

GUIDED WAVES FOR POROSITY ESTIMATION IN COMPLEX SHAPED STRUCTURES

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INTRODUCTION

One of the key benefits of modern composite materials manufacturing is that it allows the design of today's structures to have complex contours. This is increasingly being found in most all facets of composite materials industry. A typical manufacturing process for such complex shapes would be to cut the pre-preg composite sheet to dimensions using computer controlled machines, place the various pieces in a specified lay-up sequence and use the vacuum bag to remove air and waste gas while it is cooled inside an autoclave, subjected to a controlled temperature-pressure cycle. Other methods such as filament winding, braiding etc. can also be used to fabricate such structures.

This method has several advantages and works especially well for flat configurations. However, in the case of sharp curvatures and uneven contours, it is frequently observed that these regions are affected by a higher degree of porosity, especially in the sub-surface regions. This could be influenced by several factors such as imperfect pressure distribution, non-conformability of the vacuum bag etc. It now becomes important to be able to quantitatively estimate the extent of porosity in order to evaluate the manufacturing process as well as the product.

Traditional contour follower scanning techniques fail to adequately address the porosity estimation problem in these complex profiles. The conventional attenuation and velocity of longitudinal waves across the thickness of the structure does not provide sufficient reliability of evaluation. On the other hand, surface waves which easily traverse sharp curvatures are also found to be sensitive to the material property changes. Surface waves are also less attenuating, and the whole technique is thickness independent, thus suggesting the possibility of surface waves for tackling this problem.

In this paper, the surface waves are further explored in order to evaluate porosity content in such difficult configurations. The surface wave velocity was found to be sensitive to change in material properties due to the presence of porosity. A theoretical model is used to evaluate the sensitivity of the wave velocity to porosity content and fiber volume fraction. Then a new set of surface wave probes is being introduced which uses the line source mediator to generate wave modes in materials in which traditional surface wave probes do not. The sensitivity of the surface waves to porosity is then analyzed along with evaluation of the inherent limitations.

ANOMALY MODELLING

The anomalies which are being modelled are considered to be global in nature and hence their influence is directly manifested in the effective elastic constants. The modeling assumes that the wavelength of the ultrasound is of an order higher than any inhomogeneity brought about by either lay-up configurations or presence of anomalies. The effective elastic constants is built-up from the microscopic to the macroscopic level. First the single laminate is considered to be made of isotropic matrix, transversely isotropic fibers and uniformly distributed porosity. This relationship can be found in literature by many authors, notably Martin[1]. Then using the coordinate transformation relationship, the elastic constants for a given direction (usually 0°) is transformed to other orientations. This provides a set of elastic constants for any given ply-group orientation. Then finally, the various individual ply-groups are laid up by using the laminated plate theory approach discussed in Tsai [2].

Porosity content modeling

If imperfections of a composite can be modeled as a change in properties of one of the constituents of a binary fiber-reinforced composite, or by their different ratios, such tasks can be relatively easy using an effective elastic constant approach. Let us consider for example the effect of small voids. It has been established by a morphological studying of porosity defects in graphite-epoxy composites by several investigators that voids tend to be small and spherical at a low porosity volume fraction (less than 2%) and at higher volume fractions interlaminar voids due to trapped air tend to be much larger and flattened and elongated in shape. Therefore, for the case of a low void content (i. e., where the void volume fraction in the matrix is < 0.1), Hashin's [3] expressions for the elastic modulus of isotropic, homogeneous solids containing voids can be applied. Here, the influence of voids is considered as an exclusive property of the matrix alone and hence, it is justifiable to degrade the matrix properties alone. Then for all composites with specific volume fiber fractions (FF), its porosity degree (PC) can be written as

$$PC = P(1 - FF) \quad (1)$$

The density (ρ_c) of a composite is related to the density of the degraded matrix (ρ_m) and the fiber density (ρ_f) containing voids through the law of mixtures and this relationship can be represented as follows

$$\rho_c = \rho_f FF + \rho_m (1 - FF) \quad (2)$$

Once the material properties of the matrix with voids as a function of porosity degree (PC) are known, the composite material properties can be also calculated using the equations provided in detail by Martin[1] and Balasubramaniam[4]. We have thus obtained, for a unidirectional fiber-reinforced composite with isotropic or transversely isotropic fibers, expressions for effective elastic constants as a function of porosity degree (PC) and volume fiber fraction (FF).

Experimental verification

In order to verify the effective elastic constants model, experiments were conducted on a thick composite structure using ultrasonic methods already established for single sided elastic property analysis of composite materials[5]. In this work, the single sided technique was compared with the already established cube-cutting technique[6] as well as destructive analysis. It could logically be concluded that if the effective elastic constants model were to be accepted it should favorably compare with the single sided technique.

Several thick multi-layered graphite-epoxy composite specimens were considered in the study. Each had a different lay-up configuration and hence the effective material properties were different. Figure 1 shows a cross-sectional micro-photograph of one such specimen. The results obtained by comparing the model and the single sided inspection is illustrated in Table 1. From this study, it could be concluded that the error of computation is only 12% for the worst case. Thus, the effective elastic constant model does provide a reasonably reliable material property computation provided the individual fibre and matrix properties are given.

SURFACE WAVE VELOCITY COMPUTATION

A computer program has been written to calculate surface wave propagation in a half space. The traction-free surface may take an arbitrary orientation other than coincide with any crystal plane of the material. In the program, Euler angles are used to identify the traction free surface. This work is detailed extensively in Reference [7].

A plane wave form solution below is assumed

$$u_k = \alpha_k \exp\{ iP(\mathbf{n} \cdot \mathbf{r}) \} \exp\{ i[Q(\mathbf{e} \cdot \mathbf{r}) - \omega t] \} \quad (3)$$

Table 1. Elastic constant determination (MPa) using effective modulus theory (EMT) for three different specimen and comparison with single side experiments (SSE). Any discrepancy is also provided as a percentage (ERR).

	Specimen A			Specimen B			Specimen C		
	SSE	EMT.	ERR.	SSE	EMT.	ERR.	SSE	EMT.	ERR.
C ₁₁	14.0	12.4	11.7	12.4	13.2	5.2	10.4	10.2	1.5
C ₂₂	14.0	12.4	11.7	66.0	63.3	4.3	47.8	45.8	4.0
C ₃₃	126.3	132.5	4.7	59.8	62.3	4.0	66.8	67.0	0.3
C ₄₄	5.8	5.5	9.4	21.5	22.0	2.3	11.5	10.8	5.9
C ₅₅	5.8	5.5	9.4	4.6	5.2	11.0	3.8	3.8	0.0
C ₆₆	3.7	3.8	2.0	4.9	5.2	5.6	3.2	3.6	11.3
C ₁₂	4.8	4.8	0.0	21.4	19.3	9.9	3.3	3.6	8.3
C ₁₃	--	3.5	--	4.7	4.2	10.8	3.3	3.6	8.3
C ₂₃	--	3.5	--	4.7	4.2	10.8	9.2	9.5	3.3

where α_k is the displacement vector, Q is the magnitude of the propagation vector in the free surface, P is the decay parameter, $(\omega / Q) = v$ is the phase velocity. To be the solutions of surface wave, the quantity P in each of the terms of the solution must be such that the amplitudes of all the displacement components vanish as $(\mathbf{n} \cdot \mathbf{r})$ approach to $-\infty$.

The boundary conditions used is the traction free upper surface and the particle displacement approaching to zero when the depth of penetration goes to infinity. The final characteristic solution is obtained in the form given below.

$$F(Q) = \begin{vmatrix} T_1 & 0 & 0 \\ 0 & T_2 & 0 \\ 0 & 0 & T_3 \\ S_1 & S_2 & S_3 \end{vmatrix}_{9 \times 9} = 0 \tag{4}$$

Where

$$T_n = Q^2 A + Q P^{(n)} B + (P^{(n)})^2 C - I$$

and

$$S_n = QB_2 + P^{(n)} C$$

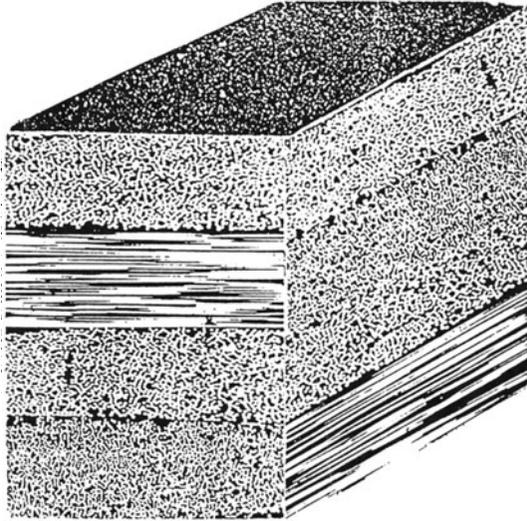


Fig. 1. The photomicrograph of the thick composite specimen used in the study.

For such complicated algebraic $F(Q) = 0$, It is necessary to use an iterative search to find the solution for surface wave phase velocity $v = 1/Q$.

An extended bisection method was used to search the slowness value of the surface waves Q ($Q = 1/v$) on a complex plane, so that the phase velocities of surface waves propagating along any direction in an arbitrary free surface of a half-space of a general anisotropy medium could be determined.

Surface wave sensitivity to porosity

The changes in the elastic constants(all nine due to orthotropic symmetry) for five different levels of porosity in a cross-ply woven graphite epoxy composite material was evaluated. Then these elastic properties were fed into the surface wave velocity estimation software and the polar surface wave velocity profiles were obtained. The polar profiles as seen from the Fig.2 illustrates the sensitivity of the surface waves to low levels of porosity. It could be observed from this figure that a 10% change in surface wave corresponds to a 8% change in porosity.

NOVEL PROBE DESIGN CONCEPTS FOR SURFACE WAVE GENERATION

Unfortunately, conventional means of surface wave generation are not possible with most composites. The conventional means, otherwise known as the resonance technique, utilizes an obliquely incident longitudinal wave

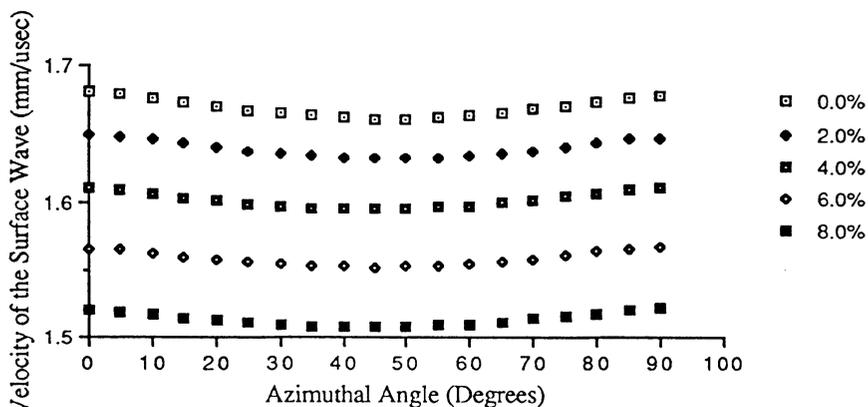


Fig.2. Surface wave sensitivity prediction to porosity content

from a liquid or solid material either near or beyond a third critical angle. This is due to the low surface wave velocity in these composites which is comparable with the commonly found polymer materials used as transducer shoes. The Snell's law criteria can only be satisfied at extremely high, impractical angles of incidence. To overcome this problem, we have adopted a line source method. Under this alternative, a sharp edged mediator (usually made from metal) is used to generate a surface wave in the composite. This mediator is coupled to a transducer whose incident angle is the surface wave critical angle, otherwise known as the third critical angle, for the given incident media/mediator combination. Thus, the surface waves are first generated on the surface of the mediator by traditional techniques. As the surface wave travels down the mediator, its thickness is decreased to a sharp line source which is placed on the composite, and then through the sharp edge, the surface waves are transmitted to the structural surface. This line source is thus able to generate surface waves as well as other modes within the composite material.

This design employs two transducers coupled to a mediator. The transducers are fixed so that the two line sources are parallel and facing each other. This way the spherical loss is eliminated and the simplified geometry reduced any multiple reverberation echoes. Measurements up to a transducer separation distance of 3" is possible using the designed probe setup. Much longer distances could also be measured using this technique due to the low attenuation levels of surface waves. A 1.0 MHz Harisonic Transducer is used and the separation distance is 1.5". The signal to noise ratio is excellent.

The connecting linkage holding the two transducers allows for a repeatable separation distance to be maintained between the two transducers. The next step in the design is to somehow measure accurately the surface wave travel distance over the curved surfaces. For simple geometry, the distance between the transducers can accurately be determined but unfortunately this distance does not always correspond to the surface wave travel distance over a curved surface. A

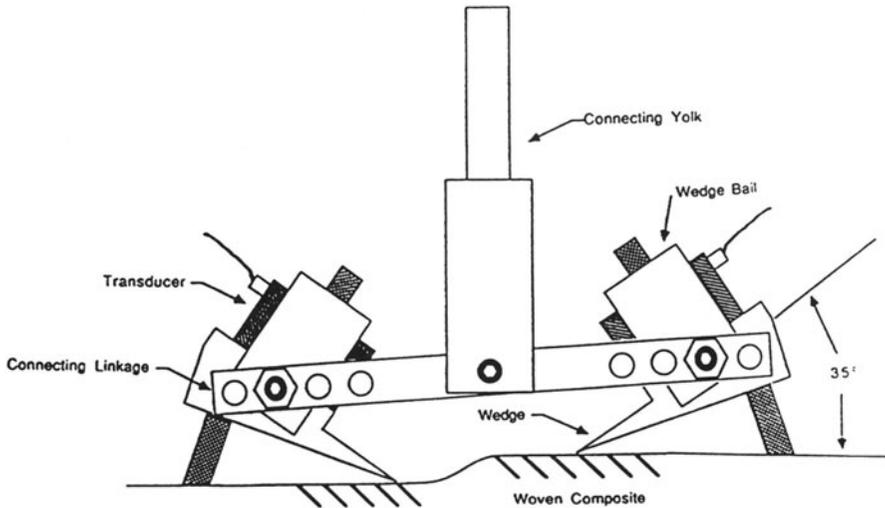


Fig. 3 The surface wave generation probe

measuring roller is currently being evaluated to accurately measure travel distance along the surface. The assembly is also capable of conforming to different size contours. This is important since there are many different geometries that could be present on the composite structure. Another useful feature is that the probe can be easily be operated using a single holder.

Experimental Measurements of the Surface Wave Velocities

The results of surface wave velocity measurements on graphite epoxy woven specimens in two perpendicular directions, i.e. 0° along warp yarns direction, 90° along filling yarns direction, for both frequency 1 MHz and 0.5 MHz are presented in tables 2. Porosity presence is a result of variations in the pressure-temperature curing cycle during the manufacturing process. Destructive testing of these samples are yet been conducted. Hence, only a qualitative estimate of the porosity content can be provided.

Surface wave velocities were measured and two features which show promise are the velocity difference between the 0° and the 90° directions and the change in the velocity with frequencies at 1.0 Mhz and the 0.5 Mhz.. Here, the second feature is due to frequency dispersion of the porous particles. It can be observed from table 2, that in the good regions both of the features have very low values compared with the porous specimens. Thus the two features considered here, show promise for porosity estimation. Further work needs to be accomplished before any strong conclusion can be made.

SUMMARY

The influence of anomalies such as spherical porosity are modeled as an influence of material degradation of the effective elastic constants. Theoretical developmental

Table 2. Velocity Measurements of Surface Waves on the Woven Composites

Quality →	Porous Specimen				Good Specimen		
Velocity Diff. Feature ($V_0 - V_{90}$)	0.149	0.123	0.049	0.157	0.0	0.007	0.009
	mm/μsecs				mm/μsecs		
Dispersion Feat. ($V_{1 \text{ Mhz}} - V_{0.5 \text{ Mhz}}$)	0.109	0.069	0.162	0.070	0.0	0.02	0.0
	mm/μsecs				mm/μsecs		

studies are being conducted for the evaluation of the parameters and the sensitivity of surface waves to porosity presence. The surface waves were first successfully generated on composite structures using a novel line source wedge transducer (due to Snell's law limitations, the regular angle shoes are not practical). New features have been defined and their sensitivity to material anomalies have been demonstrated. Features from the azimuthal velocity variations are useful in isolating specific anomaly influence from the velocity changes due to anisotropy and inhomogeneities.

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