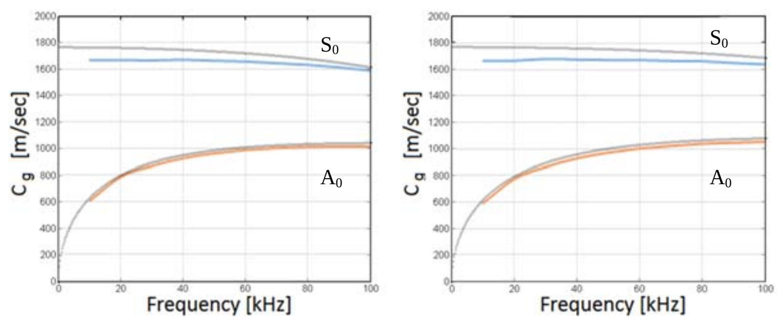


Figure 4. 3-D finite element model of FGM beams.

The 3-D FE model of the FGM beam with a centrally-located damage was also developed with the same dimensions of the FEM beam without damage. For a parametric study, the damage can have a size of 2, 4, 6, 8 and 12 mm as well varying depths of 1, 2 and 3 mm from the top surface. The excitation of the guided waves used in the 3-D FEA was performed using a piezoelectric equivalent force applied at the locations of piezoelectric patches, PZT1 and PZT2. Two wave data process methods were employed during the 3-Dimenssioal study, one is the pulse-echo method, whereby a signal was excited at PZT1 and returned wave packets from any damage and/or boundaries in the model would be received by the same PZT1. The other one is the pitch-catch method, whereby a signal was excited at PZT1 and received at PZT2. Group velocities of wave packets can be accurately calculated to distinguish wave reflections from different sources. The envelope of each of the wave modes can be obtained by employing the Hilbert transform, whereby the group velocity was calculated from the time of flight (TOF) of the peak of the propagating wave packet from the excitation point to the receiving point.

4 RESULTS AND DISCUSSION

In this section, the numerical results obtained using the devised finite element models are post-processed and discussed. The 3-D model of the FGM beam without damage is applied as a benchmarking case – Pristine and verified with the analytical results obtained using GUIGUW as shown in Figure 5. The results are in good agreement with each other for both FGCN and MLCN and the numerical results in blue and orange are a little bit lower than those analytical ones.



(a) FGCN1-2 (b) MLCN1-4

Figure 5. Dispersion curves of multilayered phenolic resin plates.

Figure 6 shows the typical results of Lamb waves obtained for the FGM beam with a damage of 8 mm at 60 kHz. Both the pulse-echo method and the pitch-catch method can identify this centralized damage and results should both methods are functional.

5 CONCLUSIONS

The dispersive characteristics of elastic guided waves propagating in functionally graded materials have been determined and investigated for NDE and SHM. It can be postulated from the numerical results extracted from the numerical simulation, Lamb waves including A_0 and S_0 modes at a frequency below 100 kHz could be used to perform damage detection in thin beams made of functionally graded carbon fiber-phenolic nanocomposites and an optimal frequency can be chosen based on the characteristic size of the damage, i.e., 60 kHz chosen for the damage of an 8-mm size. Both the pulse-echo and the pitch-catch methods can be employed for SHM and they need baseline data from a pristine host beam without damage as a benchmarking case to compare with data obtained from beams with damage and then determine the location and size of the damage. Further research could be aimed at creating a database of waveform knowledge on multiple damage types in FGMs.

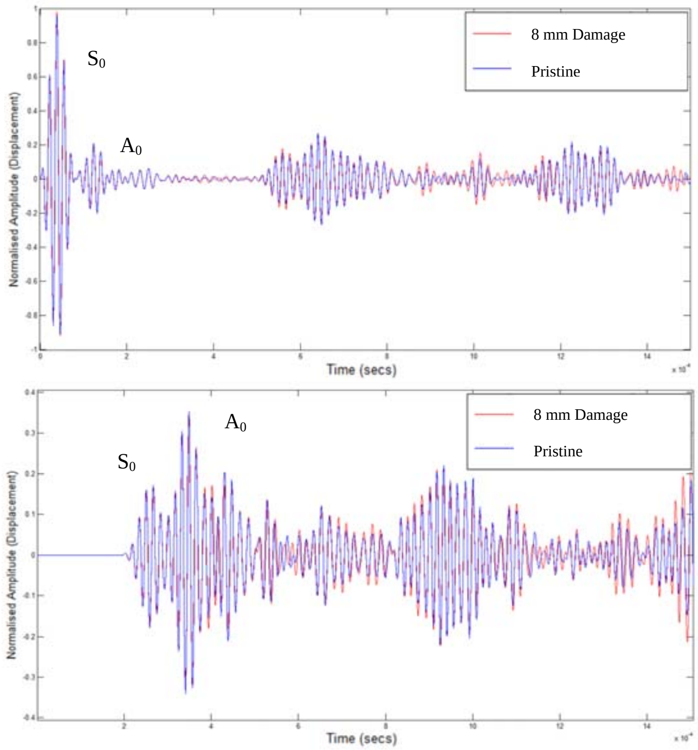


Figure 6. Comparison of damaged (8 mm delamination) and pristine specimen using the pulse-echo method (above) and the pitch-catch method (bottom) at an excitation frequency of 60 kHz.

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