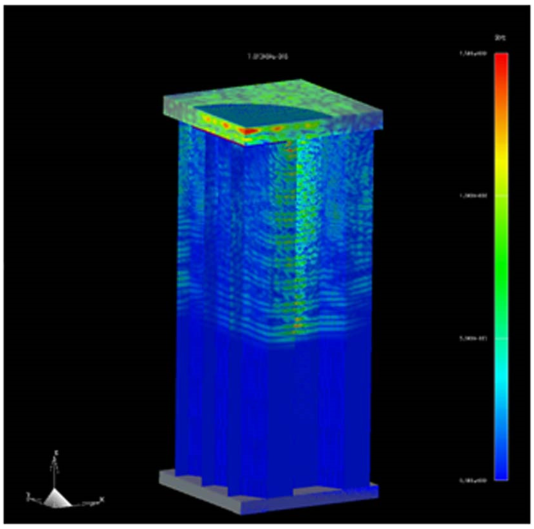
State-of-the-art Nondestructive Inspection Technology for Composite Materials



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Due to the advantages of lightweight, high strength and corrosion resistance, the application of composite materials to aerospace equipment structural materials has been increasing. For this reason, nondestructive inspection technologies for ensuring the quality of composite material products are required to enable highly accurate and highly efficient evaluation. Therefore, we are promoting the application examination and development of time-reversal phased array ultrasonic testing technology for complex shapes, near infrared optical coherence tomography technology that efficiently measures the height of surface wrinkle (fiber waviness), laser bond inspection technology for detection of weak bonds that cannot be detected by conventional nondestructive inspection, and simplified impact damage inspection technology that can be performed by uncertified operators.

1. Introduction

Composite materials such as carbon fiber reinforced plastic (CFRP) and glass fiber reinforced plastic (GFRP) are used for structural materials in aerospace products due to the advantages of lightweight, high strength, and corrosion resistance. Their application has been increasing, and the weight ratio in the Boeing 787 and Airbus A350 has reached as high as about 50%. Since composite materials have various configurations depending on the base material, fiber material, and manufacturing method such as curing/bonding methods, and also the flaws and quality levels vary accordingly, it is necessary to develop and set a quality assurance method according to the product to be inspected. In general, the composite material has a larger variation in the material strength characteristics and shape accuracy than metal, and the ratio of quality assurance-related costs to the manufacturing cost is larger than that of metal. Therefore, to establish the production of composite material products it is necessary to develop and establish highly accurate and highly efficient inspection technology and introduce it to the manufacturing site.

This paper outlines nondestructive inspection technologies for composite materials cultivated through our manufacturing and regular maintenance of fixed and rotating wing defense aircraft and commercial aircraft, and subsequently introduces several examples of the latest nondestructive inspection technologies that we developed, examined, and are introducing.

2. Nondestructive inspection technology for composite materials

Representative detection targets of laminated materials such as CFRP which are often used for the main structure of aircraft are internal air bubbles (voids, porosities), disbonds, delaminations, and foreign objects, while detection targets of honeycomb sandwich structures

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adopted for structures such as moving blades are deformation and collapse of cores, entrapped water, etc., in addition to the above.

The nondestructive inspection methods conventionally used for aircraft to detect such targets are the so-called five major methods of ultrasonic testing, radiographic testing, fluorescent penetrant testing, fluorescent magnetic particle testing and eddy current testing. In addition, infrared thermography and shearography are gradually being applied as their public standards and inspector qualification/certification criteria have been developed, but there are few examples applied to actual products in Japan. At present, the methods that are widely used for composite materials among the five major methods are ultrasonic testing and radiographic testing, and especially for the inspection of laminated materials, ultrasonic testing effective for detecting planar flaws parallel to the surface represented by delamination plays an important role. Particularly in recent years, phased array ultrasonic testing (PAUT) has become popular from the viewpoint of flaw detection efficiency, visibility of flaws and preservation of objective records.

In addition, probability of detection (POD) evaluation is becoming common as a means to quantify the detection capability of the inspection techniques as described above. **Figure 1** shows an example in which POD evaluation is performed on ultrasonic C scan data.

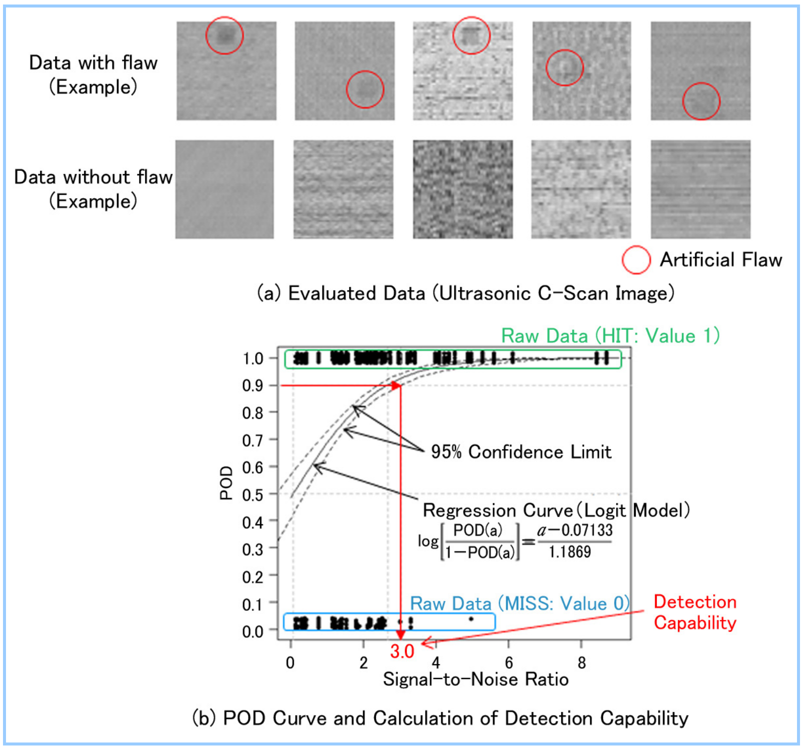

Figure 1 Example of POD Evaluation

3. Summary of state-of-the-art nondestructive inspection technology for composite materials

3.1 Time-Reversal (T/R) PAUT technology

One of the characteristics of ultrasonic waves propagating to composite material is the high attenuation rate. It is considered that this is due to viscous attenuation in the base material (resin) constituting the composite material and scattering at the interfaces between the resin and fiber. As a countermeasure against that, ultrasonic waves with a lower frequency (2 to 5 MHz) than that used for metals are often applied. The other characteristic is the anisotropy of the sound velocity and attenuation rate. That is, ultrasonic waves are relatively easy to transmit in the direction perpendicular to the surface, but show large attenuation when the incident angle changes a few degrees.

On the other hand, since the outer shape of an aircraft structure has a curvature and the thickness of the composite material varies because of weight reduction requirements, it is sometimes difficult to make the incident angle of ultrasonic waves vertical to the surface of the composite material. If the products have corner radii that change gradually, the inspection can be a bottleneck. Therefore, we focused on T/R PAUT technology developed by ZETEC and examined its application. As shown in Figure 2, the principle of T/R PAUT is relatively simple. This technique captures the surface shape using the time of flight of the ultrasound reflected from the composite material surface, and makes the incident angle of ultrasound perpendicular to the surface of the composite material by applying the time lag (delay time) of pulsing accordingly to the individual piezoelectric elements. **Figure 2** shows the results of application of T/R PAUT and conventional PAUT to the same specimen. It is indicated that stable ultrasonic signals can be obtained by applying T/R irrespective of corner R change.

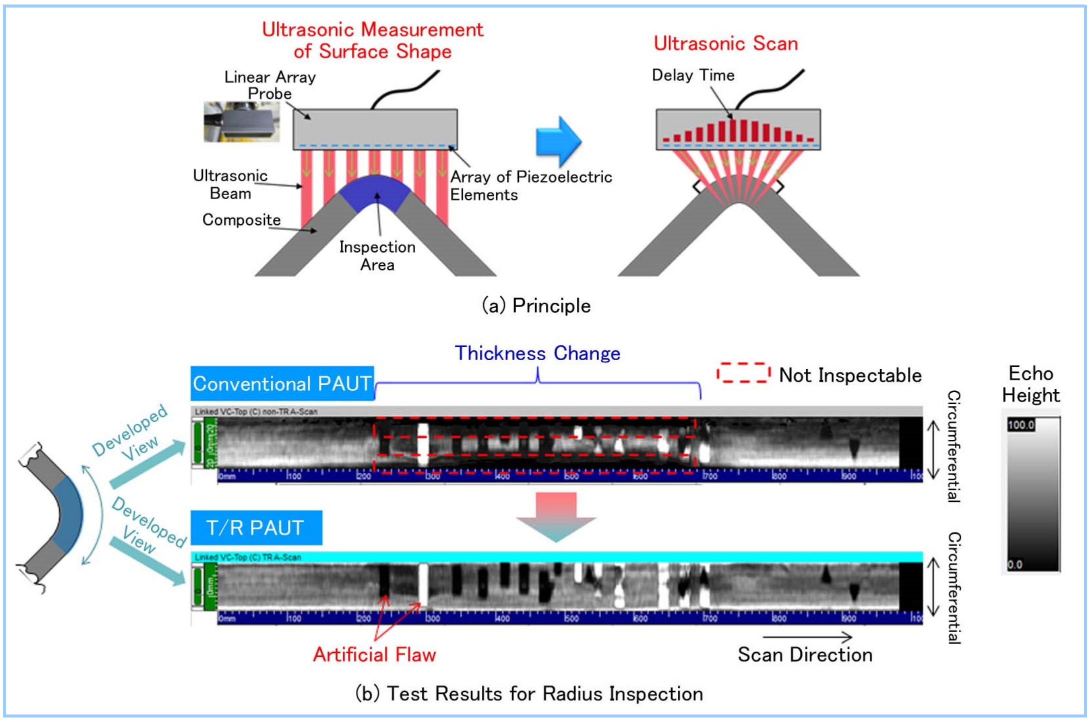

Figure 2 Principle and Test Results of T/R PAUT

3.2 Near infrared optical coherence tomography (OCT) technology

This is a technology to visualize the internal condition and structure of an object in real time by utilizing interference of near infrared backscattered light. This technology has been put to practical use in the medical field, particularly in the fundus examination, and is wide spread.

When curing a composite material, there is a concern that a wrinkle occurs mainly on the surface of a shape changing portion. Surrounding resin flows into the recess formed by the surface wrinkle and is cured in a resin-rich state, but since the surface wrinkle reduces the compressive strength of a product, it is required to accurately measure the height. When a resin-rich state is detected by visual inspection, it is required to remove the resin physically, measure the height with a depth gauge or the like, and then fill back the resin. As an alternative to the series of above operations, we examined the application of OCT technology.

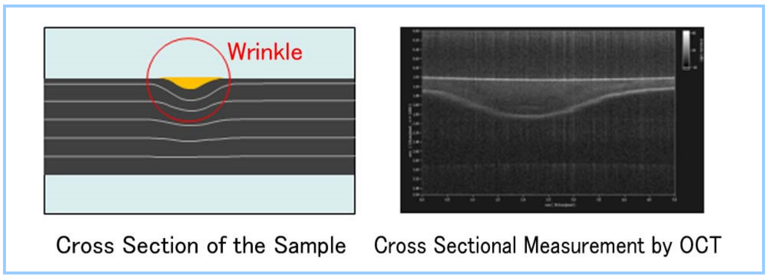

Figure 3 Cross Sectional Measurement by OCT

Figure 3 shows the results of cross-sectional measurement using Santec IVS-300. It was confirmed that the height of a wrinkle can be measured with the accuracy of ±0.1 mm in comparison to the result of cross-sectional observation of the object. Furthermore, after improving the SN ratio by optimizing the infrared incident angle, we investigated the influence of the component ratio inside the resin, moisture absorption, UV, etc., and issued the process specification that specifies the measurement and control methods. It is expected that the inspection time is reduced by about 90% by applying this technology and specifications to actual products.

3.3 Laser bond inspection (LBI) technology

Currently, adhesive bonded joints are frequently used for the structure of aircraft. However, because the Federal Aviation Administration (FAA) guidelines virtually require that adhesive bonded joints, the failure of which may cause catastrophic loss of the aircraft, be joined by fasteners[1], adhesive bonding and fastening are always used in combination for the main structure. This is because the current adhesive bonding structure is considered to be insufficient in reliability. However, the benefits of eliminating fasteners are expected to reduce weight (of fasteners, seals, and pad ups), reduce costs (for fastener drilling and binding operations), and reduce the number of parts. One of the reasons that the reliability of the adhesive bonded structure is not sufficient is that weak bonds cannot be detected by nondestructive inspection to ensure the strength of the adhesive bonding.

Research on detection of weak bonds is undertaken comprehensively in the European ENCOMB project, but it is unknown whether sufficient reliable inspection technology has been established. We investigated various nondestructive inspection technologies and then focused on and examined LBI technology, which is barely affected by factors of weak bonds.

Shockwaves generated inside a part by laser are reflected on the bottom surface of the part and phase-transformed, and generate tensile stress. The fundamental principle of LBI technology is to detect weak bonds exposed by the tensile stress using an electromagnetic acoustic transducer (EMAT) to detect it.

Figure 4 shows the results of basic tests conducted using equipment rented from LSP Technology, USA. In this test, it was confirmed that delamination occurred at the weak bond boundary surface by laser shockwaves and could be detected by ultrasonic testing. The future tasks are to associate the fracture toughness value G1C, etc., with the strength index and to quantitatively evaluate the influence of a change in the curvature/thickness and the detection capability.

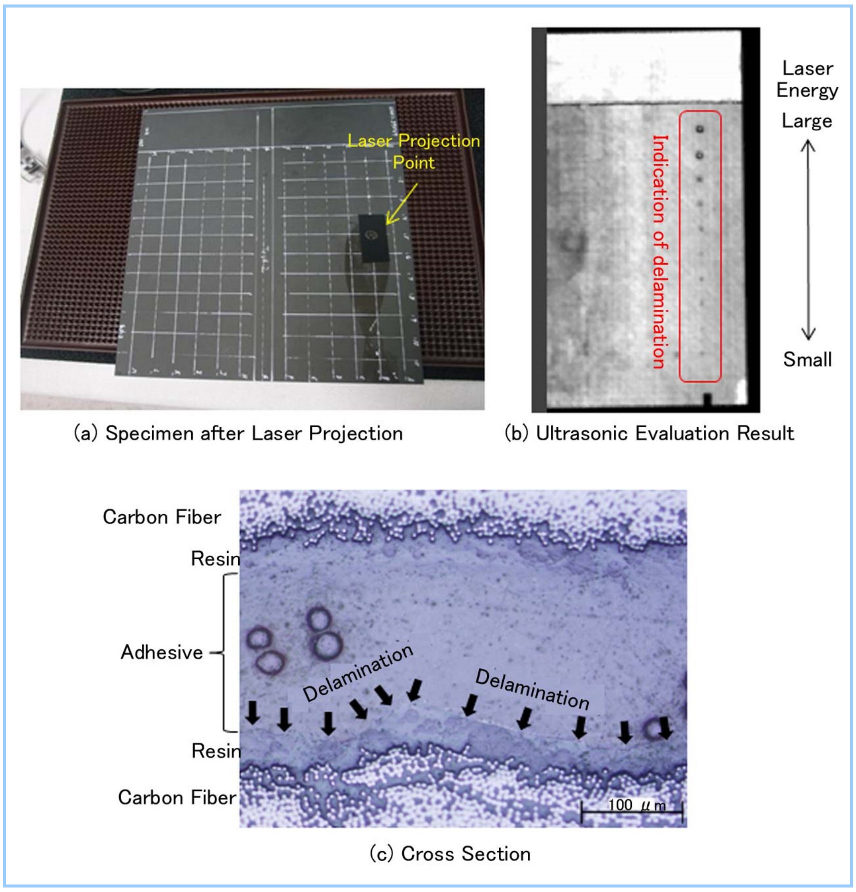

Figure 4 LBI Test Result

3.4 Simplified impact damage inspection technology

In-service scheduled maintenance of aircraft uses nondestructive inspection to detect damage due to loads applied during flight/takeoff and landing and accidental damage due to lightning strikes or object collisions. Since the time spent on the in-service scheduled maintenance is directly linked to the operational availability of the aircraft, more efficient inspection technologies are required for in-service nondestructive inspections. There is a risk of accidental damage due to the drop of a tool or collision during handling in manufacture and assembly of aircraft.

Meanwhile, operators who perform nondestructive inspections are required to obtain qualifications, and at least 80 hours of training and 800 hours of work experience are required to obtain such qualifications.[2] For this reason, it may be difficult to secure certified inspectors in a timely manner, depending on the aircraft manufacturing site or maintenance site.

Therefore, we are developing the simplified impact damage inspection system that enables even uncertified operators to judge the presence or absence of impact damage in composite materials with Go/No Go. The system scans the surface of a composite material using a wheel probe with a built-in phased array probe connected to a small ultrasonic flaw detector, and monitors the obtained ultrasonic signals with this particular technology. We will introduce this system to our manufacturing site at first, and we aim to subsequently introduce it to airline companies and Self Defense Force bases.

4. Conclusion

With the expansion of the application of composite materials to aircraft structures, further highly accurate and highly efficient evaluation is required for nondestructive inspection technologies for ensuring product quality. In this paper, we introduced T/R PAUT, OCT, LBI, and simplified impact damage inspection technology as examples of our company's efforts to meet the needs. In the future, we will accelerate the introduction of inspection simulation technology as shown in **Figure 5** in order to perform efficient testing for complex shapes such as honeycomb sandwich structures and bonded structures, and intend to further advance the accuracy and efficiency of nondestructive inspection by proceeding with development, application examination, and introduction of automated evaluation technology such as AI and signal processing, and structural health monitoring.

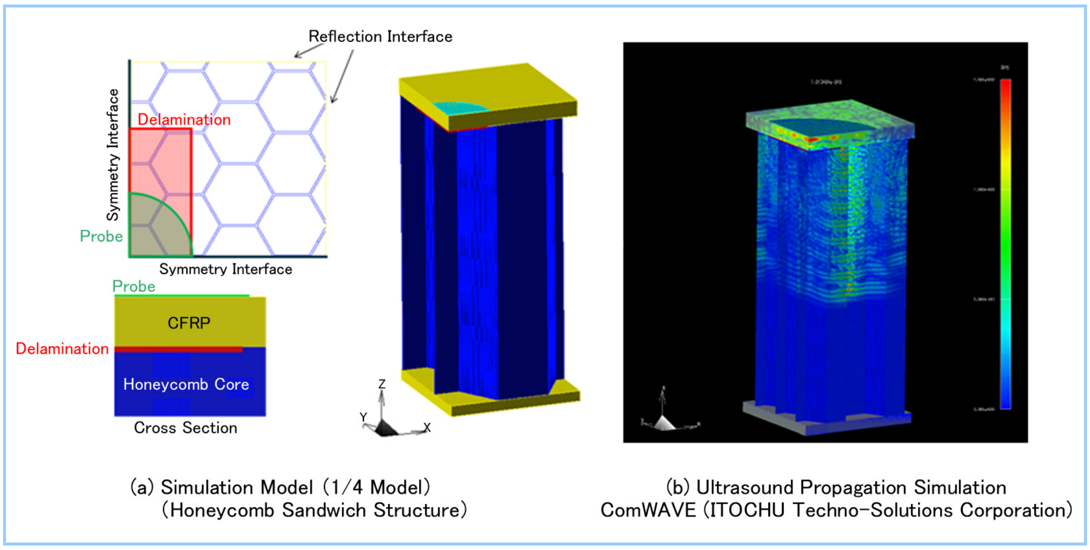

Figure 5 Example of Ultrasound Propagation Simulation

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1. Federal Aviation Administration, Composite Aircraft Structure, AC 20-107B (2009)
2. National Aerospace Standard, Certification & Qualification of Nondestructive Test Personnel, NAS410 Rev. 4 (2014)