# Numerical Simulation of Lamb Wave Propagation for Detection of Impact Damage in a Skin-stringer Composite Structure

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**Key Words:** Lamb wave, Impact damage, FEM modeling, Structural health monitoring, CFRP

## ABSTRACT

With an increase in the application rate of CFRP composites to aircraft structures, structural health monitoring systems are expected to be realized to secure the reliability of the composite structures. Hence, Fuji Heavy Industries and University of Tokyo have developed an ultrasonic structural health monitoring system consisting of macro fiber composite (MFC) actuators as ultrasonic transmitters and fiber Bragg grating (FBG) sensors as ultrasonic receivers to detect damages in a wide area of skin-stringer structure made of CFRP by propagation of Lamb waves. Especially, impact damage is the most fatal damage that the CFRP skin-stringer structure suffers from. In order to detect reliably impact damages with different size and location, the configuration of the MFC actuators and FBG sensors should be optimized. However, experimental investigation of the optimized configuration for large skin-stringer structure specimens with impact damage is inefficient and costly, while numerical simulations, such as finite element analysis (FEA), is more efficient and economical. In practice, precise modeling of the impact damage for FEA is difficult because the damage consists of multiple microscopic damages, such as delamination, shear cracks and transverse cracks. However, since the wavelength of Lamb wave is usually much longer than the dimensions of microscopic damages, it can be assumed that the damage area is homogenous anisotropic with degraded stiffness.

In this research, the authors attempted to model the impact damage by a homogeneous frustum of a cone shape with the degradation of quasi-isotropic stiffness matrix. The decreasing rate of the stiffness matrix was determined based on the velocity change of ultrasonic waves and the cross-section observation of the impact damage. Quasi-isotropic laminates can be expressed with five independent stiffness components. Among them, three coefficients are determined from velocities of ultrasonic waves measured by experiments. From the dispersion curves of group velocities of Lamb waves in a CFRP quasi-isotropic plate and the relationships between $C_{plate}$ and $C_{Rayleigh}$ and stiffness coefficients, we can obtain $v_{S_0} \approx \sqrt{\frac{C_{11}}{\rho}}$, $v_{A_0} \approx \sqrt{\frac{C_{44}}{\rho}}$. The $v_{S0}$ is the group velocity of $S_0$ mode and the $v_{A0}$ is that of $A_0$ mode. The thickness direction is expressed by $x_3$-axis. On the other hand, the velocity of longitudinal bulk wave $v_{Bulk}$ in thickness direction can be represented as $v_{Bulk} = \sqrt{\frac{C_{33}}{\rho}}$. First two coefficients can be obtained from measured propagation time of Lamb waves through the impact damage and the last one can be determined from the velocity of the bulk wave in thickness direction in the damaged area. Other two coefficients are determined based on the assumptions obtained from the observation results. Since delamination is found to be the most fatal damage form and it's reasonable to assume that the out-of-plane Poisson's ratio $\nu_{31}, \nu_{32}$ are close to 0 while the in-plane Poisson's ratio $\nu_{12}$ can be assumed to be approximately invariant through the impact process. So $C_{13}$ becomes 0 and $C_{11} \propto E_{11}, C_{12} \propto E_{11}$ which means $C_{12}$ is degraded at the same rate as that of $C_{11}$.

After that, the wave propagation behavior was simulated by FEA with this impact damage modeling in a CFRP plate and the skin-stringer structure. Then the simulation results were compared with the experimental results of the ultrasonic propagation behavior observed by the ultrasonic visualization system with laser. As a result, the simulation results showed the same tendency as the experimental results. Hence, this modeling method of impact damage for FEA could be verified to be reasonable. In the future, we will investigate the optimized locations of the MFC actuators and the FBG sensors to detect certainly impact damages in the CFRP skin-stringer structures.

## 1 INTRODUCTION

Since carbon fiber reinforced plastics (CFRP) have high strength/stiffness-to-weight ratio, design-ability and other excellent performances, it has been widely applied to a variety of structures including aircraft and automobile [1]. In those structures, skin-stringer composite structures will be employed as a principle structural component. However, the structural components will suffer from impact damage, which is one of the most fatal damage form caused by a collision with objects or tool drops. Therefore, health monitoring becomes important to secure the reliability of this composite structure. In recent years, structural health monitoring system which combines MFC actuators with FBG sensors has been developed to detect damages in a wide area of the skin-stringer structure made of CFRP. In order to monitor such a large structure's health status, impact damage with different sizes and locations must be examined and also, the location of actuators and sensors must be determined and optimized [2-3]. Hence, it will be better and necessary to start the study with a plate. However, experimental study of impact damage is inefficient and costly, and FEM simulation will be more efficient and economical. In practice, precise modeling of the impact damage for FEM is difficult because the damage consists of multiple damage forms, such as delamination, shear cracks and transverse cracks. However, since the wavelength of Lamb wave is usually longer than the length of microscopic damages, it can be assumed that the damage area is homogenous anisotropic with degraded stiffness. In this paper, we attempted to model an impact damage in a quasi-isotropic CFRP plate that guided Lamb waves propagate in, and compared the simulation result with the experimental result in order to verify the appropriateness of this simplified method for the simulation of propagation behavior of guided Lamb waves.

## 2 INVESTIGATION OF IMPACT DAMAGE

In order to investigate how lamb waves propagate in a composite material plate with an impact damage, several CFRP quasi-isotropic laminates (T700S/2500, $[45/0/-45/90]_{3s}$) with 200mm in length and width and 3.4mm in thickness are fabricated for ultrasonic experiments. An impact damage is generated in the center of the plate as shown in Figure 1.

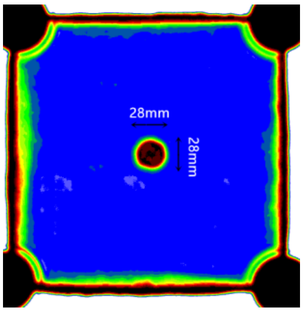




Figure 1: CFRP plate with an impact damage. Figure 2: C-scan observation of the impact damage area.

Then, a C-scan observation is conducted for measuring the damage size as shown in Figure 2. Based on the observation result, a frustum of a cone shape homogenous damage body with stiffness degradation is assumed to be equivalent to the real damage area [4]. According to this assumption, the size of damage area could be identified from the dent size and the result of C-scan result as radiuses of 2mm and 14mm in the upper and lower surfaces. After the wave propagation tests mentioned below, the plate was cut along the central axis of the damage area and the cross-section was observed by a microscope. The picture is shown in Figure 3 with the schematic of the damages.

From the observation results, the low-velocity impact damage mainly consists of two kinds of damage forms, delamination and shear crack, and delamination damages is more critical than shear cracks. Hence, the delamination damages mainly affects the stiffness in the damage area.

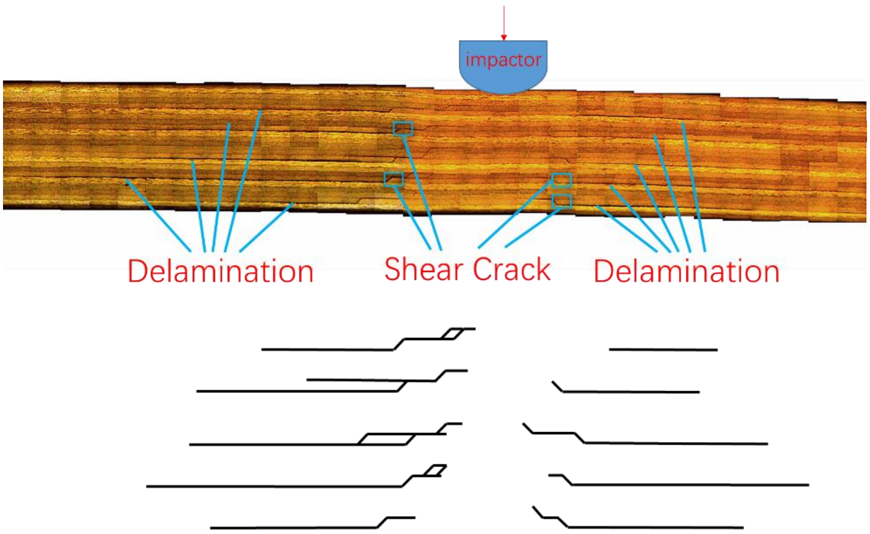



Figure 3: Cross-section observed by a microscope and the schematic of the damages.

## 3 THEORETICAL ASSUMPTION OF STIFFNESS DEGRADATION IN AN IMPACT DAMAGE AREA

Quasi-isotropic composite plate can be expressed with five independent stiffness coefficients as follows:

$$\begin{bmatrix} C_{11} & C_{12} & C_{13} & & & \\ & C_{11} & C_{13} & & & \\ & & C_{33} & & & \\ & & & C_{44} & & \\ & & & & C_{44} & \\ & & & & & C_{66} \end{bmatrix}$$

Here,
$$C_{66} = \frac{C_{11} - C_{12}}{2} \tag{1}$$

and the $x_3$-axis is in the thickness direction.

The relationship between elastic constants of quasi-isotropic CFRP plate and stiffness coefficients can be presented as follows:

$$\begin{cases} C_{11} = \frac{1-\nu_{23}\nu_{32}}{E_2E_3\Delta} \\ C_{12} = \frac{\nu_{21}+\nu_{31}\nu_{23}}{E_2E_3\Delta} \\ C_{13} = \frac{\nu_{31}+\nu_{21}\nu_{32}}{E_2E_3\Delta} \\ C_{33} = \frac{1-\nu_{12}\nu_{21}}{E_1E_2\Delta} \\ C_{44} = G_{23}, C_{66} = G_{12} \end{cases} \tag{2}$$

Here,
$$\Delta = \frac{1-\nu_{12}\nu_{21}-\nu_{23}\nu_{32}-\nu_{13}\nu_{31}-2\nu_{21}\nu_{32}\nu_{13}}{E_1E_2E_3} \tag{3}$$

Figure 4 shows theoretical dispersion curves of the group velocity of Lamb waves for the 3.4mm quasi-isotropic CFRP plate. In the frequency range below 200kHz, we can assume the relations of ultrasonic velocities as $v_{S_0} \approx C_{plate}$ and $v_{A_0} \approx C_{Rayleigh}$.

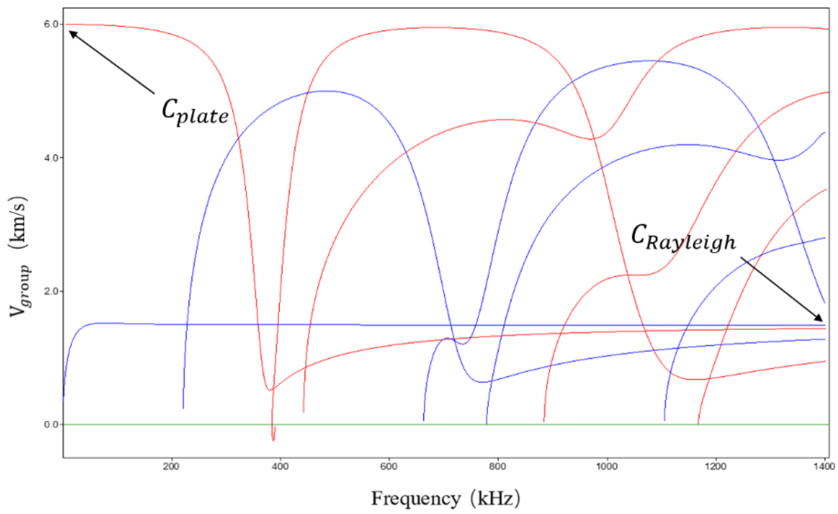



Figure 4: Dispersion curves of group velocities of Lamb waves in a 3.4mm CFRP plate.

From the dispersion relationship of a quasi-isotropic plate, we can express the velocity of the plate wave as

$$C_{plate} = \sqrt{\frac{C_{11}C_{33}-(C_{13})^2}{\rho C_{33}}} \tag{4}$$

Because $C_{13}$ is comparatively small, we can obtain the following relation:

$$v_{S_0} \approx \sqrt{\frac{C_{11}}{\rho}} \tag{5}$$

On the other hand, $C_{Rayleigh} = \alpha C_{transverse} = \alpha\sqrt{\frac{C_{44}}{\rho}}$, and $\alpha$ is close to 1. Therefore, the group velocity of $A_0$ mode is expressed as

$$v_{A_0} \approx \sqrt{\frac{C_{44}}{\rho}} \tag{6}$$

The velocity of longitudinal bulk wave in thickness direction is represented as

$$v_{Bulk} = \sqrt{\frac{C_{33}}{\rho}} \tag{7}$$

According to Figure 3, delamination is found to be the most fatal damage form and it's reasonable to assume that the out-of-plane Poisson's ratio is close to 0, namely, $\nu_{31}, \nu_{32}$=0, because the delamination cannot transfer the vertical strain. According to the equation (2), $C_{13}$ becomes 0. Besides, the in-plane Poisson's ratio $\nu_{12}$ can be assumed to be approximately invariant through the impact process. Therefore, according to the equation (2), $C_{11} \propto E_{11}, C_{12} \propto E_{11}$. That is, $C_{12}$ is degraded at the same rate as that of $C_{11}$. Then, $C_{66}$ can also be determined from equation (1).

In order to determine $v_{S_0}, v_{A_0}$ and $v_{bulk}$, two kinds of ultrasonic experiments were conducted. In the Lamb waves test, an AE sensor (NF-AE-900M) is fixed at 40mm away from the center of the impact area and a voltage signal of 3-cycle sine wave with hamming window was input to the AE sensor (Piezoelectric ceramic transducer). Then another AE sensor is successively placed along the propagation direction at a distance of S mm as shown in Figure 5. In order to excite only two modes of $S_0$ and $A_0$, input frequency was picked on 180kHz based on theoretical dispersion curves. The same test was also conducted to an intact plate.

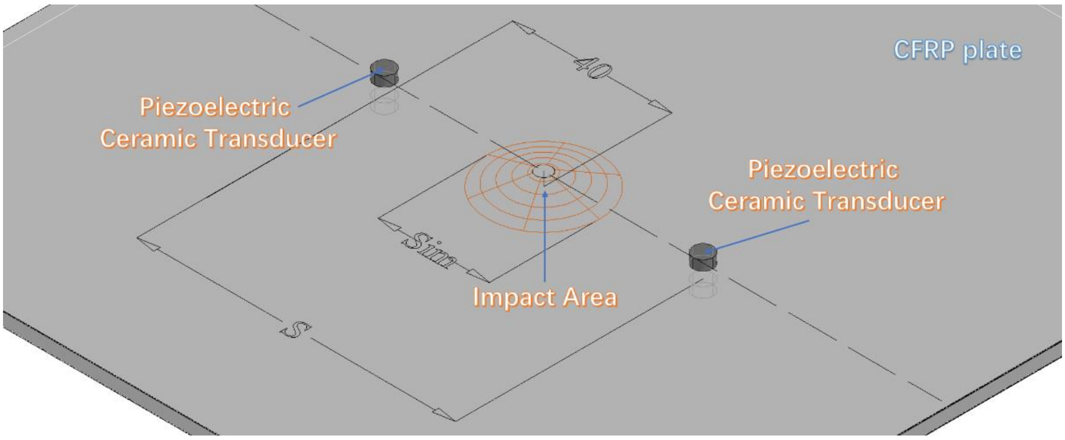



Figure 5: Experimental set up of Lamb waves propagation test for velocity determination.

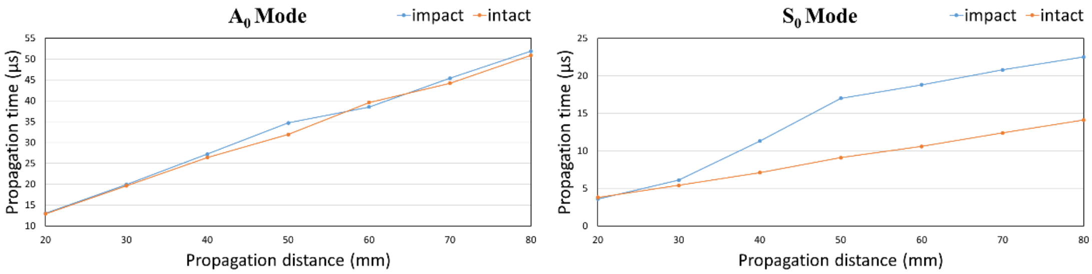



Figure 6: Propagation times of Lamb waves in intact and damaged CFRP plates.

Figure 6 apparently shows the delay of arrival time when there is an impact damage in the propagation path. Based on the homogenous assumption of impact damages, we supposed that in the impact area, Lamb waves propagate at constant velocities $V_{im}$ ($V_{im}$= $v_{S_0}$ or $v_{A_0}$).

When Lamb waves propagate with the same distance S in the intact plate and the impact damage plate separately, we can obtain the following equations:

$$\begin{cases} t_{in} \times V_{in} = S \\ t_b \times V_{im} = S_{im} \\ S_{im} + t_b \times V_{in} = S \\ t_{im} = t_a + t_b \end{cases} \tag{8}$$

Here, $S_{im}$ is the maximum diameter of the impact damage, $V_{in}$ ($V_{in}$= $v_{intact,S_0}$ or $v_{intact,A_0}$) is average Lamb waves' velocities in the intact plate, $t_{in}$ is a propagation time in the distance of S in the intact plate. $t_{im}$ is an average propagation time in the distance of S in the damaged plate. $t_a$ is the propagation time in the intact region and $t_b$ is that in the damaged region in the plate. The velocities $V_{im}$ of $S_0$ and $A_0$ can be easily obtained from equations (8). The calculated group velocities in the damaged area are as follows.

$$v_{S_0} = 1.892km/s, v_{A_0} = 1.521km/s \tag{9}$$

Then, the velocity of the longitudinal bulk wave in thickness direction was also acquired by measuring the propagation time around the impact point as shown in Figure 7. It's clear that the arrival time is increased in the area which has delamination damage.

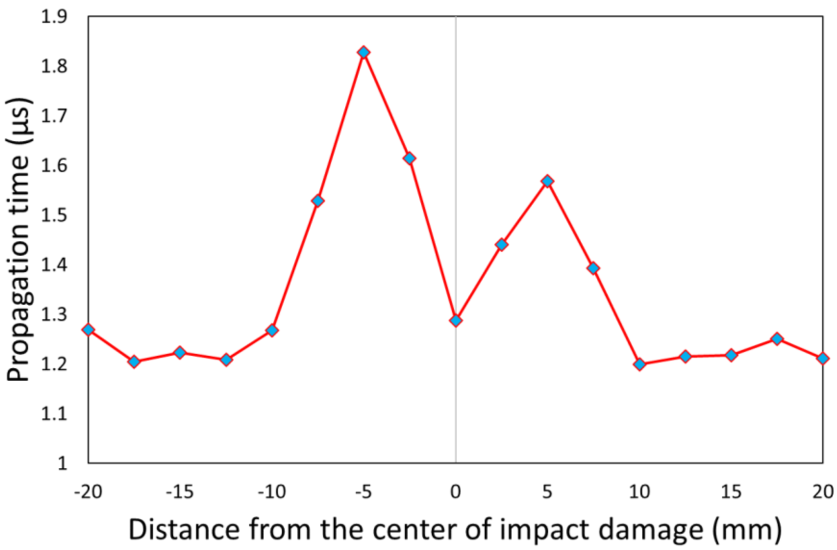



Figure 7: The delay of arrival time of the longitudinal bulk wave.

However, we can guess the delay is caused by the diffraction of acoustic waves around the delamination instead of stiffness degradation. This hypothesis can be proved by FEM simulation.

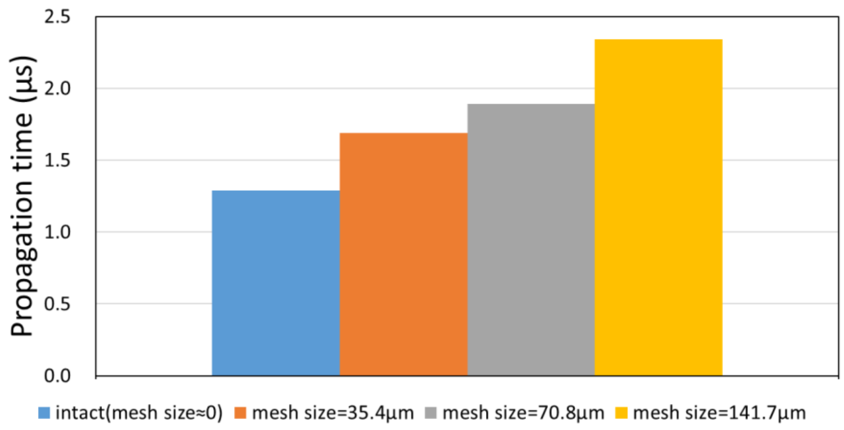



Figure 8: Calculated propagation time of the longitudinal bulk wave against mesh size.

The FEM simulation results of the propagation time of the longitudinal wave in the thickness direction are shown in Figure 8. We notice that the delay changes depending on the mesh size. Because we used double-node method to simulate the delamination and set contact condition between two adjacent surfaces in the delamination, the propagation time approaches the value in the intact plate as the mesh size becomes finer. This tendency indicates that the velocity of longitudinal wave in the thickness direction will not be decreased if the wave can directly pass the delamination. When the velocity of the longitudinal bulk wave keeps constant, $C_{33}$ will not change due to the equation (7).

Based on the above analysis procedure, the stiffness matrix of the damaged area could be determined. In this research, this modeling of the impact damage with effective stiffness degradation is called simplified modeling method.

## 4 CONFIRMATION OF QUASI-ISOTROPY IN THE IMPACT-DAMAGED AREA

In order to apply the simplified modeling method to simulate impact damage in FEM simulation, we have to confirm whether the impact damage area remains its quasi-isotropy. For this reason, we also modelled the impact damage as a multilayer peanut-shape area with double-node method as shown in Figure 9 [5-6]. This modeling and calculation of wave propagation were conducted by using an FEM software LS-DYNA (version 4.2).

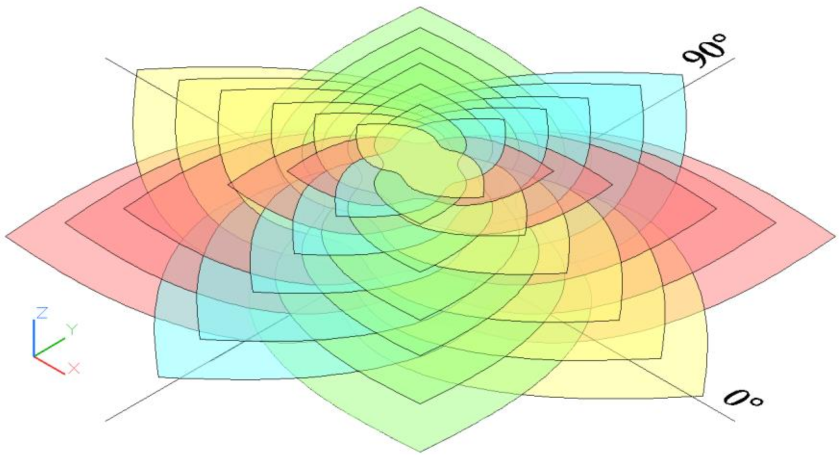
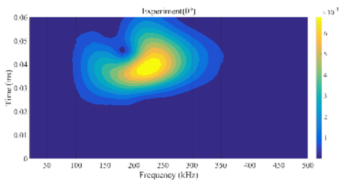
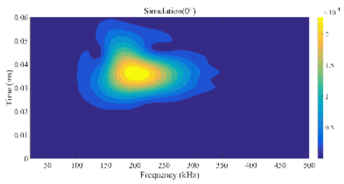
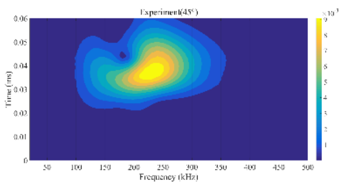
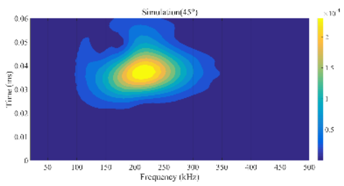
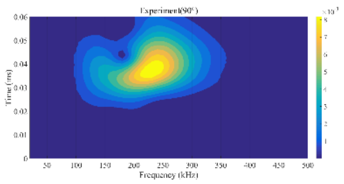
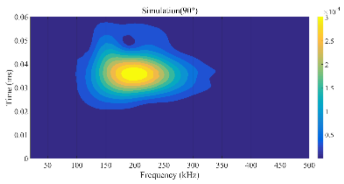



Figure 9: Modeling of an impact damage as multilayer peanut-shape delamination with double-nodes method.

The FEM model was formed with solid elements. The center of each peanuts-shape delamination was conformed with the center of the impact damage area. Then ultrasonic waves were propagated in four different directions (0˚, 45 ˚, 90 ˚, -45 ˚) with the same distance (40mm which covered the whole impact area) to investigate whether the impact area remains quasi-isotropy. At the same time, experiments to propagate Lamb waves in four directions are also conducted for comparison.

Table 1 shows wavelet transform results of the received waves obtained in the experiment and the simulation. From the comparison of the results, it is found that the arrival time and waveform barely changed in the four propagation directions. Therefore, we can assume that the impact-damaged area remains quasi-isotropy.

| | Experiment | Simulation |
|---|---|---|
| 0° |  |  |
| 45° |  |  |
| 90° |  |  |

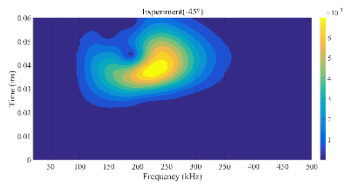
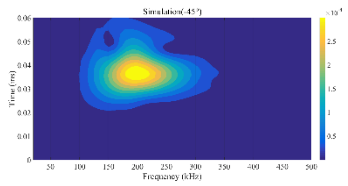
| | | |
|---|---|---|
| -45° |  |  |

Table 1: Wavelet transform results of the received waves in four different propagation direction in the experiment and the FEM simulation.

## 5 VERIFICATION OF SIMPLIFIED MODELING METHOD

Since the impact damage can be assumed to be quasi-isotropic homogeneous area, there is a possibility that the impact damages can be modeled in FEM by the simplified modeling method that uses the degraded stiffness matrix and a frustum of a cone shape.

In order to verify the accuracy of the simplified modeling method proposed in this paper, we compared the wavelet transform results of the propagated waves in various propagation distance between the multilayer peanuts-shape model and the simplified model. The FEM analysis was conducted with LS-DYNA.

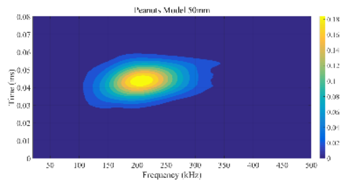
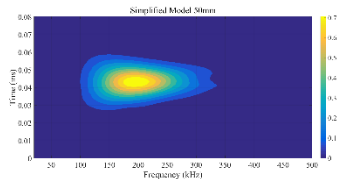
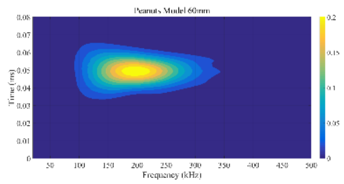
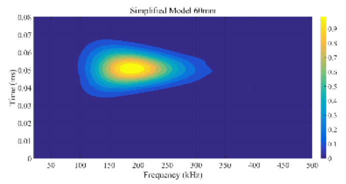
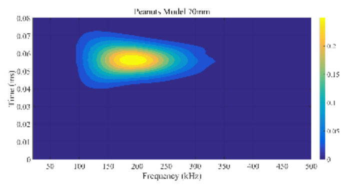
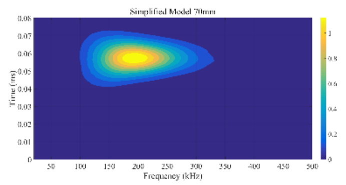
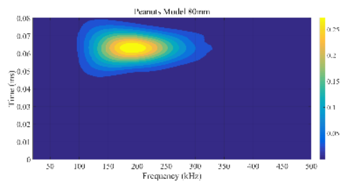
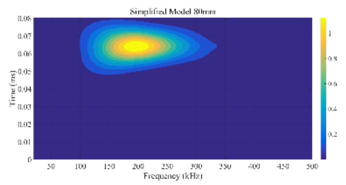
| Propagation Distance | Peanuts model | Simplified model |
|---|---|---|
| 50mm |  |  |
| 60mm |  |  |
| 70mm |  |  |
| 80mm |  |  |

Table 2: Wavelet transform results of the propagated waves in various propagation distance between peanuts-shape model and simplified model.

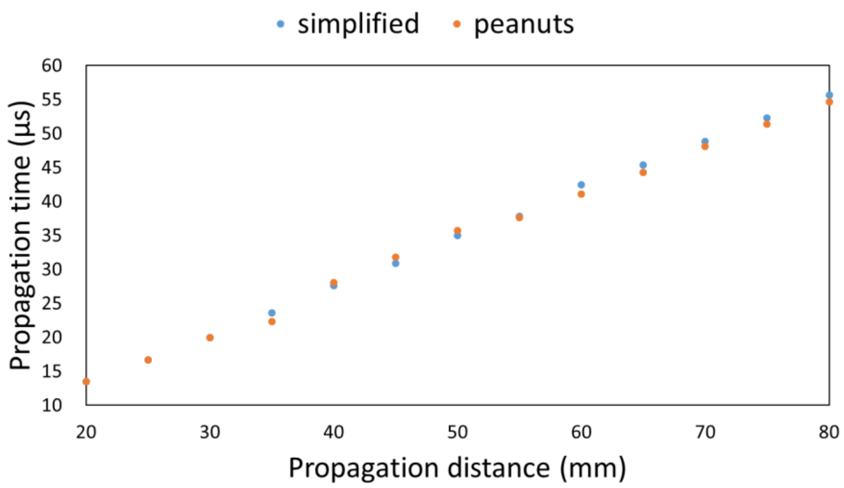
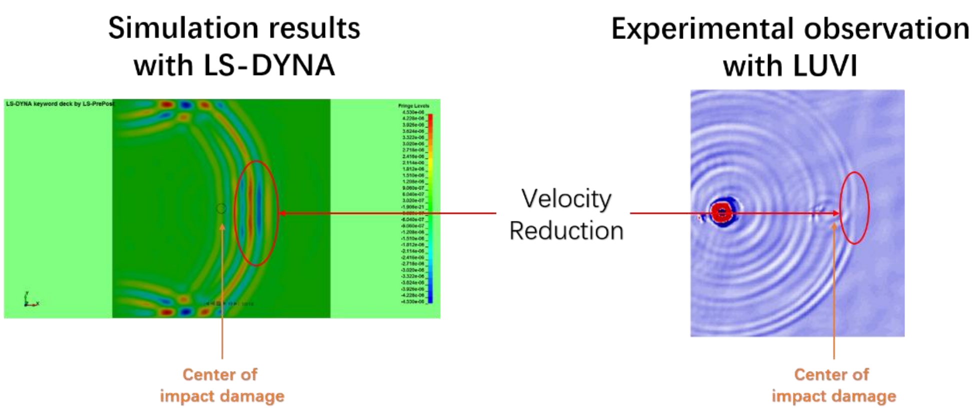



Figure 10: Propagation time of the maximum wavelet coefficient in the wavelet transform result.

We listed the wavelet transform results of the propagated waves in various different distances calculated by the multilayer peanut-shape model and the simplified model in Table 2. In order to evaluate these results quantitatively, we obtained the arrival time from the maximum peaks in the wavelet transform results of the waves propagating in different distances and plotted in Figure 10. These results show that both the wavelet transform results and the arrival time change obtained in the FEM analysis with the simplified model agrees well with that with the peanuts model.

The simulation result with the simplified modeling method of the propagation behavior around the impact damage is shown in Figure 11(a). Moreover, we used a laser ultrasonic visualization inspection system (LUVI) (Tsukuba Technology) to observe the propagation behavior experimentally to verify the simulation result. The agreement between the calculated displacement in thickness direction and the observation result from LUVI indicates the modeling of the impact damage for FEM is appropriate for simulation of ultrasonic propagation.




(a) (b)

Figure 11 Comparison of the wave propagation behavior around the impact damage between the FEM simulation with simplified modeling method and the experiment.

## 6 CONCLUSION

In this research, an impact damage in a CFRP plate was modeled as a homogeneous frustum of a cone shape part with the degradation of stiffness matrix for FEM simulation of Lamb wave propagation. The dimension of the damage area was determined by a C-scan and a microscope observation and stiffness matrix of damage area was determined from measured velocities of waves and some assumptions. It is also verified that the quasi-isotropy remains in the impact-damaged area. As a result, this simplified modeling method was confirmed to be appropriate to simulate impact damages conveniently in FEM analysis.

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