Debonding detection in CFRP bonded structures using ultrasonic waves received by optical fiber sensors

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ABSTRACT:

Carbon fiber reinforced plastic (CFRP) laminates have increasingly become popular materials for airplane structures. Since CFRP laminates have difficulties in joining with bolts or rivets, bonded structures with adhesive are more suitable to CFRP structures. However, bonded composite structures have a possibility of introducing debonding in the bonded line, which is a critical damage to the structures. Thus, detection of debonding is required for maintenance of airplanes.

This paper presents a system to detect the debonding progress in skin/stringer structures in a wing box of airplanes. This system uses piezoelectric tranducers (PZTs) to input controlled ultrasonic waves to the structures and fiber Bragg grating (FBG) sensors to receive the propagated waves. To evaluate the debonding precisely, two sensors are attached to the top and bottom surfaces of the skin/stringer structure. Comparison of received waves between these two sensors provides an effective method to determine the condition of the structures.

The applicability of this proposed system to the debonding detection was demonstrated by experimental studies. To investigate the influence of the debonding, a perfectly bonded specimen and a specimen with debonding were prepared for demonstration of this system. The results showed that the wave propagation path and received waveform were affected by the debonding. In particular, the maximum amplitude ratio and the arrival time difference were found to be important parameters to evaluate the debonding progress quantitatively.

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INTRODUCTION

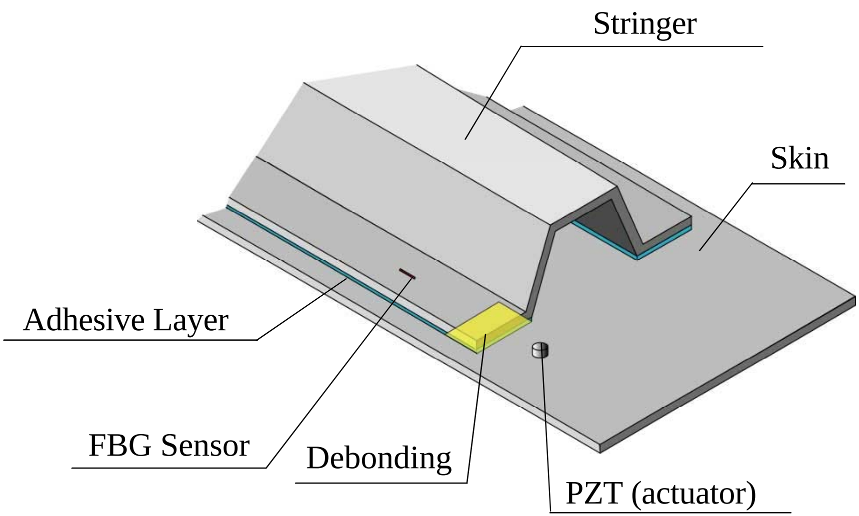
Carbon fiber reinforced plastic (CFRP) laminates have increasingly become popular materials and are applied to primary structures in the latest airplanes, such as Airbus A380 and Boing 787. For jointing of CFRP laminates, adhesion is more suitable than mechanical joints with bolts or rivets. However, bonded composite structures have a possibility of introducing debonding in the bonding line, which is a critical damage to the structures. Current non-destructive inspection methods are not efficient to detect debonding in the inaccessible areas and result in extensive time and costs. For monitoring the condition of the CFRP structures, structural health monitoring systems using ultrasonic waves generated and received by pre-installed actuators and sensors are promising and cost-effective means[1,2]. Thus, application of this structural health monitoring to bonded structures may greatly reduce the inspection burden.

This paper presents a monitoring system using ultrasonic waves to evaluate the debonding progress in skin/stringer bonded structures in a wing box of airplanes using ultrasonic waves. This system uses piezoelectric tranducers (PZTs) to generate ultrasonic waves into the structures and fiber Bragg grating (FBG) sensors to receive the propagated waves.

PRINCIPLE OF DEBONDING EVALUATION

The skin/stringer structure and the debonding are shown in Figure 1. One PZT actuator and two FBG sensors are located as shown in Figure 2. One FBG sensor is bonded on the surface of the stringer and the other is on the bottom of the skin. The waveforms received by these two sensors become different after occurrence of the debonding. Thus, comparison of the two waves is effective means to evaluate the debonding progress.

Figure 1. Skin/stringer structure.



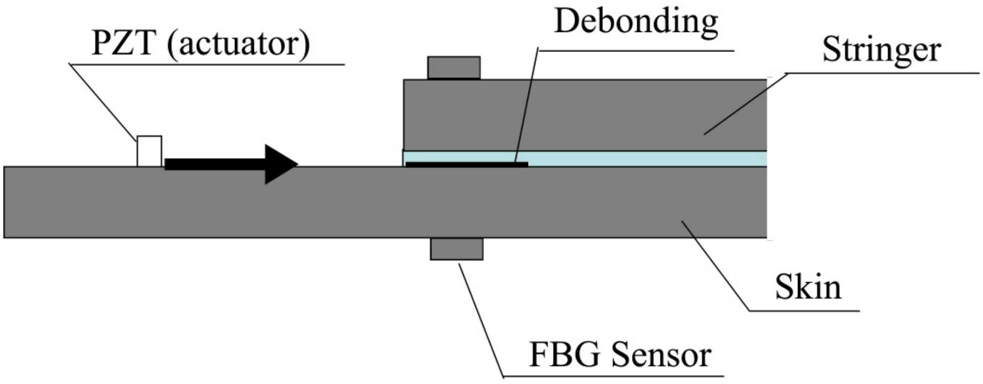


Figure 2. Location of piezo-actuator and FBG sensors.

EXPERIMENTAL SET-UP

Two types of coupon specimens simulating the skin/stringer structure were prepared: a perfectly bonded specimen and a specimen with debonding formed by a cutting blade. As a preliminary study, PZT sensors are used instead of FBG sensors in this study.

The configuration of the specimens and locations of PZTs are illustrated in Figure 3. Two CFRP quasi-isotropic laminates (T700S/2500, TORAY, $[45/0/-45/90]_{3s}$) were bonded in the secondary bonding process using adhesive films (Metlbond 1515-3M). Debonding was introduced by the following procedures; artificial defect of 2mm was introduced using a Kaptom film embedded during the bonding process, and the debonding was developed by insertion of a cutting blade into the artificial defect. A three-cycle sine wave of 300 kHz with a hamming window as shown in Figure 4 was used to drive the PZT actuator. A propagating ultrasonic wave was received by PZT sensors on the upper and lower laminates of the specimens. The positions of the sensors were changed from L = 2mm to 30mm at 2mm intervals.

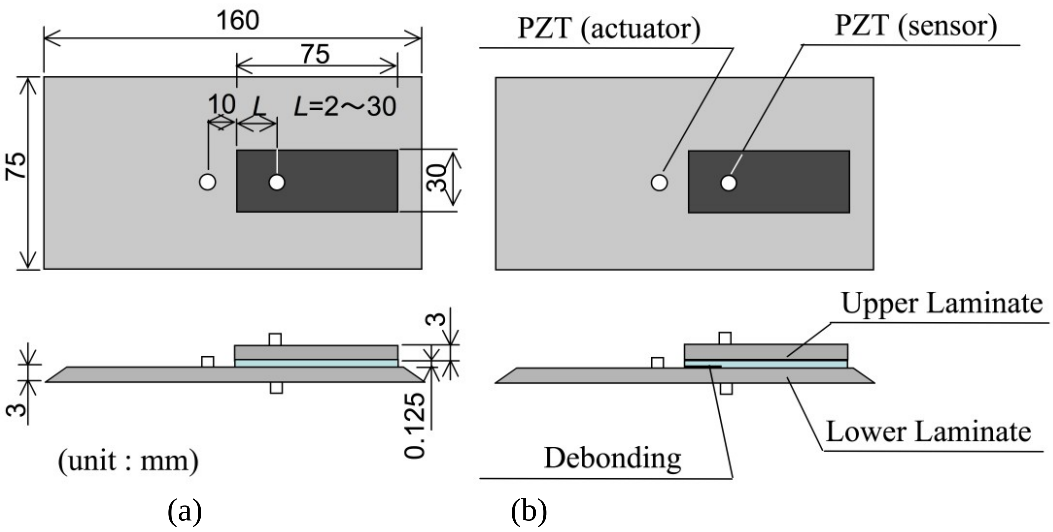


Figure 3. Configuration of the specimens and locations of PZTs :
(a) perfectly bonded and (b) with debonding.

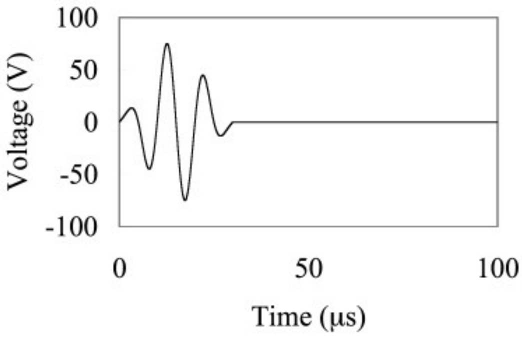


Figure 4. Three-cycle windowed sine burst input signal.

DEBONDING OBSERVATION

Figure 5 shows the cross-section photograph of the specimen with the debonding. It is clear that the debonding length is about 16mm from the edge of the upper laminate. Soft X-ray apparatus (SOFTEX, M-100S) was also used to observe the debonding shape. As a result, the debonding length was found to be constant of 16mm over the whole width of the upper laminate.

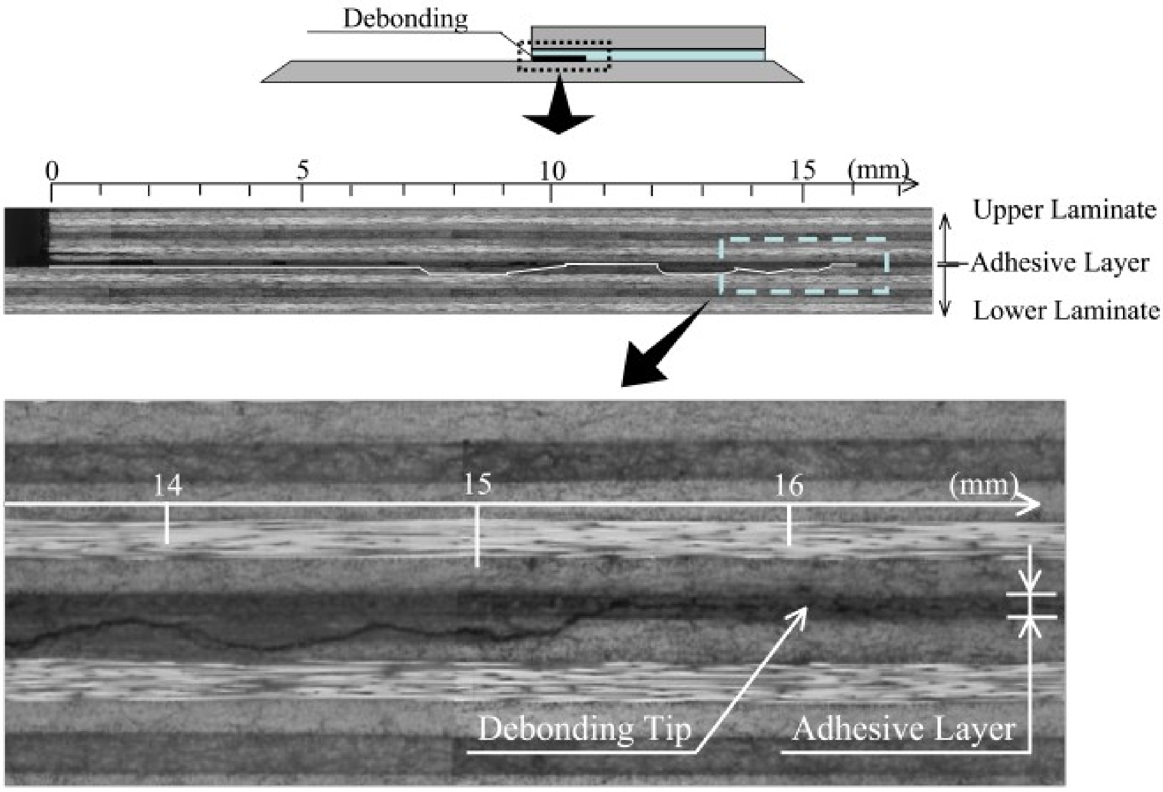


Figure 5. Cross-section observation of the specimen with debonding.

EXPERIMENTAL RESULTS AND DISCUSSION

Figure 6 shows the outputs of the PZT sensors located at L = 10mm for the perfectly bonded structure, and Figure 7 shows the outputs for the structure with debonding. Envelope curves obtained by Hilbert transform were drawn with measured waveforms in Figures 6 and 7. As shown in Figure 6(a), maximum amplitude A_m is defined as maximum value of the envelope curves, and arrival time T_a as the time when the envelope curve becomes maximum.

It is clear from Figure 6 that the waveforms measured by the PZT sensors on the upper and the lower laminates in the perfectly bonded structure are almost the same except the phase difference. In contrast, the A_m of the PZT sensor on the upper laminate in the structure with debonding is much smaller then that on the lower laminate (Figure 7).

The A_m and T_a are plotted as a function of the sensor position from L = 2mm to 30mm in Figures 8 and 9 respectively. As shown in Figure 8, it is clear that the A_m on the upper laminate becomes larger and that on the lower laminate becomes smaller in the debonded region of the specimen with debonding than that of the perfectly bonded spesimen. In addition, the T_a on upper laminate in the debonded region was delayed as shown in Figure 9. These changes are because the ultrasonic wave propagates around the debonding tip to the upper laminate since the ultrasonic wave cannot pass through the debonding. Hence the wave to the upper sensor is attenuated and delayed.

Figure 10 shows the maximum amplitude ratio R_m defined as the ratio of the A_m of the upper sensor to that of the lower sensor. It is clear that the R_m is close to 1.0 in the bonded region while the R_m in the debonded region is much smaller than 1.0. Figure 11 shows the time difference of arrival time T_a between the upper and the lower sensors. It is found that T_a increases in proportion to the distance between the sensor and the debonding tip in the debonded region.

These tendency of the R_m and T_a was considered to be correlated with the relative position of the sensor and the debondig tip. Thus, in the actual situation, one pair of the sensors located near the stringer edge seems suffiient to estimate the debonding length.

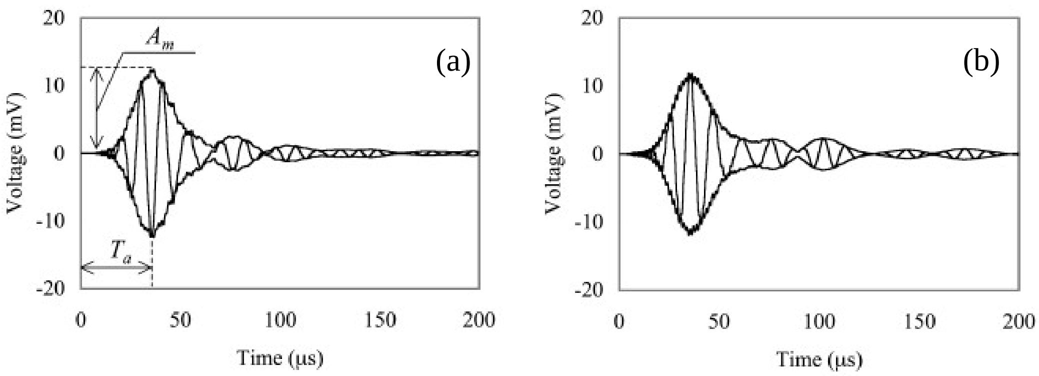


Figure 6. PZT sensor responses at L = 10mm for perfectly bonded structure: (a) on upper laminate and (b) on lower laminate.

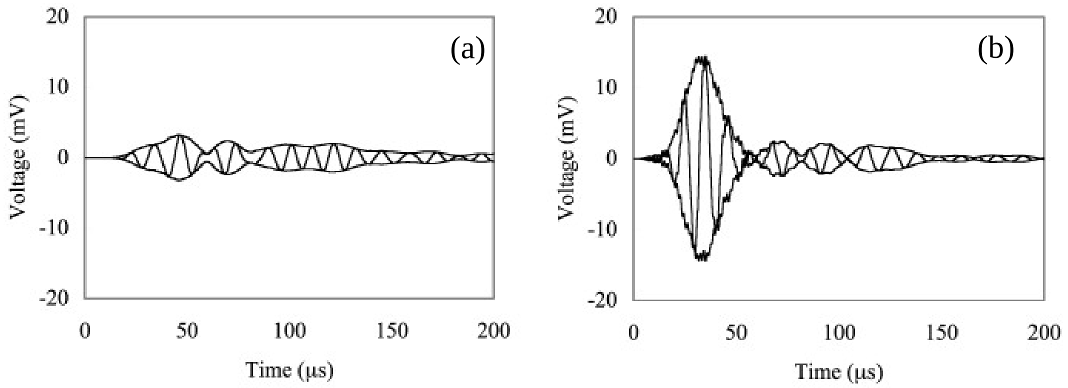


Figure 7. PZT sensor responses at L = 10mm for structure with debonding:
(a) on upper laminate and (b) on lower laminate.

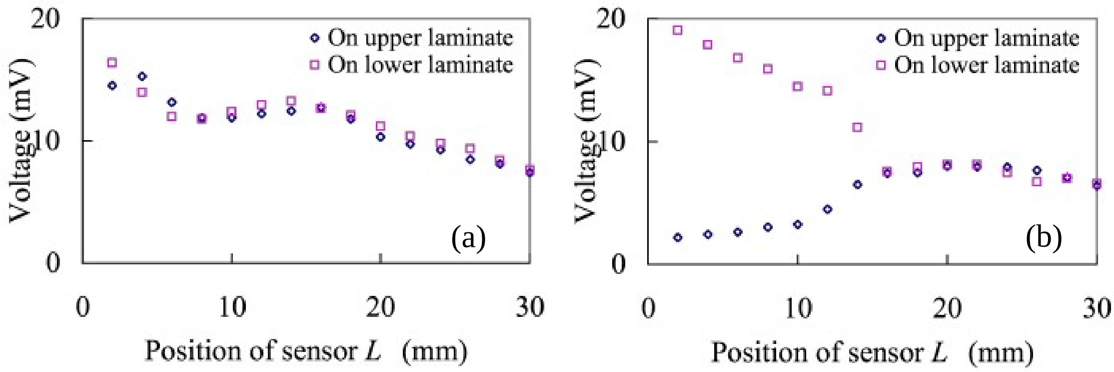


Figure 8. Maximum amplitude A_m:
(a) perfectly bonded structure and (b) structure with debonding.

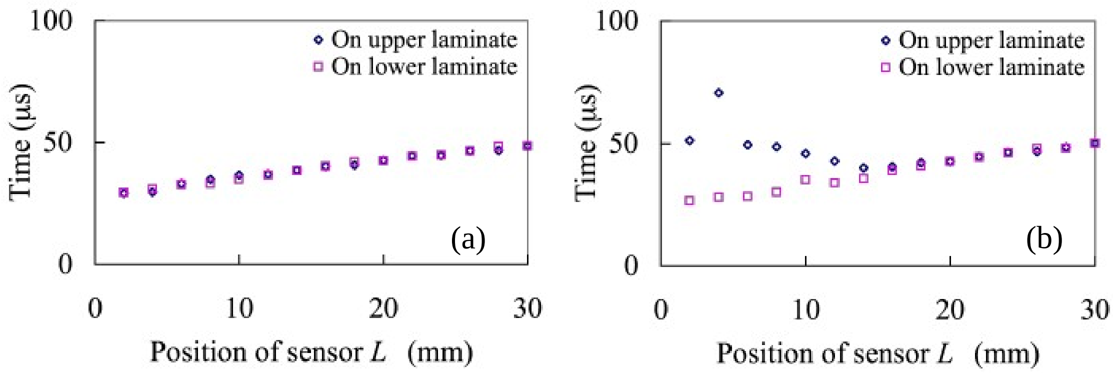


Figure 9. Arrival time T_a:
(a) perfectly bonded structure and (b) structure with debonding.

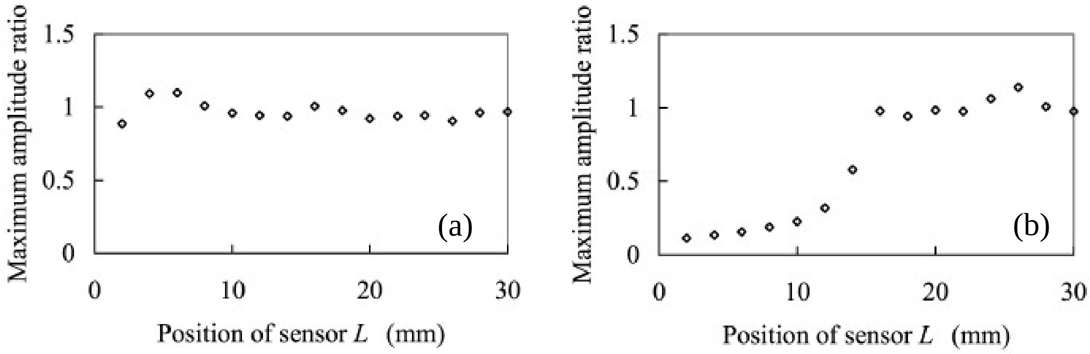


Figure 10. Maximum amplitude ratio R_m:
(a) perfectly bonded structure and (b) structure with debonding.

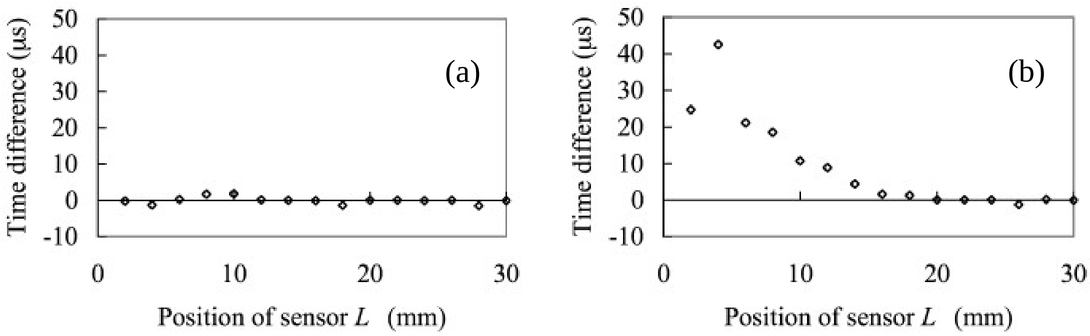


Figure 11. Arrival time difference T_a :
(a) perfectly bonded structure and (b) structure with debonding.

CONCLUSIONS

Comparison of the waveforms measured by the two sensors attached to the skin and stringer surfaces was effective to detect the debonding in the bonded structures. The maximum amplitude ratio certainly showed the presence of the debonding at the sensor point. In addition, the arrival time difference could evaluate the debonding length from the sensor point. Consequently, the debonding progress was successfully evaluated quantitatively using these parameters.

ACKNOWLEDGEMENTS

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