Inspection of Thick Composites for Near Surface Flaws

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ABSTRACT

Composite components proposed for future structural applications include very thick sections that may be subjected to extremely high static and cyclic surface loads. There is a concern that minute material imperfections close to the outer surface region resulting from fabrication or surface finishing processes of these components may initiate delamination and eventual separation of the outer fibers during operation or cyclic testing. Conventional ultrasonic C-scan immersion techniques, commonly used for inspection of composite parts, are not sufficiently sensitive to identify small defects in thick composite structures which may be as large as 10 cm in thickness. Novel approaches based on ultrasonic Rayleigh waves have been successfuly applied to the outer fiber surface of a thick composite structure after repeated cyclic testing. The aim is to identify minute manufacturing imperfections close to the surface region and to determine if such flaws have caused cracks or delamination during the cyclic tests.

In this paper, first the ultrasonic Rayleigh wave methods of flaw detection and ways of optimizing detection sensitivity and resolution will be described. Then, results of the optimization and sensitivity tests on carbon fibre composite specimens containing small simulated flaws 0.1 to 2 mm below the surface will be provided. Finally, the results of the application of the Rayleigh wave techniques on an actual thick composite section will be presented.

INTRODUCTION

Composite components have been used extensively in stuctural applications in aerospace and other safety-concious industries. Nondestructive evaluation (NDE) is often included in the original qualification and acceptance procedures. Also, inspections are conducted during service to ensure structural health and integrity. Inspection of composite parts less than 2 cm in thickness is easily done using ultrasonic pulse-echo or through-transmission techniques using an automated scanning system. However, composite parts developed for some future structural applications include very thick sections (about 10 cm in thickness) that may be subjected to extremely high static and cyclic surface loads. There is a concern that minute material imperfections close to the outer surface region resulting from fabrication or surface finishing processes of these components may initiate delamination and eventual separation of the outer fibers during cyclic tests or in operation.

The sensitivity of conventional ultrasonic methods in such applications is inadequate due to increased attenuation, particularly at high frequencies (>5 MHz) which may be necessary for resolution of minute defects. In particular, detection of small flaws near the outer surface using the normal pulse-echo tests is a major problem since the surface echoes and the transducer ringing prevents identification of small signals resulting from flaws close to the surface. Also,

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in the normal through-transmission tests, the high attenuation of the thick composite material makes it impossible to detect small defects. Novel approaches based on ultrasonic Rayleigh waves have been applied to detect minute defects close to the outer surface of a thick composite structure. The application and results of this approach are described in this paper.

ULTRASONIC RAYLEIGH WAVE TECHNIQUES

Rayleigh waves are generated when the ultrasonic incident beam strikes the test material at or above the critical angle of longitudinal and shear waves /1,2/. When the immersion mode is used (i.e. the test component is immersed in water for acoustic coupling between the probe and the test piece), as Rayleigh waves propagate, their energy is quickly dissipated or "leaked" into the adjacent fluid. As a result, "leaky" Rayleigh waves propagate only a few wavelengths (λ) on the surface before their energy drops below the noise level. Also, their effective range is only about one wavelength below the surface. Therefore, leaky surface waves are often used to characterize thin films and coatings. Leaky Rayleigh waves can be generated and detected using several approaches; two methods are described in this paper.

Method A:

Leaky Rayleigh waves are generated in a simple way by placing a flat or focused transmitting/receiving probe at the oblique Rayleigh wave angle as illustrated in Fig. 1. The Rayleigh wave angle is slightly larger than the critical angle of the shear or transversal wave in the test material. Snell-Descartes' law defines the critical angle of a wave for a given material as:

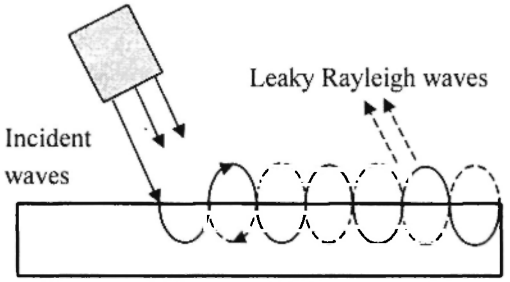
$$\sin(\theta_c) = \frac{V_{inc}}{V} \quad (1)$$

where θ_c is the critical angle, V_{inc} is the velocity of the incident wave and V the velocity of the wave in the material. The critical angle exists only if $V_{inc} < V$. For an isotropic material, the Rayleigh wave velocity is a function of both longitudinal and transversal waves /3/ as shown below:

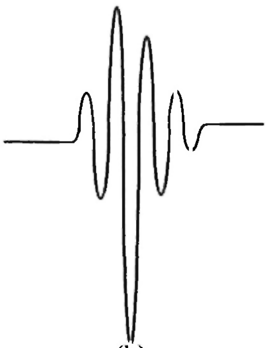
$$V_R = A(V_T / V_L).V_T \quad (2)$$

where V_L and V_T correspond to the velocities of the longitudinal and transversal waves in the material, respectively. $A(V_T / V_L)$ is a function of both velocities and since it is always less than unity:

$$V_R < V_T < V_L \quad (3)$$



(a)



(b)

Fig. 1: (a) Generation and detection of ultrasonic Leaky Rayleigh waves using an ultrasonic probe at critical angle with respect to the test specimen. (b) A typical ultrasonic Leaky Rayleigh wave signal.

From equations 1 and 3, it is evident that the Rayleigh wave angle is larger than the critical angle of the transversal wave. When Rayleigh waves are used for inspection of surface and near-surface flaws, if there is no discontinuity in the beam path, the return energy is basically the scattering of the beam by the material surface texture. However, when a discontinuity is present in the beam path, a portion of the energy is reflected back. This energy is leaked into the coupling agent and picked up by the same probe, resulting in an increase in the overall returned signal. Optimal echo amplitude is obtained when impinging surface waves are perpendicular to the plane of the flaw. Thus, flaw orientation would have an effect on the returned signal. Optimization of leaky Rayleigh waves is achieved by using a sharp edge of the test specimen as a target and adjusting the probe angle and distance until the optimal signal is obtained. Surface and near-surface features are detected by mapping the returned Rayleigh wave echo as the function of the probe location. C-scan images generated in this way can indicate the location of flaws. However, flaw images usually do not resemble the actual shape or size of the flaw due to the fact that the probe is at an angle with respect to the test material.

Method B:

Alternatively, an ultrasonic probe with a large aperture (larger than the critical angle) can be placed perpendicular to the surface of the test material in such a way that its focal point is below the surface, i.e. defocused. This approach is widely used in acoustic microscopy /4,5/. In this way, in addition to the direct reflection of the normal incident beam (or specular waves), leaky Rayleigh waves resulting from the skimming of the beam striking the material at or above the critical angle and edge waves radiated from the transducer edge are generated and detected as illustrated in Fig. 2. Distinction and optimization of leaky Rayleigh waves from direct reflections and edge waves are achieved by defocusing the probe, i.e. by moving the probe towards the sample surface until the Rayleigh echo is adequately separated from the other unwanted signals and an optimal amplitude is obtained. Fig. 2-b shows typical signals obtained at a defocused condition. Signal "A" corresponds to the specular reflection and "B" corresponds to the leaky Rayleigh waves. It must be noted that in this way Rayleigh waves are generated in a full circle, allowing flaw detection independent of the orientation of the flaw.

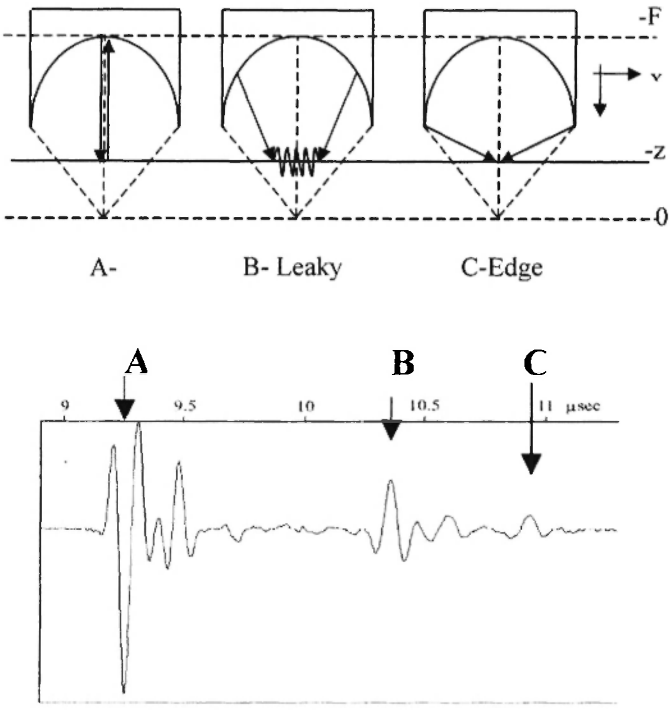


Fig. 2: Wave types and corresponding signals when a large aperture probe is defocused. Signal A is the specular reflection, signal B is leaky Rayleigh wave echo and signal C is the edge echo.

It is believed that two different mechanisms contribute to the flaw detection using leaky Rayleigh waves, as illustrated in Fig. 3. Crack-like discontinuities that are close to perpendicular to the surface interrupt the propagation of Rayleigh waves and therefore can be detected from the change in the corresponding echo amplitude /6-10/. On the other hand, planar defects, such as delamination, that are close to parallel to the surface may create a resonance effect, if an appropriate wave frequency is chosen, resulting in a change of amplitude and frequency of the returned echo. Both amplitude and frequency analyses were done to identify the different flaw types in this study.

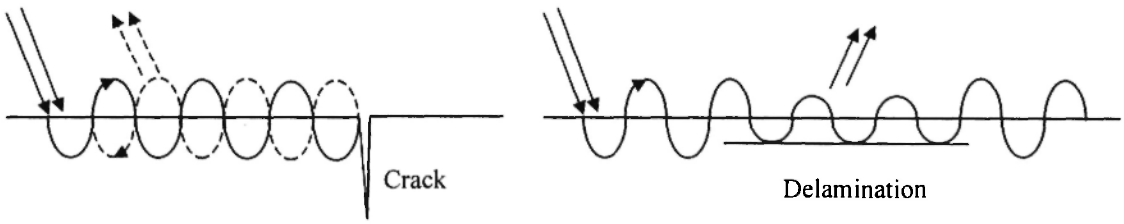


Fig. 3: Mechanisms contributing to the Rayleigh wave detection of cracks and delamination.

EXPERIMENTS

Test Procedure

A commercial transmitter/receiver was used to excite a 10 MHz frequency, 12.5 mm focal length and 12.5 mm diameter probe. Scanning of the probe was carried out in a fully automated ultrasonic immersion system using water as the coupling media. The transducer index size was 0.2 mm. C-scan images were obtained by placing a gate on the echo corresponding to the Rayleigh waves and monitoring the signal amplitude as a function of the probe location.

Calibrations

For the Rayleigh wave inspection technique, like many other NDE methods, it is necessary to establish the optimal test configuration and the sensitivity of the inspection system. The goal of the inspection was to detect small manufacturing or test-induced flaws close to the surface of a thick composite structure made of filament-wound carbon fiber epoxy. In order to check the sensitivity and resolution of the Raleigh wave techniques for detecting near-surface flaws, a calibration specimen was used. The specimen was made of a unidirectional carbon/epoxy system using the same material and fabrication method as the actual component. A series of 0.40 mm diameter flat-bottom holes were drilled in the calibration specimen such that the holes ended at different distances from the top surface as shown in Fig. 4.

RESULTS AND DISCUSSION

As previously mentioned, Rayleigh waves penetrate only about one wavelength below the surface of the material and thus they are not effective beyond this range. At a frequency of 10 MHz, the Rayleigh wavelength in a unidirectional carbon fiber epoxy composite is approximately 0.2 mm. Therefore, it is expected that only holes # 1, 2 and 3 from the left would be detected. The experimental result is shown in Fig. 5, which confirms this prediction. Reference lead tapes were used in order to identify the location of the holes on C-scan images since the holes were very small and their indications could be confused with other possible manufacturing flaws. It is evident that at 10 MHz, 0.4 mm discontinuities as near as 0.1 mm below the surface could be detected with good resolution using the leaky Rayleigh wave technique.

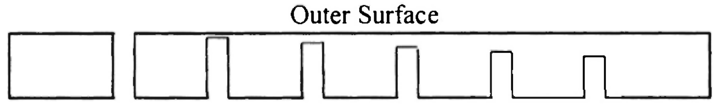


Fig. 4: The cross-section of a calibration specimen containing drilled holes below the surface

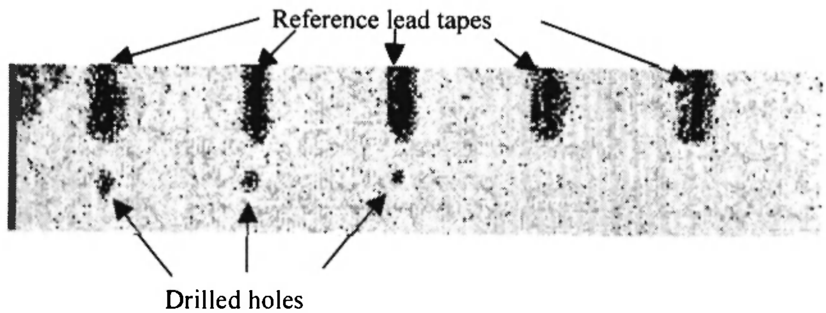


Fig. 5: Amplitude pulse-echo C-scan at Rayleigh wave angle. Probe characteristics are 10 MHz; focal length 12.5 mm; diameter 12.5 mm.

After calibration tests the thick composite structure was inspected using the same 10 MHz probe and the Method A described above. Note that at this frequency, only the detection of discontinuities located down to approximately 0.2 mm below the surface is possible. Fig. 6-a shows the amplitude C-scan trace of a section of the thick composite structure. In this case, the probe was positioned such that the Rayleigh waves propagated in the direction of fibers. The Rayleigh angle set in this case was 49.2°. This is slightly larger than the critical angle for transversal waves. Fig. 6-b shows a similar C-scan where the probe was positioned at 20° to the material but perpendicular to the fiber direction mapping the backscattered waves by the materials surface and near-surface features. The critical angle for the transversal waves in the direction perpendicular to the fibers is too large and not very effective for flaw detection. The critical angle for a given wave type is different since the wave velocity is different in the fiber direction and normal to the fibers.

In the images shown in Fig. 6-a and 6-b, feature R represents a reference lead tape that was attached to the surface; feature D shows large defects; and feature F indicates fiber separation from the surface. As seen in Fig. 6-a, a large number of porosity-like defects were present close to the surface. Some of these, such as those identified as feature D, are probably large delamination-like cavities. In Fig. 6-b, the same large defects are also shown. In addition, two white indications are present on both sides of one of these defects that are identified as feature F. These are images of areas of the top surface where some fibers were separated during spin testing of the structure. It is clear that one of the detected near-surface defects exceeded the critical size and caused this undesirable failure during tests. The background noise in Fig. 6-b is due to scattering of the ultrasonic beam striking the fibers at a normal angle and is expected.

In addition, Method B was used to look at the very end of the areas where fibers had separated in an attempt to identify possible cracks perpendicular to the outer surface. An example of the results is shown in Fig. 7-a, indicating the presence of cracks along the fibers. These cracks were neither visible to the naked eye nor under a microscope. However, using solid rubber replication followed by microscopy of the replica, these cracks could easily be identified, as seen in Fig. 7-b and 7-c, verifying the ultrasonic results.

CONCLUSION

Near surface flaws cannot be detected using the conventional ultrasonic inspection techniques but are of great concern in some structural composites when subjected to extremely high surface loads. Novel approaches based on ultrasonic leaky Rayleigh waves have been used to detect small'flaws on and a few plies below the surface of thick composite structures. The detection sensitivity and resolution of the Rayleigh wave procedures have been established using reference specimens with known defects. These tests indicated that the Rayleigh wave methods have the ability to identify small defects as close as 0.17 mm below the

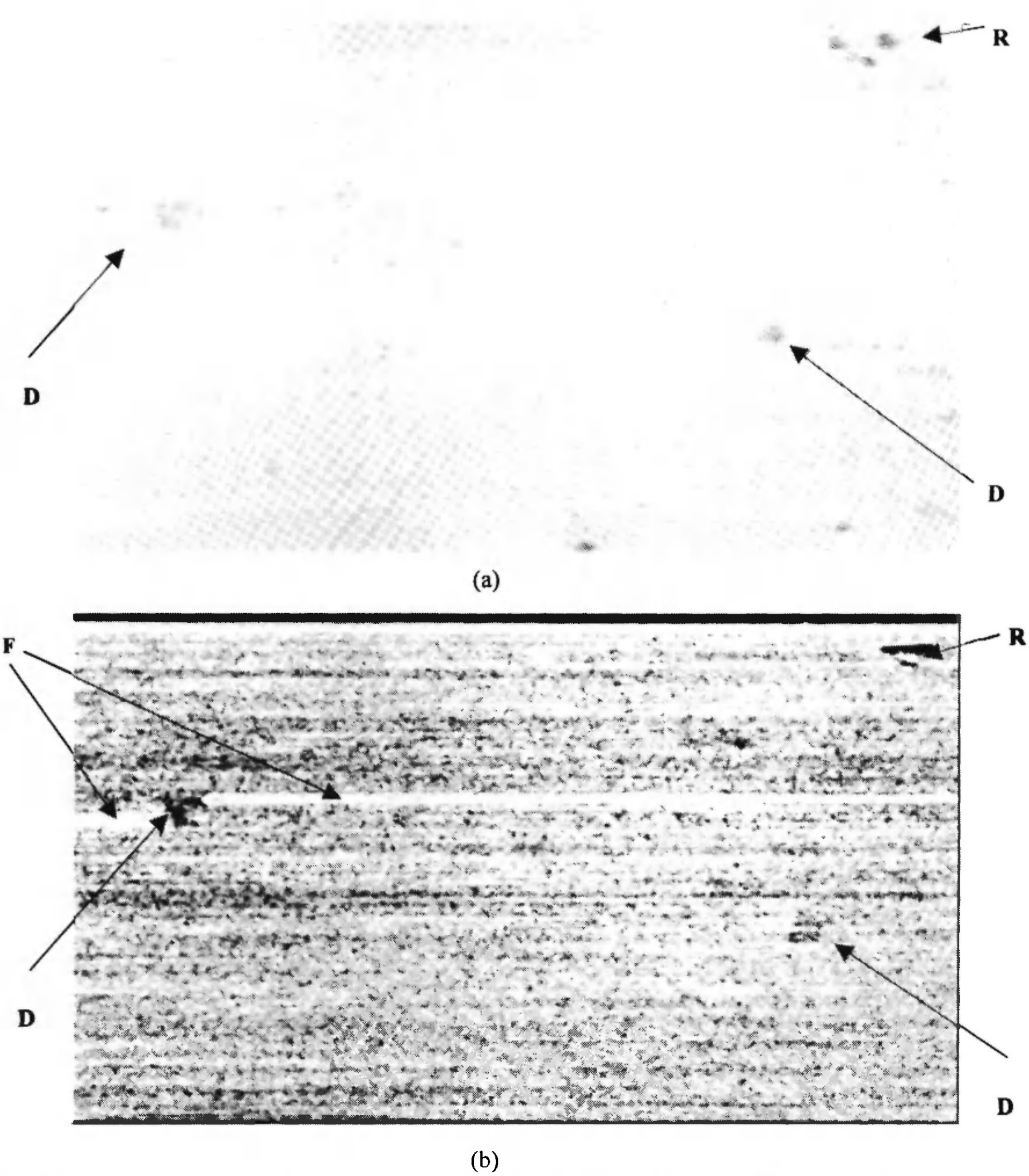
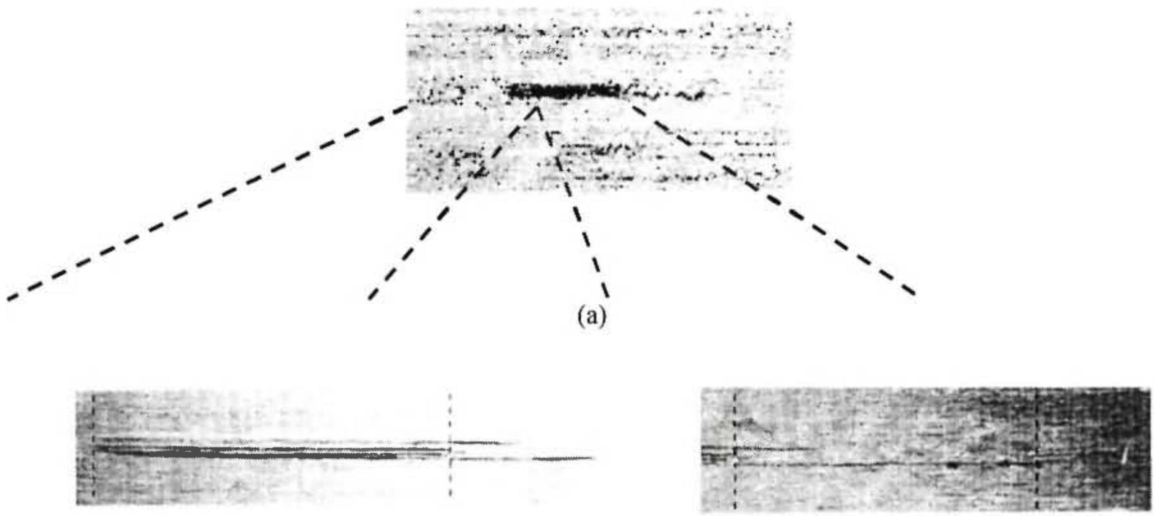


Fig. 6: Amplitude C-scans of a thick composite structure inspected at oblique incident angles (a) using Rayleigh waves travelling in the fibers direction and (b) using backscattered waves when the beam is perpendicularly to the fibers direction.

surface with good sensitivity and resolution. The techniques have been applied to a real structure approximately 10 cm in thickness where delamination-like cavities have been detected just below the surface. During spin testing of the structure at a high RPM, some of the detected cavities caused separation of fiber bundles from the surface. Further tests using Rayleigh waves also have identified surface cracks that could neither be seen by the naked eye nor under optical microscopes, but could be verified by optical examination of the rubber replica of the cracks.



(a)

(b)

Fig. 7: (a) Amplitude C-scans of the tip of the surface damage using ultrasonic defocusing Rayleigh wave method and (b-c) the corresponding micrographs of the rubber replica.

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