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초음파 트랜스듀서 투과법을 이용한 CFRP 복합적층판의 특성평가

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Characteristics Evaluation of CFRP Composite Laminates Using a Through-Transmission Method of Ultrasonic Transducers

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Abstract

When propagating the thickness direction of composite laminates ultrasound waves interacts strongly with the orientation and sequence of the plies in a layup. Also the layup orientation greatly influences its properties in a composite laminate. If one ply of the layup orientation is misaligned , it could result in the part being rejected and discarded. Now, most researchers cut a small coupon from the waste edge and use a microscope to optically verify the ply sequences on important parts. Those may add a substantial cost to the product since the test is both labor hard and performed after the part is cured. A nondestructive technique would be very beneficial, which could be used to test the part after curing and require less time than the optical test. Therefore we have developed, reduced, and implemented a novel ply-by-ply vector decomposition model for composite laminates fabricated from unidirectional plies. This model decomposes the transmission of a linearly polarized ultrasound wave into orthogonal components through each ply of a laminate. It is found that a high probability shows between the model and tests developed in characterizing cured layups of the laminates.

1. Introduction

Composite materials [1] are attractive for a various applications due to the advantages. Increasingly, more and more high performance engineering structures are being built with critical structural components made from composite materials. Especially, the importance of carbon-fiber reinforced plastics (CFRP) in both space and civil aircraft have been generally recognized, and CFRP composite laminates are widely used. So, CFRPs are a material class for which nondestructive material property characterization is as important as flaw detection[2]. Fiber reinforced composite

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laminates often possess strong in-plane elastic anisotropy attributable to the specific fiber orientation and layup sequence. However one of important factors is the layup sequence which can influence the CFRP composite performance. This greatly effects its properties in the composite laminate. If one ply is misaligned in the layup sequence, it can drastically alter the mechanical performance of composite laminates. So most manufacturers cut a small sample from the waste edge and use a microscope to optically verify the ply orientations on critical parts, which can add other cost to the composites due to intensive labor and performance after curing.

Recently, some researchers have utilized a nondestructive method using a 4 GHz microwave to determine the fiber orientation in the CFRP composites. This method is based on the electrical anisotropy in the orthotropic directions of a unidirectional laminate, with the principal direction aligned with the direction of the fibers. For this method, an incident standing wave is projected into the sample at a given orientation. The differences between the received signals, one with the receiving unit polarized horizontally and one with the receiving unit polarized vertically with respect to the apparatus, were used to determine the fiber orientation in samples constructed from two to eight plies of prepreg tape. Also, they also conducted a research using a 35 GHz microwave to determine fiber orientation in carbon fiber reinforced plastics. Studies were performed on thick composite laminates by Komsky, Zgonc, and Daniel [3]. So, they have developed and successfully used to predict the layer orientation for a 70-ply layer laminate through a neural network. And Komsky, Daniel, and Lee[4] have been researched the interaction of ultrasonic shear waves with thick composite laminates. This research studied the transmission of shear waves through laminates with both the transmitter and receiver aligned and fixed with respect to the fiber directions in the outer layers of the sample. Results of the experiments showed that changing the layer orientations in the laminate caused a direct effect on the received signal shape and amplitude. A layer-by-layer vector decomposition model was presented to theoretically explain the interaction of shear waves as they propagated through the laminate, but no simulated results were given for the samples tested.

In this study, we have found that the transmitted signals of normal incident ultrasound wave, shear wave in a "crossed polarizer" configuration were found to be particularly sensitive to ply misorientation and layup sequence in a laminate. Therefore, a new technique is presented for determining ply orientation errors and sequencing errors in a composite laminate using through transmission of shear waves based on the theoretical ply-by-ply vector decomposition. The test is performed by rotating the transducers and plotting the peak-to-peak amplitude as a function of the transmitter orientation with the transducers in a crossed arrangement and the received signal. Simulated and experimental results are presented for laminates fabricated from 32 plies which confirm the high sensitivity to detect a single ply orientation error. The test was also successfully used to detect sequencing errors for symmetric and non-symmetric laminates about the mid plane, i. e. $[(0/45/90/-45)_4]_S$ versus $[(0/45/90/-45)_8]_T$.

Ultrasound shear waves require a highly viscous couplant between the transducer and the test piece. The usual shear wave couplant is burnt honey; unfortunately, it is very difficult to maintain a consistent property for burnt honey. Experimental measurement results could not be duplicated with a high degree of quantitative reproducibility due to the inconsistency of the couplant from test to test.

2. Theoretical Model

This model decomposes the transmission of a linearly polarized ultrasound wave into orthogonal components through each ply of a laminate[5]. The input to the first ply is decomposed into one component which propagates through the first ply parallel to the fibers and one component which propagates through the first ply perpendicular to the fibers. These two components then become input for the second ply, where each one is then decomposed into components parallel and perpendicular to the fibers in the second ply. This process continues for all remaining plies in the laminate. After all of the components have been decomposed and have propagated through the last ply in the laminate, the components are projected onto the axis of the receiver and are combined to predict a received signal. The model is general and applies to any layup produced from plies with orthogonal properties.

In the above attenuations, α_i, β_i, and ρ are the attenuation coefficients, (h_i) is the thickness of the i^th ply, and (tt) and (tr) are the couplant thicknesses at the transmitter and receiver, respectively. Losses due to beam spreading and interface losses, which depend on the ply to ply orientations and thicknesses, are included in the $f_{ij}(\delta)$ signal reduction factor. The ply-by-ply vector decomposition model can now be derived.

A wave pulse, S_T, is generated by the transmitter at angle α_T and propagates through the couplant to the face of the first ply. The wave now has the amplitude $S_T e^{-\rho(tt)}$ due to the signal attenuation of the couplant, and a time shift equal to the thickness of the couplant divided by the wave velocity through the couplant. This signal is then decomposed into two components through the angle $\Delta\theta_1 = \alpha_T - \alpha_1$ in directions parallel and perpendicular to the fibers in the first ply. These two components shown in Fig. 1 then propagate through the first ply and are reduced by their respective attenuation, interface, and beam spreading losses. Time shifts of the two components, caused by the fact that ν_α and ν_β are not equal, are tabulated along with the magnitude changes due to losses in lieu of the typical phase term e^{-ikx}. New values and time shifts for each component are now given by Eq. (1).

Parallel Component exiting 1st ply:

$$S_T e^{-\rho(tt)} e^{-\alpha 1(h1)} f_{11}(\delta)\cos(\Delta\theta_1)@[\Delta t=(tt)/ \nu_\rho+(h1)/ \nu_\alpha]$$

Perpendicular Component exiting 1st ply:

$$S_T e^{-\rho(tt)} e^{-\beta 1(h1)} f_{12}(\delta)\sin(\Delta\theta_1)@ \ [\Delta t = (tt)/ \nu_\rho + (h1)/ \nu_\beta] \tag{1}$$

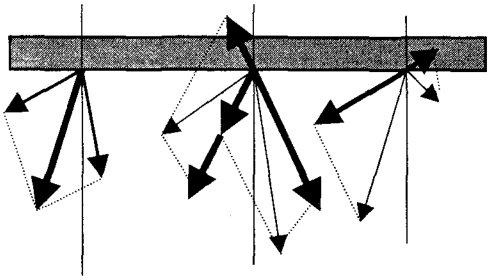

Fig.1 Schematic of the ply to ply vector projections

3. Experimental Method

3.1 Specimen Configurations

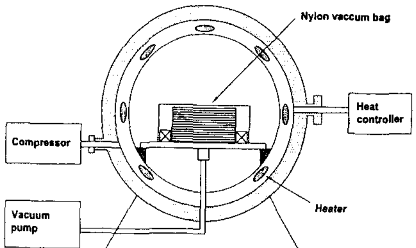

Fig. 2 Schematic diagram of autoclave

The laminates of the specimens were manufactured from uni-directional prepreg sheets of carbon fibers(CU125NS) by Korea HANKUK Fiber Co., had the material properties based on the manufacturer's specifications. The CFRP composite laminates are made of 32 plies of these sheets stacked at different angles. They are cured by heating to the appropriate hardening temperature (130℃) as means of a heater at the vaccum bag of the autoclave shown in Fig 2. Three types of specimens were used in this experimentation. Their lay-up, stacked with 32 plies, indicates that specimen A is $[(0/45/90/-45)_8]_T$, specimen B is $[(0/45/90/-45)_4]_S$ and specimen C is $[(0/45/90/-45)_4]_S$ with the 16th ply at $+45^0$ instead of -45^0. Test specimens were prepared with dimensions 70mm × 70mm × 4.23mm (width × length × thickness). And the fiber-direction of specimen surface is manufactured to correspond to 0° direction.

3.2 Experimental Setup

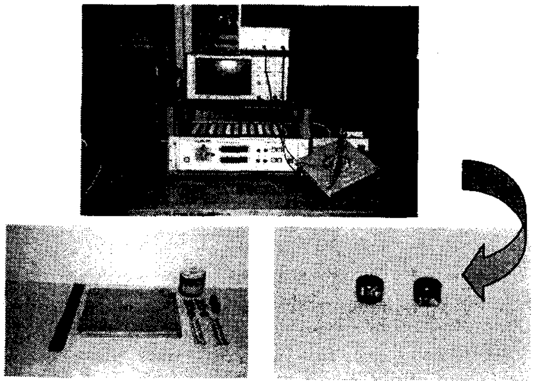

Fig. 3 Instrumentation for ultrasound testing

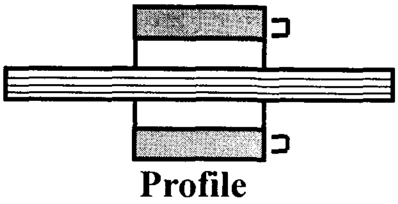

Fig. 4 Schematic of through-transmission method for ultrasound pulses

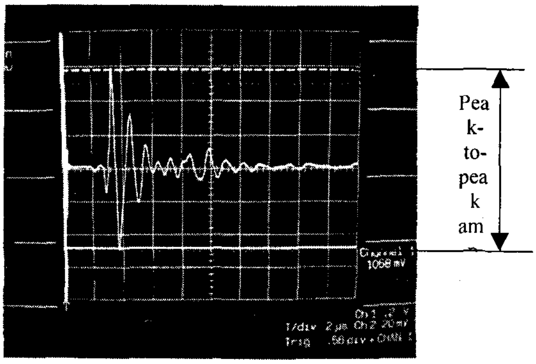

Fig. 5 Typically peak to peak amplitude of through-transmission method

Standard instrumentation for ultrasound testing was used to perform the experiments shown in Fig. 3. This instrumentation included a Panametrics #5052PR pulser/receiver and a LeCroy 9400 digital oscilloscope. The waves were generated and received using a pair of Panametrics V153, 12.7 (mm), 1 MHz, shear wave transducers which were coupled to the composite laminates using a burnt honey couplant supplied by Panametrics. A simple fixture was fabricated from two 196 x 196 x 6 (mm) aluminum plates to hold the composite laminate being tested. Each plate has a 18 (mm) hole in the center, to keep the transducers aligned during testing, and one 6 (mm) hole at each corner for aligning the plates. A polar grid for orienting the transducers is mounted on the outside face of each plate and the transmitter face plate has a second polar grid mounted on its inside face. This grid is used for orienting the composite laminate. Other components of the fixture include miscellaneous hardware shown in Fig. 3 as well.

3.3 Measurement Techniques

The fixture is assembled for experimental data acquisition by first placing the test specimen face down on the transmitter face plate and aligning its 0^0, 45^0, 90^0axis between two transducers. Two bolts are then inserted up through opposite corners of the plate, the receiver face plate is lowered carefully onto the laminate, and two wing nuts are then installed on the bolts. The fixture is then flipped over and the remaining two bolts are inserted and secured with wing nuts. Next, a thin layer of burnt honey couplant is applied to the faces of the transducers, which are then inserted into the 18(mm) holes in the fixture. The transducers are held against the laminate under a slight pressure during the test by means of the rubber stoppers, steel washers, and steel clamping bars. And figure 5 shows typically peak to peak amplitude of through-transmission method from a LeCroy 9400 digital oscilloscope.

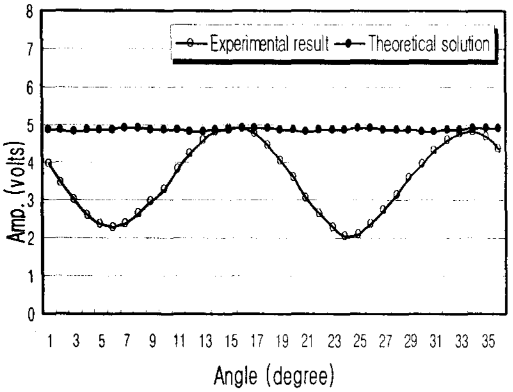

Fig.6 Comparison of experimental and theoretical results for specimen A.

4. Results and Discussion

Experimentation consists of performing a polar scan using a through transmission with the transducers in a crossed arrangement, that is, the receiver polarization is oriented at 90^0 to the polarization of the transmitter. For an isotropic material, this test will produce a null, or zero received signal at any transmitter orientation. However, for a laminate consisting of orthotropic plies, this test is very sensitive to fiber orientation and ply sequence as shown by both computer modeled and experimental results. The specimens used for this test are based on a realistic layup sequence used in manufacturing composite components and possible errors which can occur during fabrication. When the fixture is assembled for experimental data acquisition by first placing the test specimen face down on the transmitter face plate and aligning its 0^0, 45^0, 90^0axis between two transducers, it is found that aligned angle 90^0 is very sensitive between transmitter and receiver in the through-transmission method. Specimens A, B and C were compared to demonstrate the test's capability and sensitivity in determining a misoriented ply or an unsymmetrical layup with the same base sequence as a symmetrical layup with experimental and theoretical solutions shown in Figs. 6 and 7. First of all, in the case of specimen A with unsymmetric layups, experimental and theoretical solutions

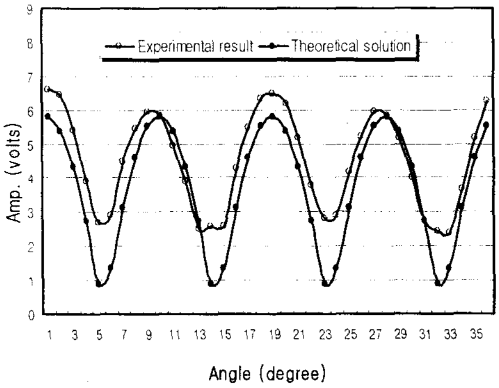

Fig.7 Comparison of experimental and theoretical results for specimen C

were obviously shown in Fig.6. And figure 7 shows comparisons of experimental and theoretical solutions in the case of specimen C with a single misoriented ply with symmetric layups. So it is found that relation is in good agreement with amplitude and angle between experimental and theoretical results. Therefore, a strong correlation is observed in this figure.

5. Summary

A through-transmission ultrasound test method has been performed to evaluate the layups of the laminates By using the CFRP composite laminates manufactured from one-directional prepreg sheets, Both theoretical and experimental results demonstrated the high sensitivity. In the case of specimen A with unsymmetric layups, experimental and theoretical solutions were obviously shown. And, a strong correlation is observed much more between experimental and theoretical solutions for the specimen C with a single misoriented ply with symmetric layups. This high sensitivity is ideally suited for characterizing the layup sequence in a laminate and detecting realistic manufacturing errors. And the implementation of the reduced ply-by-ply vector decomposition model has been successfully utilized to qualitatively model the behavior of ultrasound waves transmitted through a composite laminate fabricated from unidirectional plies. This model has the capabilities to qualitatively predict the effects of a ply misorientation and layup symmetry. This was demonstrated by comparing the theoretical and experimental results.

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