Abstract
論文内容の要旨

Title of Dissertation: Numerical simulation of Lamb wave propagation in CFRP skin/stringer structures for ultrasonic SHM systems to detect impact damage

論文題目: 衝撃損傷を検知する超音波 SHM システムのための CFRP スキン/ストリンガ構造におけるラム波伝播の数値シミュレーション

氏名: 鄧　培文

Name of Author: DENG PEIWEN

1. Introduction

Carbon fiber reinforced plastic (CFRP) composites have been widely applied to various lightweight structures including aircraft and automobiles because of its high specific strength and high specific stiffness [1]. Those composite structures are usually semimonocoque, such as skin/stringer structures as shown in **Fig. 1**. When impact damages are caused in the semimonocoque structures by bird collision, a dropped tool, or a hail storm, the mechanical properties degrade largely.

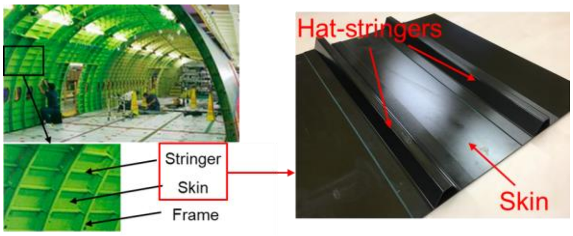


Fig. 1 Typical skin/stringer structures.

However, barely visible impact damages are difficult to be identified, though they are fatal damages to degrade the property of compression after impact [2]. Therefore, structural health monitoring (SHM) systems to detect the impact damages with integrated sensors have been developed for the past several decades. Some kind of the SHM methods use ultrasonic guided waves, in particular, Lamb waves to detect damages [3]. SUBARU and our research groups have also developed a SHM system consisting of a micro fiber composite (MFC) actuator, which is a film-type piezoelectric transducer, and a fiber Bragg grating (FBG) sensor, which is a kind of optical fiber sensor, to detect damages in a wide area of CFRP structures [4-6].

A reliable SHM system based on Lamb waves for impact-damage detection requires an optimal configuration of ultrasonic actuators and sensors to handle various damage situations. In order to determine the optimal configurations, the wave propagation behavior should be clarified for various impact damages with different dimensions and locations [7]. Although the optimal configuration can be determined experimentally [8], the experimental investigation for various configurations of sensors and actuators is usually costly, laborious, and time-consuming. In contrast, investigations of the optimal configurations based on numerical simulations, such as finite element method (FEM) analysis, is more efficient and economical.

2. Simplified modeling method of impact damages

2.1 Simplified modeling method

In order to observe an actual impact damage, we prepared a CFRP quasi-isotropic laminate (T700CS/2500,

$[45/0/\text{-}45/90]_{3s}$, thickness: 3.4 mm, we didn't use T700S/2500 because it is no longer marketed) and applied impact load to the plate. Then, we observed the impact damage by an ultrasonic C-scan to measure the dimension of the damaged area. After that, we cut the plate and observed its cross-section by a microscope in detail as shown in **Fig. 2.** From these observations, we assumed the impact-damaged region as a frustum with degraded stiffness constants [9].

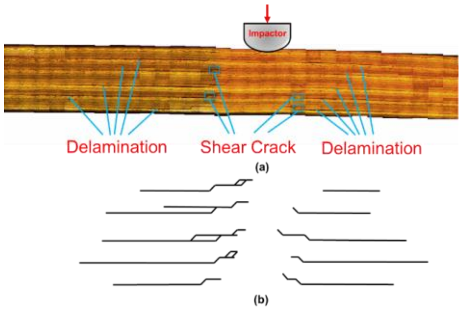


Fig. 2 (a) Cross-sectional image observed by a microscope and (b) the schematic of the damages.

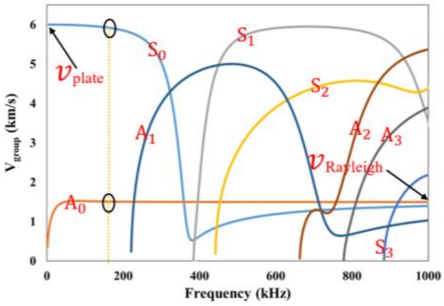


Fig. 3 Dispersion curves of group velocities of Lamb waves in a 3.4 mm CFRP quasi-isotropic plate.

To establish the simplified model, the degradation rates of the stiffness coefficients in the impact-damaged area must be determined. Among the five independent stiffness coefficients, three coefficients C_{11}, C_{33}, and C_{44} can be determined from the ultrasonic velocities and the other two C_{12} and C_{13} can be deduced according to the previous cross-sectional observation.

First, the degraded values of C_{11} and C_{44} will be determined using the following equation (1). **Fig. 3** shows a group velocity dispersion curves of Lamb wave in a 3.4 mm CFRP quasi-isotropic plate. In the frequency range from 40 kHz to 220 kHz, we can assume the group velocity of S_0 mode v_{S_0} is close to that of plate wave v_{plate}, and group velocity of A_0 mode v_{A_0} is close to that of Rayleigh wave v_{Rayleigh}. Therefore, we can derive the equation (1):

$$v_{S_0} \approx \sqrt{\frac{C_{11}}{\rho}},\ v_{A_0} \approx \sqrt{\frac{C_{44}}{\rho}},$$
$$C_{11} \propto v_{S_0}^2,\ C_{44} \propto v_{A_0}^2. \tag{1}$$

Hence, we measured v_{S0} and v_{A0} experimentally by propagating Lamb waves in the setup shown in **Fig. 4**.

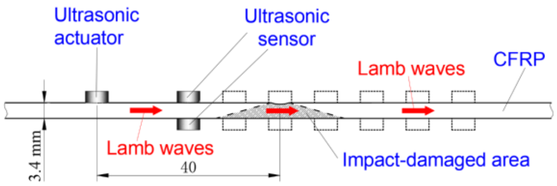


Fig. 4 Experimental setup to measure the velocity of Lamb waves in the damaged area to determine C_{11} and C_{44}.

Then, we assumed that C_{33} was not degraded in the microscopic sense. After that, the degraded value of C_{13} and C_{12} were determined based on the theoretical assumption shown in **Fig. 2**.

2.2 Verification of the validity of the simplified modeling method

To verify the validity of our simplified modeling method, we compared the calculated wave propagation behaviour based on this model with that calculated based on a precise damage model and that observed by an experiment. We call the precise FEM model of the impact damage "multiple-delamination model". In this model, peanut-shaped delamination is considered [10-11]. **Fig. 5** shows our multiple-delamination model where each peanut-shaped delamination between adjacent plies extends along the direction of the adjacent ply.

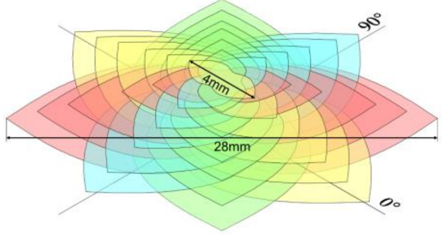


Fig. 5 Schematic of the delamination used in the multiple-delamination model of an impact damage

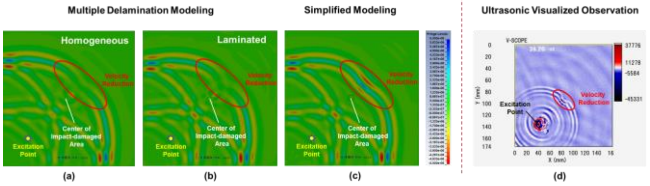


Fig. 6 Comparison of Lamb wave propagation behavior between the FEM analyses and the experimentally observation.

Using a commercial FEM software LS-DYNA, we calculated the Lamb wave propagation with "multiple-delamination model". Then we compared the calculation results by FEM with the simplified model, the multiple-delamination model and the experimental observation results in **Fig. 6**. From these results, we found that the simplified modeling method is quantitatively appropriate for modeling the impact damage in the simulation of Lamb wave propagation in quasi-isotropic composite structures.

3. Investigation in a complex-shaped CFRP structure

Then we verified the applicability of our proposed simulation method in a complex-shaped structure. CFRP quasi-isotropic skin/hat-shaped-stringer structure (T800S/3900-2, $[45/0/-45/90]_s$,). Then FEM analysis was performed with a commercial FEM software ComWAVE as shown in **Fig. 7.** The input wave to the MFC was a three-cycle sinusoidal wave at 100kHz or 180kHz. Since the skin/stringer structure can be assumed as a periodic structure, just one unit area between two adjacent stringers is modeled with periodic boundary conditions on both sides. The mesh size is determined by the thickness of one ply in the laminate.

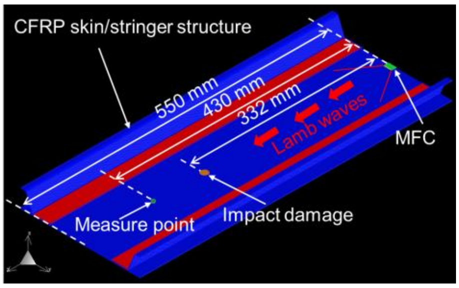


Fig. 7 Simulation configuration in a CFRP skin/hat-shaped-stringer structure

For the verification of the FEM simulation, an experimental measurement was conducted with the same configuration as shown in **Fig. 8**. The received strain waves were compared between the experimental results and the simulation results as shown in **Fig. 9**.

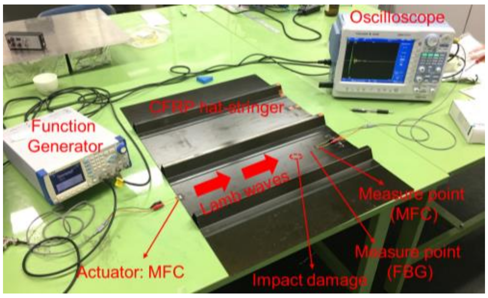


Fig. 8 Experimental setup for Lamb wave propagation in a CFRP skin/stringer structure with an impact damage.

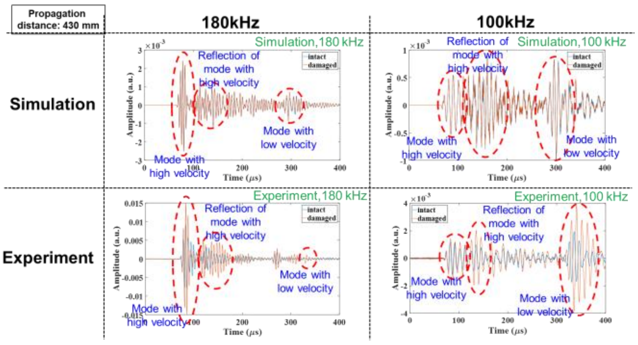


Fig. 9 Comparison of waveforms between simulation and experiment results with a propagation distance of 430 mm.

Fig. 9 shows the results in both the intact and damaged cases. The simulated waveforms agree with the measured waveforms in experiments from the viewpoint of the appearance of multiple modes in the Lamb waves. These results show the difference in the propagation time between the intact case and damaged case around 300 μs in both simulation and experiment at the input frequency of 100 kHz. In order to clarify the modes responding to the impact damage, we attempted to calculate the theoretical dispersion curves in the following chapter.

4. Theoretical investigation

4.1 Introduction

For a deeper understanding of the ultrasonic propagation behavior in the results in **Fig. 9**, we should clarify the modes in the waves by calculating the theoretical dispersion curves of a CFRP skin/stringer structure.

The theoretical calculation of velocity dispersion in a flat plate with an infinite width is relatively easy, because the wave behaviour can be expressed in the two-dimensional cross section [12]. However, in the case of a skin/stringer structure, reflection from the stringers on side edges cannot be neglected. Hence, the mode behaviour becomes much complex due to the transverse oscillations. To theoretically calculate the dispersion curves in an arbitrary cross-sectional shape, semi-analytical finite element (SAFE) method is most effective [13]. However, when the SAFE method is applied to a whole of CFRP skin/stringer structure, the calculation cost becomes very large. Therefore, we attempted to introduce periodic boundary conditions into the SAFE method in order to calculate only one unit in the periodic stiffened structure.

4.2 Dispersion curves in the skin/hat-shaped-stringer structure

By using the modified SAFE method, we calculated the results of dispersion curves from 0 to 300 kHz in the CFRP skin/hat-shaped-stringer structure. The results are shown in **Fig. 10**.

In **Fig. 10**, the group velocities of modes are found to be concentrated in three regions. The three mode groups are respectively the group A with the lowest velocity of transverse waves, group B with the middle velocity of shear-horizontal waves and group C with the highest velocity of longitudinal waves. The deformation states of the modes in the three groups are shown in **Fig. 11**.

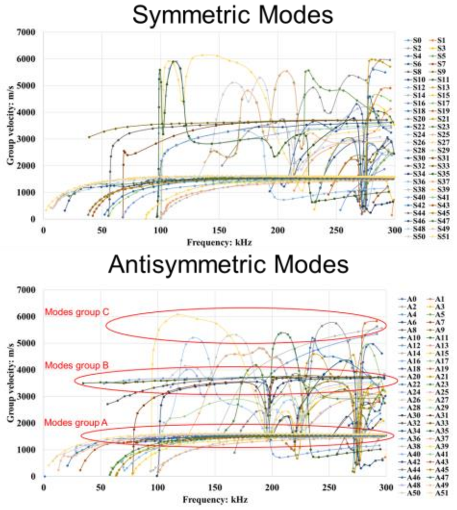
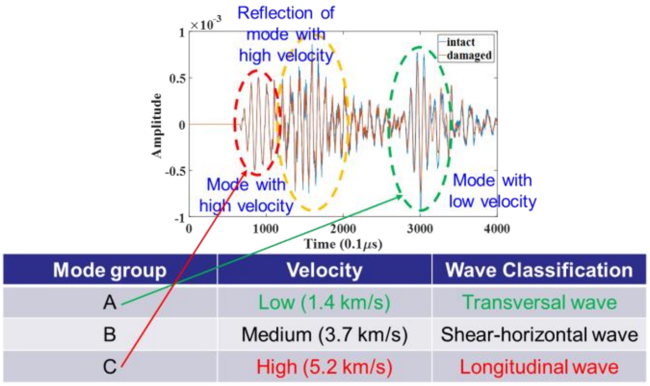


Fig. 10 Calculated group velocity dispersion curves in the CFRP skin/hat-shaped-stringer structure.

Fig. 11 Deformation state of modes in the three groups.



Mode group	Velocity	Wave Classification
A	Low (1.4 km/s)	Transversal wave
B	Medium (3.7 km/s)	Shear-horizontal wave
C	High (5.2 km/s)	Longitudinal wave

Fig. 12 Modes identification with dispersion curves.

Then we compared the calculated dispersion curves in **Fig. 10** with the waveform at 100 kHz obtained from simulation results in **Fig. 9**. We found that the wave modes with high velocity and low velocity in the FEM simulation results could be identified as the mode group of longitudinal waves and transversal waves respectively. This is shown in **Fig. 12**.

Furthermore, it can be inferred that the most sensitive mode to the impact damage is transversal mode of group A. Therefore, the configuration of the SHM system should be designed to excite the transversal mode group A strongly to detect impact damages more reliably. Also, the existence of impact damage could be related to the presence of a difference in propagation time of the transversal mode group A in the received waveform.

5. Conclusions

In this thesis, a simplified modeling method of impact damages was constructed and the appropriateness of it was verified through the comparison with the precise multiple-delamination model and the experimental observation. Then, the proposed FEM simulation method was applied to a CFRP skin/hat-shape-stringer structure and the results of simulation agree well with those of experiment. In order to have a better understanding of the waveforms, the propagation behaviors of the guided wave were investigated theoretically by using modified SAFE method to calculate dispersion curves of the CFRP skin/stringer structures.

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