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ULTRASONIC WAVE VELOCITY OF CRACKED FRP LAMINATES

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SUMMARY: The possibility of using lowest symmetric Lamb wave for evaluation of laminate stiffness reduction is investigated. Ultrasonic wave velocities are measured for both uncracked and cracked FRP crossply laminates with different cracked ply thickness. It is confirmed that under long wavelength approximation, even if the laminate is cracked, wave velocity of S_0 Lamb mode is primarily dependent on overall laminate stiffness and well predicted by well-known plate velocity. The dependence of wave velocity on the propagation direction is also evaluated to discuss damage induced anisotropy.

KEYWORDS: FRP laminate, Lamb wave, nondestructive evaluation, ultrasonic testing

INTRODUCTION

Composite materials play an increasingly important role in industry today, mainly because their high specific stiffness, strength and excellent fatigue resistance. Generally, many of these components are in the form of laminated plates. As composite plates are being used in safety-critical application such as in aircraft structure, the nondestructive testing(NDT) of composite plates becomes more important. Conventional NDT of composite plates by ultrasonic techniques such as the C-scan usually uses waves propagating normal to the surface of the plates. This type of testing is very time consuming for the inspection of large structure because the transducer must be scanned over the whole area to be tested. Lamb waves, which propagate in the plane of plate-like structure, are useful for long-range testing of composite laminates since they can propagate a long distance along the laminate. A large region can be tested for each transducer position. Over the past few decades, many workers have paid special attention on the essential features of Lamb wave in laminated medium[1-7], and the use of Lamb waves for NDT of composites has been extensively investigated[8-14].

Because laminated composite plates are designed to carry in-plane load in most cases, there is a need for ultrasonic testing methods to evaluate material properties in the in-plane directions of composite laminates. Measurement of ultrasonic wave speed is directly related to material stiffness, so that it is a quantitative parameter that gives information about the mechanical state of the material. It may also be related indirectly to information about strength and residual life. In this work, the lowest symmetric Lamb wave(S_0 mode) is used

and change in wave velocity due to matrix cracks is related to the stiffness reduction of composite laminates. The dependence of wave velocity on the propagation direction is also evaluated for both uncracked and cracked laminates to discuss damage induced anisotropy.

ULTRASONIC WAVE VELOCITY OF UNCRACKED LAMINATES

Specimen

In the present study, to detect matrix cracks by the naked eyes glass fiber reinforced plastics(GFRP) were used in experiments. GFRP plates were fabricated with Scotchply prepreg by autoclave molding system in accordance with the manufactures' recommended process. Material properties of a unidirectional laminate are given in Table1. In this table, L and T are referred to fiber direction and transverse direction respectively. Rectangular coupon specimens were cut from plates by diamond saw. Each specimens is 300×15mm in dimension. Volume fraction of glass fibers is about 50%. Laminate configurations to be tested and thickness of the plate are summarized in Table 2. Since wave propagation characteristic of Lamb mode depend on thickness of the plate, unidirectional laminates with different thickness were prepared. Crossply laminates with different center ply thickness were also prepared to evaluate size effect of matrix cracks in a later section.

Table 1 Material properties of unidirectional laminate.

E_L [GPa]	E_T [GPa]	G_L [GPa]	ν_L	ρ [kg/m^3]
36.3	12.5	3.78	0.326	1850

Table 2 Laminated plates used for experiments.

Laminate configuration	Thickness [mm]
$[0_6]$	1.34
$[0_{10}]$	2.38
$[90_6]$	1.52
$[90_{10}]$	2.52
$[0/90_4/0]$	1.50
$[0/90_6/0]$	2.04
$[0/90_8/0]$	2.52

Measurement of wave velocity

The aim of the present study is to use the lowest symmetric Lamb wave to monitor the stiffness reduction of laminated composite plates. The method suggested by Tang and Henneke[15], which measures the lowest Lamb wave speed, is used in this investigation. A summary of the experimental procedure is given here. Figure 1 is the configuration of the experimental setup. A PZT transducer having a center frequency of 140kHz was used as the transmitter and a broadband transducer was used as the receiver. Both the sending and

receiving transducers were mounted flat against the specimen surface via couplant. A pulse signal is applied to the transmitting transducer, which is simultaneously received by digital storage oscilloscope, and a signal from receiving transducer is also monitored by the oscilloscope through amplifier. A sample wave detected is shown in Fig.2. Time difference(Δt) between two input signals was measured to evaluate wave velocity; first zero-cross point of the signal(point A in Fig.2) was used as wave head. To eliminate uncertainty of distance between two transducers, measurements were carried out for 5 different distances for each specimen(L=30□70mm, stepped by 10mm). Moreover, at each transducer position, the averaged waveform for 100 cycles was used to enhance the reliability of the measurement without noise. Figure 3 shows an example of measured L *vs.* Δt relation. As shown in this figure, the relation is almost linear so that wave velocities can be precisely calculated by the slope of the graph. It should be noted that in these cases wavelength is about 10 times lager than the thickness of the specimen therefore long-wavelength approximation is valid.

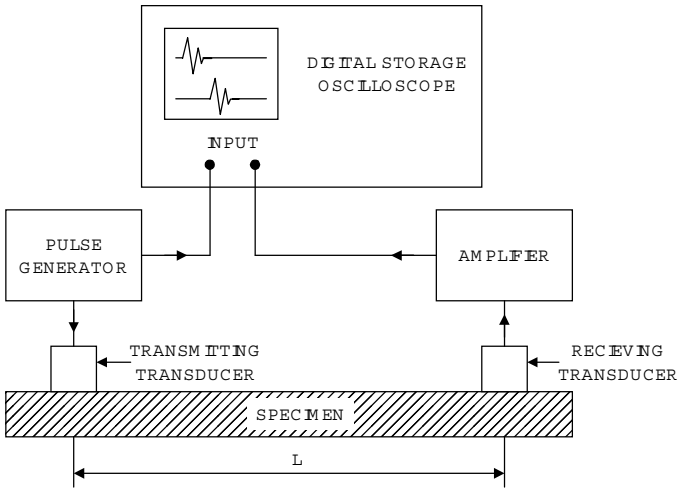

Fig.1 Schematic of experimental setup.

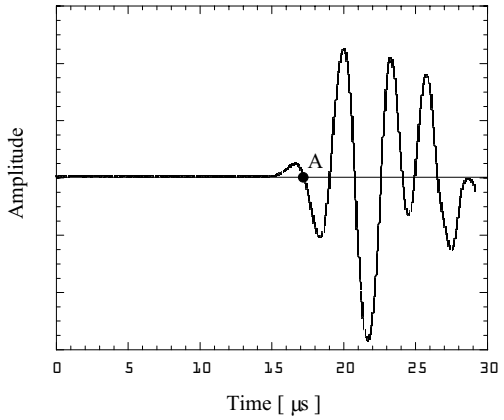

Fig.2 Sample wave monitored by digital storage oscilloscope.

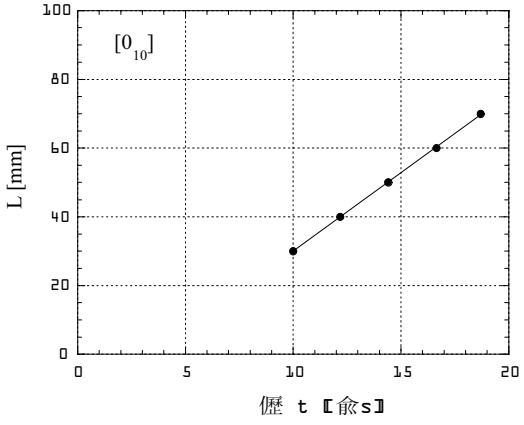

Fig.3 Example of velocity measurement. The slope of the graph corresponds to the wave velocity.

The measured wave velocities are summarized in the left hand side of Table 3. It is apparent that waves travel faster in the plate having large stiffness in the propagating direction, such as $[0_6]$ or $[0_{10}]$. The dependence of wave velocity on thickness, which is generally observed in Lamb waves, was not confirmed in this experiment. This is because wave velocity is not sensitive to thickness in lower frequency region used in this investigation. For low frequency region, in other words under long wavelength approximation, it is well known that the wave velocity of S_0 Lamb mode is approximated by the so-called plate velocity. The wave velocity of generalized orthotropic laminates is given by Reuter[16] as the following equation.

$$V = \sqrt{\frac{2(Q_{11}Q_{66} - Q_{16}^2)}{\rho\left\{(Q_{11} + Q_{66}) - \sqrt{(Q_{11} - Q_{66})^2 + 4Q_{16}^2}\right\}}} \tag{1}$$

where ρ is the mass density and Q_{ij} is the overall laminate stiffness in the coordinate defined parallel to the wave propagation direction(x_1 : propagation direction, x_2 : transverse direction). We predicted the wave velocity of laminated composite plates by substituting the material properties in Table 1 into Eq.(1). The predicted values are shown in the right hand side of Table 3. The agreement between measured velocity and predicted ones are fairly good, which indicate that the waves propagate as S_0 Lamb mode in laminated plates. Indeed, the surface deformation of laminated plates due to wave propagation is monitored by setting two receiving transducers on upper and lower surface of the same position. An example deformation for $[0/90_4/0]$ is shown in Fig.4, in which the gray area corresponds to specimen cross-section. The deformation of the specimen at wave head is confirmed to be symmetric(S_0 mode). It should be noted that in the present experimental method, the lowest antisymmetric Lamb mode(A_0 mode) can be also excited in the specimen as seen in the right side of Fig.4. However, wave velocity of A_0 mode is much smaller than that of S_0 mode, so that A_0 mode wave could not be separated from the mixed signal.

Table 3 Wave velocity of laminated plates.

Laminate configuration	Measured [m/s]	Predicted [m/s]
$[0_6]$	4533	4496
$[0_{10}]$	4583	4496
$[90_6]$	2648	2648
$[90_{10}]$	2660	2648
$[0/90_4/0]$	3418	3385
$[0/90_6/0]$	3202	3216
$[0/90_8/0]$	3008	3111

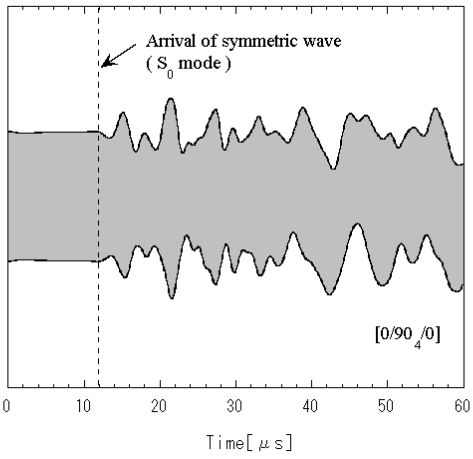

Fig.4 Surface deformation of a laminated plate due to wave propagation. $[0/90_4/0]$

EFFECT OF MATRIX CRACKS ON ULTRASONIC WAVE VELOCITY

Three types of crossply laminates, $[0/90_4/0]$, $[0/90_6/0]$ and $[0/90_8/0]$ were used for this investigation to evaluate the effect of crack size on wave velocity. The strategy for measurement of wave velocity is the same as that for uncracked specimens. In experiment, in order to evaluate crack effect precisely, crack formation positions were controlled and equally spaced cracks were formed in each specimen. At first, shallow flaws were introduced by a knife-edge on the desired positions of the specimen side edge, then uniaxial tension was applied to the specimen until all precracks span over the thickness and width direction entirely. Following the above technique, crossply laminates having different crack density, i.e. the number of cracks per unit length, were prepared. The selected crack densities are 1, 2 and 5[1/cm]. It should be mentioned that in case of $[0/90_4/0]$, control of crack formation position was difficult, so that almost saturated crack density 5[1/cm] was only used.

In Fig.5, the dependence of the wave velocity on crack density for three crossply laminates is shown as plot points. In this figure, vertical axis represents the normalized value by the velocity of the uncracked laminate. It is shown that for all laminates wave velocity is continuously decreased with the increase of crack density. It is also observed that the reduction of wave velocity is more pronounced in the laminate having thicker cracked ply(90°ply). Since reduction of macroscopic laminate stiffness is larger when the cracked ply is thick, the change in wave velocity observed in Fig.5 reflects the stiffness reduction directly. This makes us imagine that ultrasonic waves propagate in the form of S_0 Lamb mode even after crack formation. If the macroscopic laminate stiffness of the cracked laminate is known, the wave velocity of S_0 Lamb mode for low frequency is predicted by substituting effective stiffness into Eq.(1). However, all components of effective stiffness matrix are generally unknown, therefore we use predicted value of the stiffness matrix. In reference [17], we have proposed the damage mechanics model which can formulate the nonlinear response of composite laminate including a cracking ply, where effective stiffness

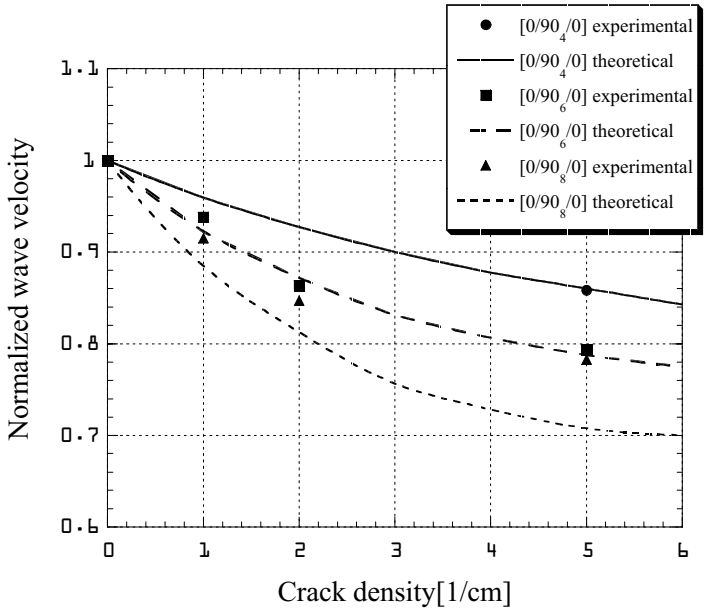

Fig.5 Dependence of ultrasonic wave velocity on crack density.

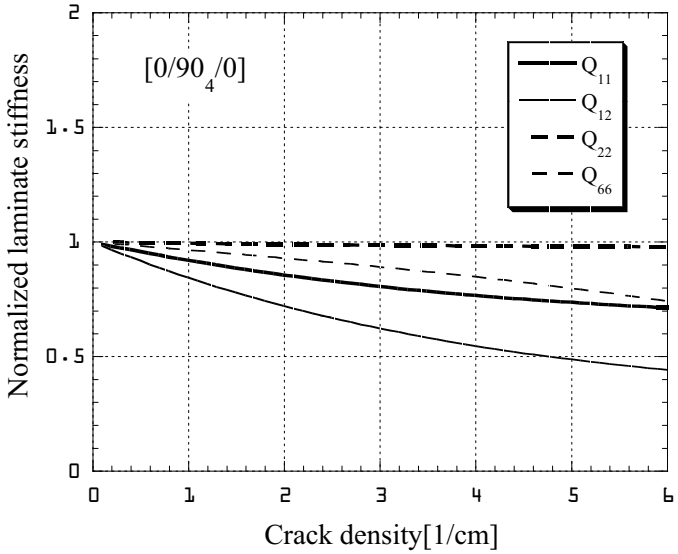

Fig.6 Reduction of laminate stiffness due to matrix crack formation.

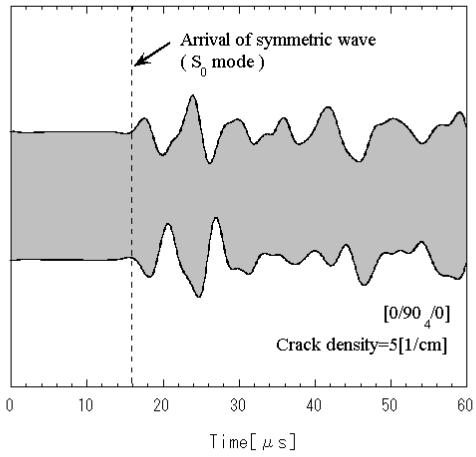

Fig.7 Surface deformation of a cracked laminate due to wave propagation. [0/90$_4$/0]

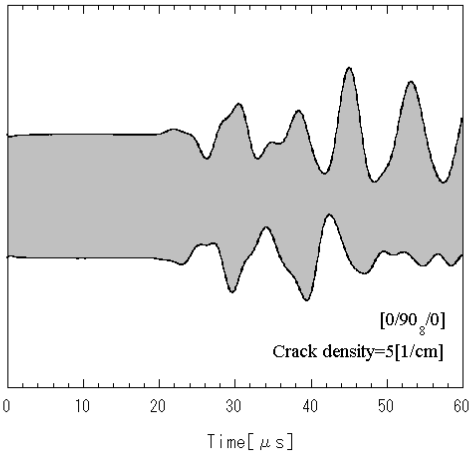

Fig.8 Surface deformation of a cracked laminate due to wave propagation. [0/90$_8$/0]

matrix at arbitrary crack density is obtained. Figure 6 shows an example of the change in stiffness matrix with crack density. All the matrix components are referred to the laminate principal axis. In this figure, Q_{16} and Q_{26} are absent because these components are always zero for crossply laminates. By evaluating the stiffness component at given crack density from Fig.6, then introducing them into Eq.(1), the wave velocity of S_0 Lamb mode is predicted. The results are drawn in Fig.5. The predicted values are in good agreement with experimental results for [0/90$_4$/0] and [0/90$_6$/0], in contrast a poor agreement is shown for [0/90$_8$/0]. Figure 7 and 8 show the surface deformation of the cracked specimens due to wave propagation. The symmetry of wave head is good in [0/90$_4$/0]; on the other hand, the wave head is corrupted in [0/90$_8$/0]. From the above results, it can be said that waves travel as S_0 Lamb mode even after crack formation so long as the crack size is not so large. For the laminate with large cracks such as [0/90$_8$/0], the present method for velocity measurement, using the wave head as arrival time, leads to considerable error because of the corruption of wave head.

EVALUATION OF DAMAGE INDUCED ANISOTROPY

In the preceding chapter, the wave velocity of rectangular coupons, which is approximated as one-dimensional problem, was considered. However, composite plates are usually in the form of the two-dimensional plate and designed to support multi-axial in-plane load. Therefore, here we deal with the wave velocity in two-dimensional plates, especially the dependence of wave velocity on the propagation direction. Schematic view of the experimental setup is shown in Fig.9. A circular plate with the diameter of 90mm is cut from a crossply laminated plate and simply supported by the outer circumference of the plate to guarantee the same boundary condition for each transducer position. We prepared three uncracked circular plates of $[0/90_4/0]$, $[0/90_6/0]$ and $[0/90_8/0]$ and one cracked circular plate of $[0/90_4/0]$ to evaluated the effect of laminate configuration and matrix cracks on wave velocity of crossply laminates. The crack density of the laminated plate is about 5[1/cm]. It should be emphasized that not all the cracks span the entire width of the specimen, some start from the left side and the others start from the right side of the specimen. The transmitter is mounted at the center of the plate and the wave velocity was measured as the same method used for rectangular specimens. The distance between two transducers is 30 □ 40mm (stepped by 5mm).

Figure 10 shows the variation of the wave velocity against mutual angle θ for three uncracked laminates. The vertical axis is the normalized values by the velocity at $\theta = 0^{\circ}$. In this figure, the experimental values are shown as plot points and the corresponding theoretical predictions made from Eq.(1) are drawn as lines. It is shown that for both experiments and predictions the anisotropy of wave velocity increase with the increase of the center ply thickness, which respects that the anisotropy of effective stiffness is more pronounced when the center ply is thick. Although the agreement between experiments and predictions are not so good in a quantitative sense, the experimental profile of the angular dependence of wave velocity is well predicted by the Reuter's theory. The quantitative discrepancy might come from the difference between one-dimensional and two-dimensional wave propagation problems. That is, the Reuter's theory is originally based on the assumption of one-dimensional wave propagation; on the other hand, the wave propagation evaluated in this experiment is apparently two-dimensional.

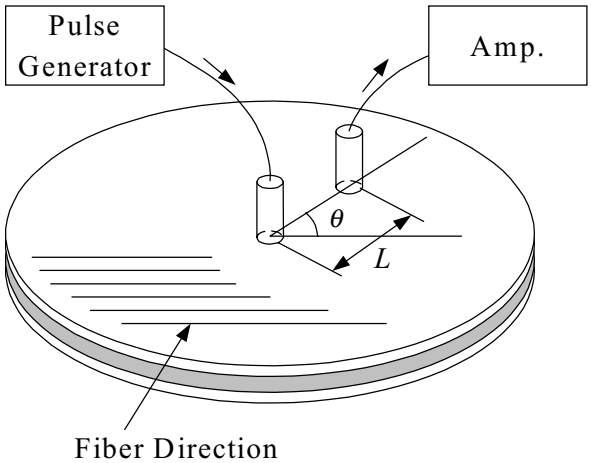

Fig.9 Experimental setup for measurement of angular dependence of ultrasonic velocity.

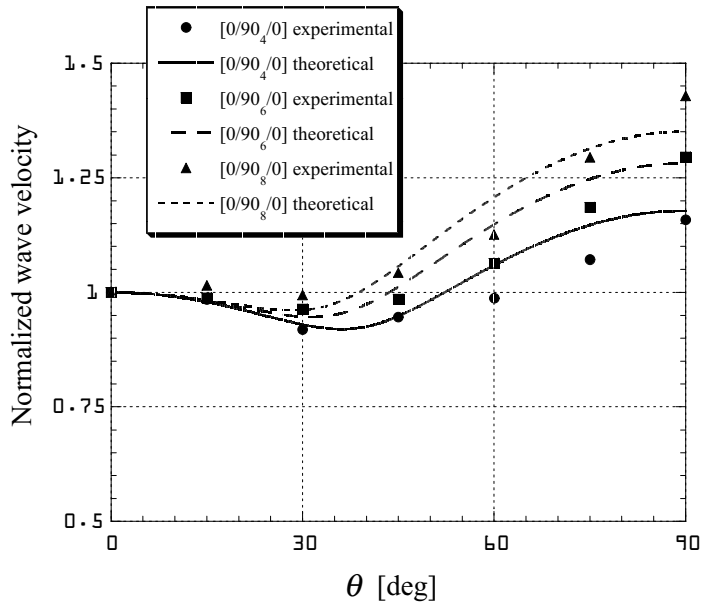

Fig.10 Angular dependence of wave velocity of uncracked FRP laminates.

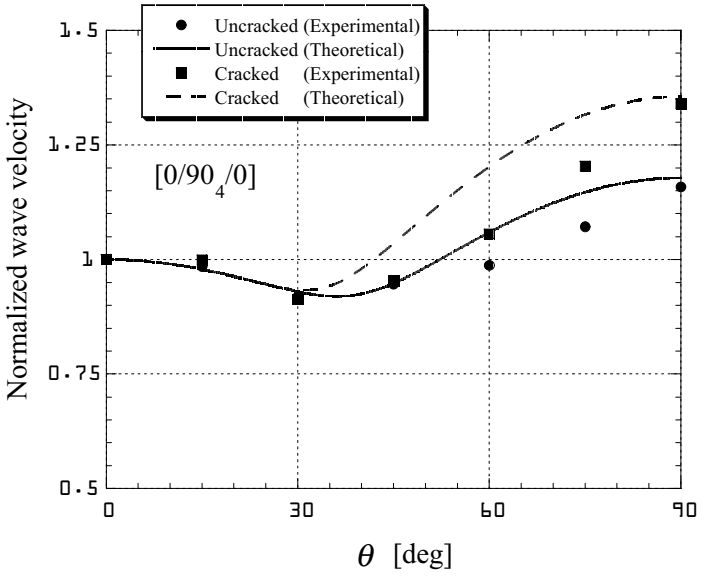

Fig.11 Comparison of angular dependence of wave velocity between uncracked and cracked FRP laminates.

In Fig.11, the angular dependence of wave velocity for the cracked specimen is compared to that of uncracked specimen for [0/90$_4$/0]. It is apparent that anisotropy of experimentally measured wave velocity is enhanced when the laminate is cracked, and the same is true for the prediction. As has been mentioned in the previous chapter, ultrasonic waves will propagate in laminated plates as S_0 Lame wave even after crack formation, therefore this result indicates that the anisotropy of the effective stiffness of the laminated plate is pronounced due to crack formation. Generally, existence of cracks enhances the anisotropy of the ply, which in turn leads to the anisotropy of the overall laminate stiffness. The quantitative discrepancy may be because of the same reason for the uncracked specimens.

As shown in this chapter, profile of the angular dependence of wave velocity is strongly dependent of laminate configuration and damage state. It is confirmed that the change in angular dependence indicates the change in effective stiffness of the laminate; large anisotropy implies that damage is accumulated in one direction. Although the ultrasonic wave velocity is influenced by temperature and other unexpected factor such as small deviation of laminate thickness etc., the change in anisotropy of wave velocity can be a useful factor for representation of damage state of FRP laminates.

CONCLUTION

A simple method that two transducers are mounted flat against plate surface was used to evaluate ultrasonic wave velocity of uncracked and cracked FRP laminates. It is confirmed that for low frequency region, present method induces S_0 Lamb mode in uncracked laminated plates, and the wave velocity is well predicted by the plate velocity, the limiting case of S_0 Lamb wave. The same method was applied to cracked laminates, to evaluate the effect of cracks on wave propagation in laminated plates. It was found that waves travel as S_0 Lamb mode even after considerable numbers of cracks are formed in the plate. The wave velocity of the cracked laminate was predicted by introducing laminate effective stiffness into the theory of plate velocity. The prediction is fairly good when the cracked ply is thin. Finally, the damage induced anisotropy was evaluated by the change in wave velocity, and we concluded that the change in angular dependence of wave velocity could be a useful factor to evaluate the damage state of the laminated plate.

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