Delamination Detection in Fiber Metal Laminates Using the Mode Conversion of Lamb Waves

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DELAMINATION DETECTION IN FIBER METAL LAMINATES USING THE MODE CONVERSION OF LAMB WAVES

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ABSTRACT

Fiber metal laminates (FMLs) consisting of FRP composites and thin metal foils are gathering attention as structural materials for aircrafts. However, it is difficult to apply the conventional ultrasonic method to detect the inside damages because of the total reflection at the first interface between the FRP and the metal. Recently, the authors have developed a new delamination detection method based on the mode conversion of Lamb waves. In this research, therefore, this method was applied to detect the inner delamination in the FML. MFC actuators and FBG sensors were bonded to both top and bottom surfaces of the laminate in order to excite or receive only A modes or S modes separately. The laminates with an artificial delamination were manufactured by embedment of Teflon films in the middle of the thickness, and Lamb waves were propagated through the delaminated area. The results indicated that excited A_1 mode was converted into S_0 mode in the delaminated area and it returned to A_1 mode again after passing through the delamination. Since the velocity dispersion is clearly different between the two modes, the delamination length could be estimated quantitatively from the change in the dispersion of received A_1 mode.

KEYWORDS : *fiber metal laminates, Lamb wave, delamination, mode conversion*

INTRODUCTION

As one of the composite materials suitable to aircrafts, fiber metal laminates (FMLs) are gathering attention [1]. Since the FMLs are hybrid laminates consisting of fiber reinforced plastic (FRP) composite and thin metal foils as shown in Figure 1, they have high fatigue and impact resistances. However, the FMLs have a possibility to have a delamination at the interface between the FRP layers and the metal foils due to the large difference in mechanical properties [2]. Moreover, it is difficult to apply the conventional ultrasonic C-scan to investigate the damage states inside of the plate, because the vertically-incident ultrasonic wave totally reflects at the first interface owing to the large difference in the acoustic impedance between the two materials. Hence the delamination existing at deeper interfaces cannot be detected.

Recently, the authors have developed a new delamination detection method based on the mode conversion of broadband Lamb waves [3]. Therefore, in this research, this method was applied to detect the interface delamination in the FML. The FML consists of a 16-ply CFRP quasi-isotropic laminate and three 50μm Ti foils inserted into the laminate. The laminates have an artificial delamination by embedment of Teflon films with different length in almost middle of the thickness. Then macro fiber composite (MFC) actuators and fiber Bragg grating (FBG) sensors were bonded to both the top and bottom surfaces of the laminate, and only A modes are excited by the two MFCs and extracted from the received waves in the two FBGs.

Through the experiments and numerical simulation, we investigated the mode conversion behavior at the both ends of the delamination damage from the dispersion change in the received waves. On the basis of the mode conversion behavior and the velocity dispersion difference between the modes, we attempted to evaluate the delamination length.

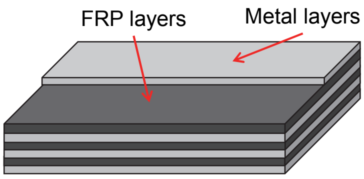


Figure 1: Schematic of FML

1 SYSTEM CONFIGURATION

The MFC actuator is a flexible actuator developed at the NASA Langley Research Center. It consists of many thin rectangular PZT fibers sandwiched between layers of an epoxy adhesive and a polyimide film with an electrode pattern. The MFC actuators (M-2814-P2 (d_{31} effect), Smart material, Corp.) were cut into a longitudinal length of 6mm and were bonded to the laminate with a cyanoacrylate adhesive. The FBG sensor is a type of optical fiber sensors. The FBG is fabricated in an optical fiber to have a periodic variation in the refractive index along a certain length of the core. When broadband light is injected into the core, the FBG reflects a narrow spectral component at the Bragg wavelength that is proportional to the applied strain. In this research, we used a high-speed optical wavelength interrogation system developed by Hitachi Cable Ltd to observe the Bragg wavelength shift [4]. The FBG used in the present research was coated with polyimide (Fujikura Ltd; sensor length: 1.5mm) and was bonded to the surface of the laminate with cyanoacrylate adhesive.

A waveform generated by the system is amplified by a high-speed bipolar amplifier (HSA4012, NF Corporation) and input into the MFC to excite ultrasonic waves. The wave propagated in the structure then reaches the FBG sensor, and the strain change is converted into a voltage signal by the system. The FBGs and MFCs can be integrated with composite laminates since they are very small and lightweight. The system also has high reliability because the components are flexible and have high fracture strain.

2 SPECIMENS

The FML specimens used in this research consist of 16-ply CFRP quasi-isotropic laminate (T700SC/2592, Toray Industries, Inc.) and three 50 μm Ti foils (Nippon Steel & Sumitomo Metal) inserted into the laminate and the laminate configuration is as follows: [45/0/-45/90/Ti/45/0/-45/90/Ti/90/-45/0/45/Ti/90/-45/0/45].

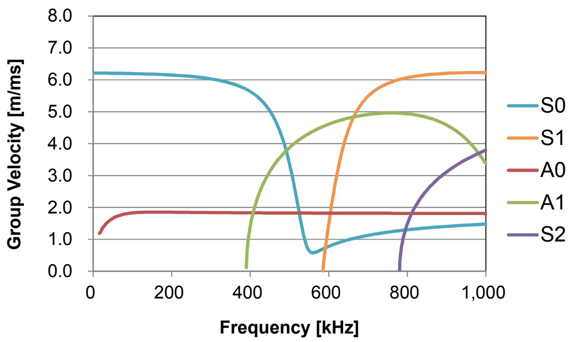


Figure 2: Theoretical dispersion curves of group velocities for the specimen used in this research

Since the thickness of the one-ply CFRP is about 0.15 mm and that of Ti foil is about 0.05 μm, total thickness of the FML was 2.35 mm. In order to investigate the propagation behavior of Lamb wave modes in the MFL, theoretical dispersion curves were calculated. In order to make calculation easy, each 4-ply CFRP laminate, which indicates [45/0/-45/90] or [45/0/-45/90], was homogenized. The group velocities of all the modes propagating in the MFL under 1 MHz were obtained using the DISPERSE software and plotted in Figure 2.

3 MODE SEPARATION IN EXPERIMENTS AND SIMULATIONS

As shown in Figure 2, the number of modes increases with an increase in the frequency. Hence, to identify modes observed in experiments and simulations in this research, mode separation is needed. Hence, as illustrated in Figure 3, two sets of MFC and FBG were bonded to both the top and bottom surfaces of laminate at the same positions.

The S modes of Lamb waves have the same strain at both the top surface and the bottom one, while the strains induced by the A modes at the top and bottom surfaces have opposite signs. Therefore, when the voltage signal is input to both the top and the bottom MFCs with the same phase, only S modes are excited. Conversely, when the phase of the input signal into the bottom MFC is changed so that it is opposite to that into the top MFC, only A modes are excited, because strains with opposite signs are generated between the surfaces. This excitation method is a classical approach used in much research. On the other hand, when the two waves received in the top FBG and the bottom one are superposed, only S modes are extracted from the received waves. In contrast, when the wave received at the bottom surface is subtracted from that at the top surface, only A modes can be extracted.

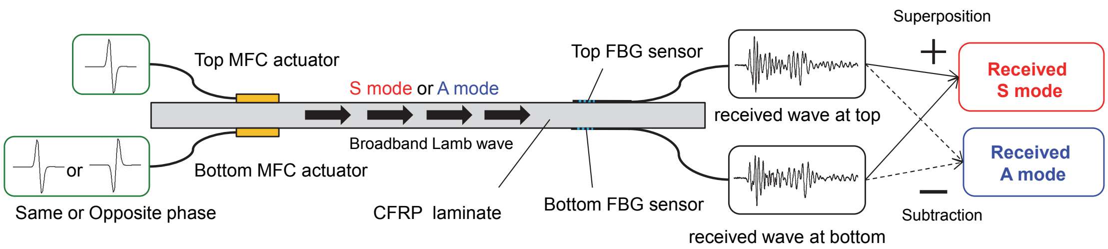


Figure 3: Separation of S modes and A modes by using two MFCs and two FBGs

In this research, we used a one-cycle or three-cycle sinusoidal wave with Hamming window at the frequencies from 100 kHz to 800 kHz at 100 kHz intervals as an input voltage signal. Then the continuous wavelet transform (CWT) was applied to the measured waveform to observe the dispersion characteristics.

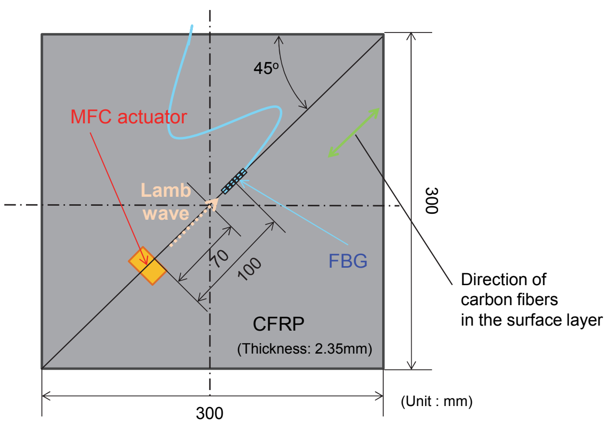
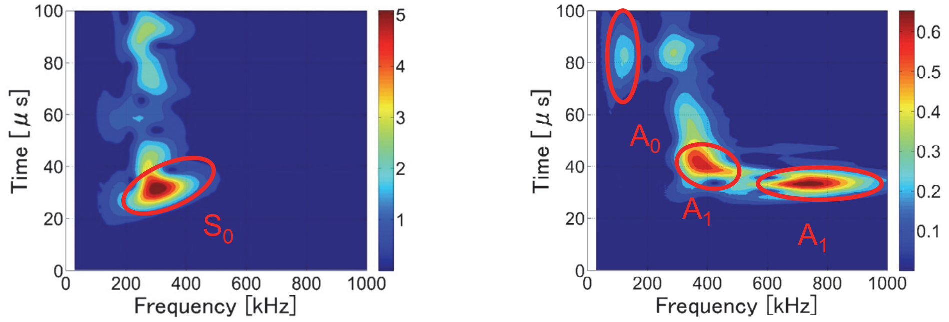


Figure 4: Schematic of the experiment setup for mode separation

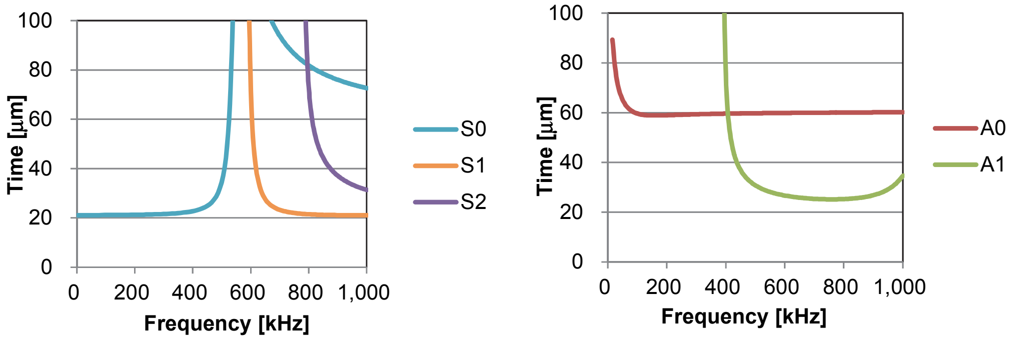
As one example, we propagated S modes and A modes of Lamb waves separately in the FML specimen under the condition shown in Figure 4. The reason why we propagated the waves in the diagonal direction of the square specimen is the prevention of receiving the reflected waves from the edges of the plate.

The CWT result in the case of S mode excitation and S mode reception at 400 kHz is shown in Figure 5(a) and that of A mode excitation and A mode reception at 600 kHz is shown in Figure 5(b). Moreover, the corresponding theoretical dispersion curves of propagation time calculated from the group velocity and the propagation length are shown in Figure 6. Compared with the theoretical results in Figure 6, the modes observed in the experiments (Figure 5) are identified as S_0, A_0, and A_1 modes clearly, and the reflection waves from edges of the specimen are very small.



(a) S modes at 400 kHz (b) A modes at 600 kHz

Figure 5: CWT results of same mode transmitting and receiving



(a) S modes (b) A modes

Figure 6: Theoretical dispersion curves of propagation time

4 INVESTIGATION OF MODE CONVERSIONS AT A DELAMINATION TIP

Lamb waves usually convert their modes at the points where the thickness of the plate changes, because the mode dispersion curves strongly depend on the thickness of the plates [5]. Since the dispersion curves are function of the frequency × thickness, the frequency in the horizontal axis in the graphs, such as Figure 2, doubles when the thickness is halved. Hence, if there is a delamination in the middle of the thickness of the FMLs, it is expected that the frequency dispersion curves of the Lamb waves that pass through the delaminated area will change because of the mode conversions at both tips of the delamination.

In order to clarify the mode conversions at the starting point of a delamination in the FML, the conversion behavior was investigated by experiment. To simulate the delamination in the middle of the thickness of the FML (the laminate configuration: [45/0/-45/90/Ti/45/0/-45/90/Ti/90/-45/0/45/Ti/90/-45/0/45]; thickness: 2.35 mm), and to place an FBG sensor on the inner surface of the delamination for mode observation in the received waves, the specimen shown in Figure 7 was manufactured. The left part of it was normal FML, and the right part of it corresponds to the lower sub-laminate in the delaminated area consisting of [90/-45/0/45/Ti/90/-45/0/45]. In order to simulate the left tip of the delamination, two Teflon films, each 0.10 mm thick, were stacked and embedded on the lower surface of the middle Ti foil. The films were inserted to 15 mm from the right end of the normal FML, where the upper sub-laminate was cut. For observation of mode conversion behavior, FBG sensors were bonded on both the surfaces at the points of 75 mm far from the MFCs in the intact area and 175 mm far from the MFCs in the delaminated area.

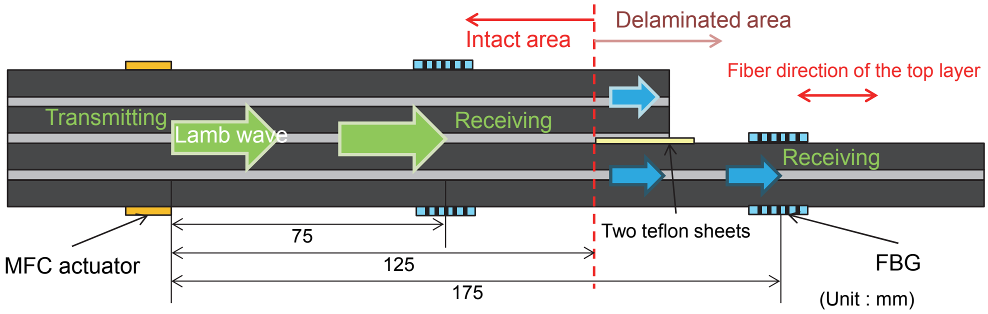
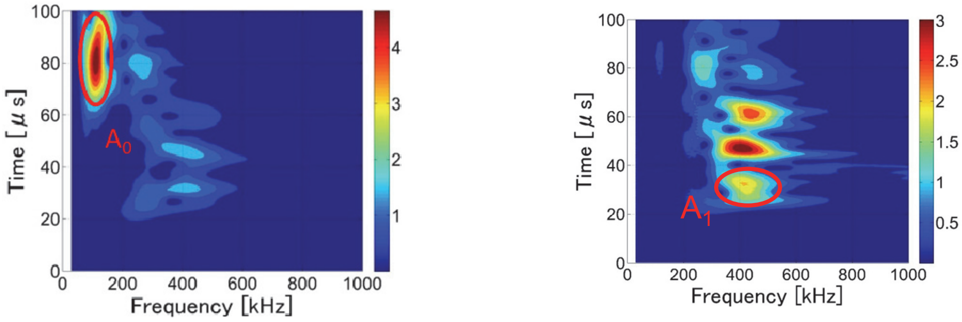


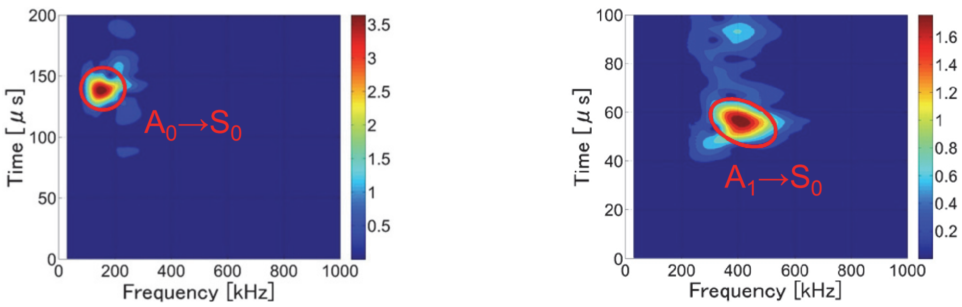
Figure 7: Schematic of the specimen for observation of mode conversions at the delamination tip

In this experiment, two MFCs were synchronously actuated with opposite phase to excite A modes. First, the CWT results of A modes received in the intact area (75 mm from the MFCs) are shown in Figure 8(a) at 200 kHz and Figure 8(b) at 400 kHz. In the result of 200 kHz excitation, A_0 mode is observed clearly. Then, in the case of 400 kHz excitation, A_1 mode is observed. Next, the CWT results of S modes received in the delaminated area (175 mm from the MFCs) are shown in Figure 9(a) at 200 kHz and Figure 9(b) at 400 kHz.



(a) 200 kHz (b) 400 kHz

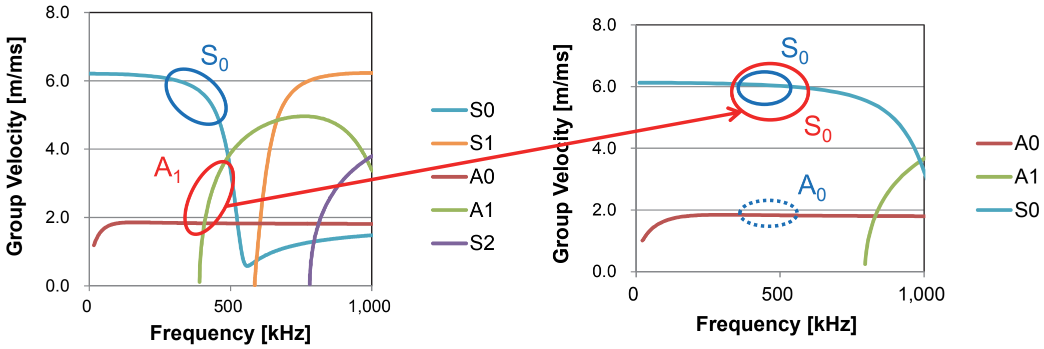
Figure 8: CWT results of A mode transmitting and receiving in the intact area



(a) 200 kHz (b) 400 kHz

Figure 9: CWT results of A mode transmitting and S mode receiving in the delaminated area

Hence, we attempted to identify the mode propagation behavior in the delaminated area. The propagation time obtained from Figure 9 for the propagation length of 175 mm consists of the length in the intact area of 125 mm and that in the delaminated area of 50 mm as shown in Figure 7. Therefore, the propagation time in 75 mm in the intact area was obtained from Figure 8 and converted to the time propagating in 125 mm. Then the time was subtracted from the propagation time in 175 mm obtained from Figure 9 in order to obtain the propagation time in 50 mm in the delaminated area. After that, the obtained time for 50 mm in the delaminated area was compared with the theoretical dispersion curves of the propagation time in the lower sub-laminate (eight-plies CFRP and one Ti foil). As a result, the propagation times in 50 mm in the delaminated area are about 7.4 µs at 100 kHz (A_0 mode in the intact area) and about 8.4 µs at 400 kHz (A_1 mode in the intact area). These times are much shorter than the propagation time of A_0 mode and close to that of S_0 mode in the delaminated area. These results indicate that the A_0 and A_1 modes in the intact area are converted into S_0 mode in the delaminated area. Incidentally, in the experiment of S mode excitation, it was found that S_0 mode in the intact area mainly keeps S_0 mode in the delaminated area and was slightly converted into A_0 mode by the delamination. These relations of mode conversions are illustrated in Figure 10.

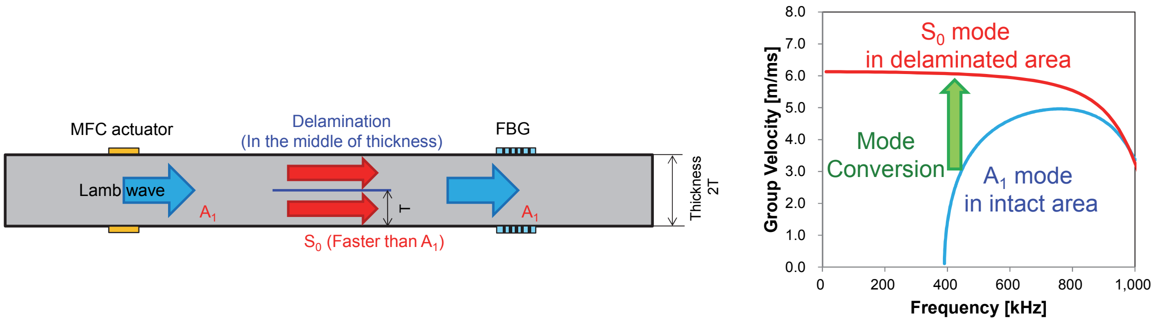


(a) in the intact area (b) in the delaminated area

Figure 10: Mode conversion behavior at the starting point of the delamination

5 EXPERIMENT TO DETECT AN INSIDE DELAMINATION

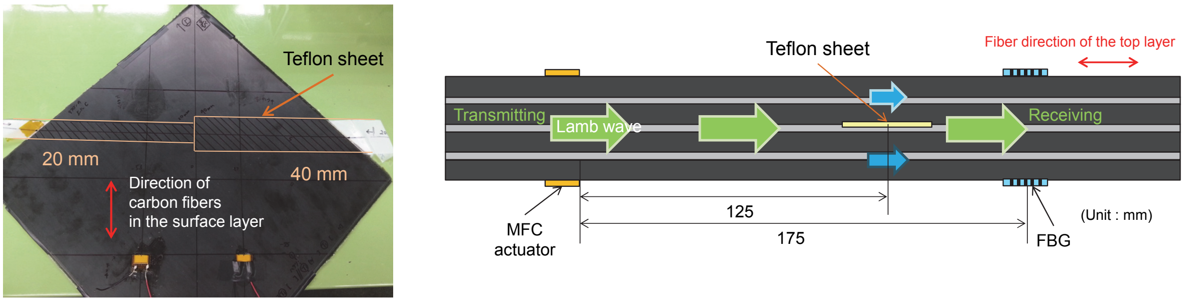
The mode conversion behaviors observed above indicate that the delamination detection method proposed in our previous paper [3] can be used. In the method, we use the mode conversion behavior: A_1 in the intact area is converted into S_0 mode in the delaminated area and the S_0 mode returns to A_1 mode again after passing through the delamination as shown in Figure 11(a). In this case, the dispersion of the group velocity differs between the A_1 mode in the intact region and the S_0 mode in the delaminated region as plotted in Figure 11(b). Since the S_0 mode is faster than the A_1 mode, the arrival time of the A_1 mode at the FBG sensors decreases with an increase in the delamination length. Furthermore, since this difference in the velocity increases as the frequency decreases, the frequency dispersion of the A_1 mode received in the FBGs is expected to change depending on the delamination length. Hence, from the changes in the dispersion of received A_1 mode, we can estimate the delamination length.



(a) Mode conversion due to the delamination (b) Change in the group-velocity dispersion

Figure 11: Principle of delamination detection based on the mode conversion

This method was confirmed by experiments. The picture of the specimen is shown in Figure 12(a) and the cross-sectional figure is in Figure 12(b). In this experiment, one Teflon sheet with the thickness of 0.05 mm is inserted on the upper surface of the middle Ti foil to form an artificial delamination between the CFRP and the Ti foil. The length of the artificial delamination L_D was changed as 0 mm, 20 mm, and 40 mm by embedment of the Teflon sheets with different lengths whose center was 125 mm away from the MFCs. Then, the FBGs were positioned 175 mm away from the MFCs.



(a) Picture of the specimen (b) Cross-section of the MFL with an artificial delamination

Figure 12: Specimen used in this experiment to estimate the delamination length

The input wave to MFCs is a three-cycle sinusoidal wave with Hamming window at the frequency of 400 kHz. Then, A modes were excited by the two MFCs with opposite phase and the A modes were extracted by subtraction between the two waves received in the two FBGs. After that, CWT was applied to the obtained waveforms and the maximum peak points were extracted from the CWT results. The peak points of A_1 are plotted in Figure 13. It is confirmed that the waves arrive earlier and the slope of the dispersion becomes small with an increase in the delamination length L_D.

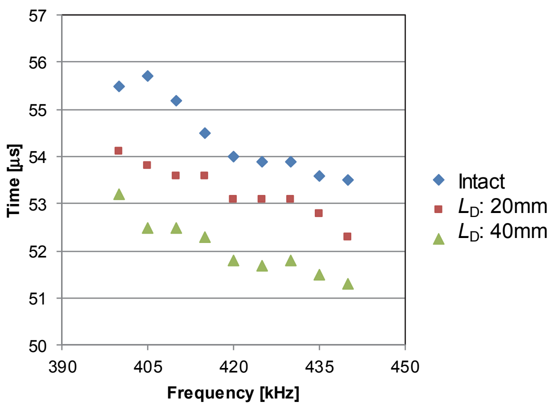


Figure 13 Maximum points extracted from the CWT results of the received A_1 mode in experiments

6 NUMERICAL SIMULATION OF THE DELAMINATION DETECTION

In order to validate the experimental result, we also conducted numerical simulation of the experiment with two-dimensional finite element analysis (FEA) using LS-DYNA software. In the FEA model, all the components were modeled with shell elements for 2D plane strain. The element dimensions in the MFCs were 125 µm in the longitudinal direction and 60 µm in the thickness direction. The CFRP parts were assumed as quasi-isotropic homogeneous plate and the element dimensions in CFRP were 125 µm × 125 µm. Then the Ti foils were assumed as isotropic plate with the element dimensions of 125 µm in the longitudinal and 60 µm in the thickness directions.

The received waves obtained by FEA were processed in the same way as the experiments and the extracted maximum peaks in the A_1 mode are plotted in Figure 14. The tendency of the dispersion to change depending on the delamination length L_D agrees well with the experimental results shown in Figure 13. With an increase in the delamination length L_D, the arrival time of the A_1 mode decreased and the slope of the dispersion became weaker. This agreement between the experimental results and FEA results indicates that this method based on the mode conversion is also effective to detect delamination damage in MFLs.

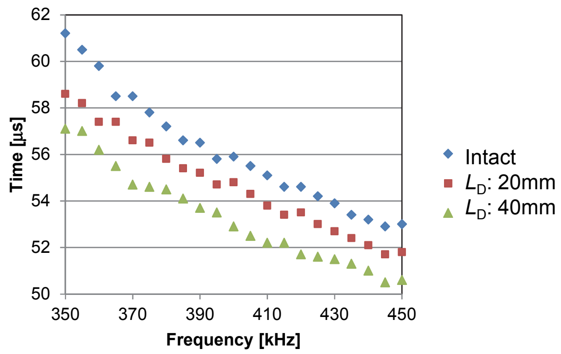


Figure 14 Maximum points extracted from the CWT results of the received A_1 mode in FEA

7 CONCLUSIONS

In this research, we investigated the applicability of Lamb waves as non-destructive method for FMLs. First, the dispersion curves measured for FMLs were confirmed to agree with the theoretical dispersion curves, leading the possibility of identification for Lamb wave modes. Secondly, we manufactured a specimen simulating the starting tip of the delamination in order to investigate the mode conversion behavior. The obtained results indicated that the delamination detection method proposed in our previous research can also be used to FMLs. Then, we conducted the experiments and FEA for the specimens with different delamination lengths and observed the change in the dispersion of A_1 mode. The results between the experiments and FEA agreed very well and it was found that the change in the dispersion of A_1 mode, which is converted to S_0 mode in the delaminated area, is effective to estimate the delamination length quantitatively in the middle of the thickness between the CFRP and the Ti foil in the FMLs.

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