

Relationship Identification Between CFRP Impact Damage and Ultrasonic Guided Waves Using 3D Finite Element Simulation

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Abstract: The propagation characteristics of Lamb waves in carbon fiber reinforced plastics with low velocity impact (LVI) damage were investigated by numerical simulation. In order to accurately simulate lamb response to the multiple types of damage, a three-dimension finite element model was built. First, various types of damages were obtained by low velocity impact with variety of impact energy on composite plates. Then, Lamb waves are loaded into the composite plate with multiple damages. Four sensors are arranged in a diamond shape with the damage as the center. One sensor sends Lamb wave and the other three receive Lamb wave signal to extract the signal containing damage information. Finally, the power spectrum density was introduced to characterize the relationship between lamb waves and damage. The results demonstrate that the evolution law of damage is consistent with the theory and the sensitivity of power spectrum density to damage was verified. This study provides a new in-depth research method for damage detection and analysis.

Keywords: Carbon Fiber Reinforced Plastics, Finite Element Analysis, Low Velocity Impact, Guide Wave

1. Introduction

Carbon Fiber Reinforced Polymers (CFRP) materials have wide application prospects in aerospace, sports, automobile and other fields [1]. During the service life, sudden transverse loads may occur due to the effects of external objects, such as the falling tools in the assembly or maintenance process or the effect of hail ice during the use of the aircraft shelf [2]. These low velocity impact may lead to failure of composite materials such as fiber fracture, matrix cracking or delamination at microscopic level. It suffers great internal damages resulting in barely visible impact damage [3] which threatens the safety of aircraft, spacecraft etc. Therefore, the measurement of the CFRP damage is of great significance.

Many scholars have studied the detection of LVI damage using non-destructive testing [4-7]. Due to the advantages of long propagation distance, fine anti-interference and high

sensitivity to various types damages, Lamb wave is regarded as the most effective and important method for damage detection of plate structures [8-9]. Liu X *et al* [10] proposed a method for detecting delamination in composites based on the nonlinear Lamb waves. Yang Bin *et al* [11] studied the Lamb wave propagation behavior in composites by simulation. Based on the time-dependent elliptic theory, a defect imaging algorithm based on MATLAB is proposed. Yuan S *et al* [12] presented a novel method to determine and localize impact damage based on lamb wave mode. Compared with isotropic media, the propagation of Lamb waves in composites becomes more complex due to anisotropy [13]. In order to explore the potential of Lamb wave in nondestructive testing of composite materials, it is essential to study its propagation properties in anisotropic laminated structures, which depends on the type and size of the damage and the excitation frequencies.

Finite element analysis (FEA) is used to simulate the real

physical system by means of mathematical approximation. This can reduce the physical experiments and minimize the cost of experiments. Besides, it can also discriminate the law of response and provide a theoretical basis for practical application. In the process of damage simulation in the existing literature, most scholars use through hole or prefabricated stratified method to simulate damage. For example, Yang B *et al* used a through-hole to simulate the damage of composite plates, and explores the propagation law of lamb in damaged composites [11]. Yelve N P *et al* simulates the damage of composite plates by precast damage. [14] This method of damage simulation rarely occurs in practical application, because the formation of the composite damage is a step-by-step process. The laminate is firstly damaged by the low velocity impact, and then the delamination appears, and at last the fiber damage will occur. In general, matrix damage and delamination are dominating in the whole LVI process [15]. Furthermore, most available FEA pay attention to two dimensional (2D) models to simulate the guided wave characteristics in anisotropic media. Feng B researched the interactions of Lamb waves with the delamination using 2D finite element simulations [16]. Ng C T presents a theoretical and FEA of the scattering characteristics of the Lamb wave at delamination. The necessity of applying 3D simulation model to Lamb wave testing of composites is discussed [17]. Based on these reports outlined above, we should note that, in order to accurately simulate the multiple types of damage caused by low velocity impact and the interaction between the guided waves and the damage in the simulated thin composites, 3D simulation is needed.

In this paper, we established a 3D FE model to simulate the Lamb wave propagation behavior in during LVI damaged CFRP laminate. First, the composite damage including matrix damage, delamination damage and fiber damage was obtained by LVI. The damage introduced into the board is based on the Hashin damage criteria established by Hashin *et al*. Then, the Lamb wave propagation in composite under various types of damage was simulated. Finally, power spectrum density (PSD) is introduced to discuss the interaction between Lamb waves

and impact damages under different excitation frequencies.

2. The Interaction Mechanism of Lamb Wave with Damage

Lamb wave is an ultrasonic guided wave propagating between two parallel free surfaces. Lamb waves are widely recognized as one of the most effective methods for detection of damage in particularly metallic, composites. Lamb wave has many advantages such as propagate long distances, wide transmission range, low energy consumption and high sensitivity to different types of defects [18]. Lamb wave behavior follows the particle motion equation under free boundary conditions.

Propagation of Lamb waves in a multilayer composite, the interaction of waves depends on not only the separate components, but also their interfacial properties. In composites, a single guided wave mode is defined by six wave modes. Figure 1 illustrates an n-layered of composite. The six wave combinations and interference form Lamb wave mode and its propagation in the composites [19]. If the semi-infinite space is regarded as a vacuum, it is assumed that the stress on the upper and lower surfaces of the laminate is zero [20]. S. Pant studied the global matrix of Lamb wave following [21]:

$$\begin{Bmatrix} p_{i1} \\ p_{i2} \\ p_{i3} \\ p_{i4} \end{Bmatrix} = \begin{bmatrix} [-Z_{l2,top}] & [0] & [0] \\ [Z_{l2,bot}] & [-Z_{l3,top}] & [0] \\ [0] & [Z_{l3,bot}] & [-Z_{l4,top}] \\ [0] & [0] & [Z_{l4,bot}] \end{bmatrix} \begin{Bmatrix} \{U_{l2}\} \\ \{U_{l3}\} \\ \{U_{l4}\} \end{Bmatrix} \quad (1)$$

Where Z is global matrix. p_{ik} is the displacements and the stresses vector. U is amplitude vectors. It can be seen that the characteristics of Lamb waves in multilayered plates depend on the type, size, frequency and incidence angle of incident waves [11].

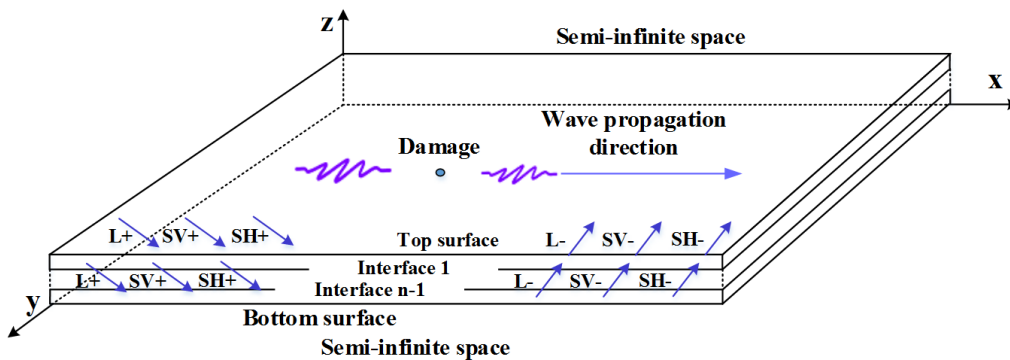


Figure 1. Guide wave propagate in the n-layered composite.

In general, the damage of composite consists of fiber damage, matrix damage and delamination. In this paper, evolution rules of variety damage in accordance with Hashin criteria, as shown in Ref. [22]. When lamb wave meets damage in propagation, Lamb waves will scatter, reflect and

mode transform. This is because the defect changes the symmetry of the plate and the propagation condition of Lamb waves in the plate. These signals with damage information are received by the other sensors. The location or degree of damage can be determined by signal processing.

3. Simulation of LVI Damage

For composite, the layup pattern is $[0^\circ / 90^\circ]_4$. Figure 2 shows the 3D FE model. The composite size is $200\text{mm} \times 200\text{mm} \times 2.2\text{mm}$. Material parameters are listed in Table 1. The element SC8R is used for the laminate, cohesive

element COH3D8 is used for the interface in adjacent layer. The impactor with the mass 2.0kg and diameter 1.9 cm is modeled as a discrete rigid body. Different impact energy can be obtained by changing the speed of the impactor. Seven impact energies 1 J, 2 J, 3 J, 4 J, 5 J, 6 J and 7 J are used. The element size is $1.0\text{mm} \times 1.0\text{mm}$. ‘General contact’ is used to define the contact response.

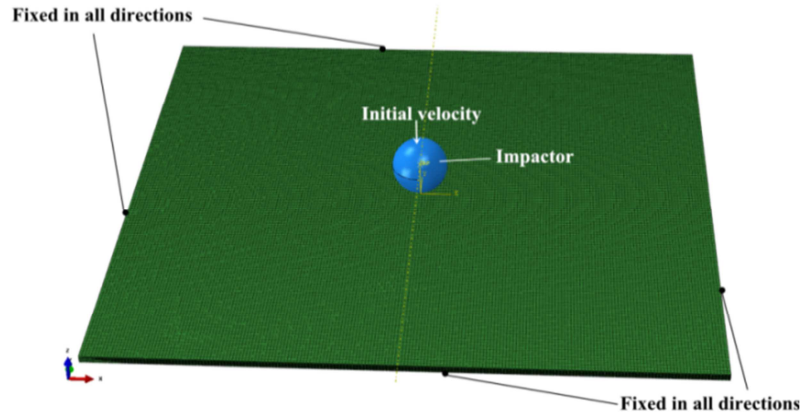


Figure 2. 3D FE model.

Table 1. Material properties of composite.

Ply properties	$E_1=143.4\text{GPa}$, $E_2=E_3=9.27\text{GPa}$, $G_{23}=3.2\text{GPa}$, $G_{12}=G_{13}=3.8\text{GPa}$, $\nu_{12}=\nu_{13}=0.31$, $\nu_{23}=0.52$, $X_T=2945\text{MPa}$, $X_C=1650\text{MPa}$, $Y_T=54\text{MPa}$, $Y_C=240\text{MPa}$, $\hat{S}_{12}=\hat{S}_{23}=\hat{S}_{13}=89.9\text{MPa}$, $\Gamma_{11}^T=91.6\text{N/mm}$, $\Gamma_{11}^C=79.9\text{N/mm}$, $\Gamma_{22}^T=0.22\text{N/mm}$, $\Gamma_{22}^C=0.76\text{N/mm}$
Interface properties	$G_1^C=0.33\text{N/mm}$, $G_2^C=G_3^C=0.8\text{N/mm}$, $\eta=1.45$ $T_1^0=33\text{MPa}$, $T_2^0=T_3^0=54\text{MPa}$

Through FE modeling, details of LVI can be obtained. Figure 3 shows the LVI process of composites under impact energy of 4 J. The whole process of impact can be divided into three stages. a) No damage layer appeared during this period, as shown in Figure 3(a). b) The stage of damage propagation.

Various types of damage occur and rapid propagation in composites, as shown in Figure 3(b-d). c) Impact rebound period. The impactor rebounded and the damage gradually stabilized, as shown in Figure 3(e-f).

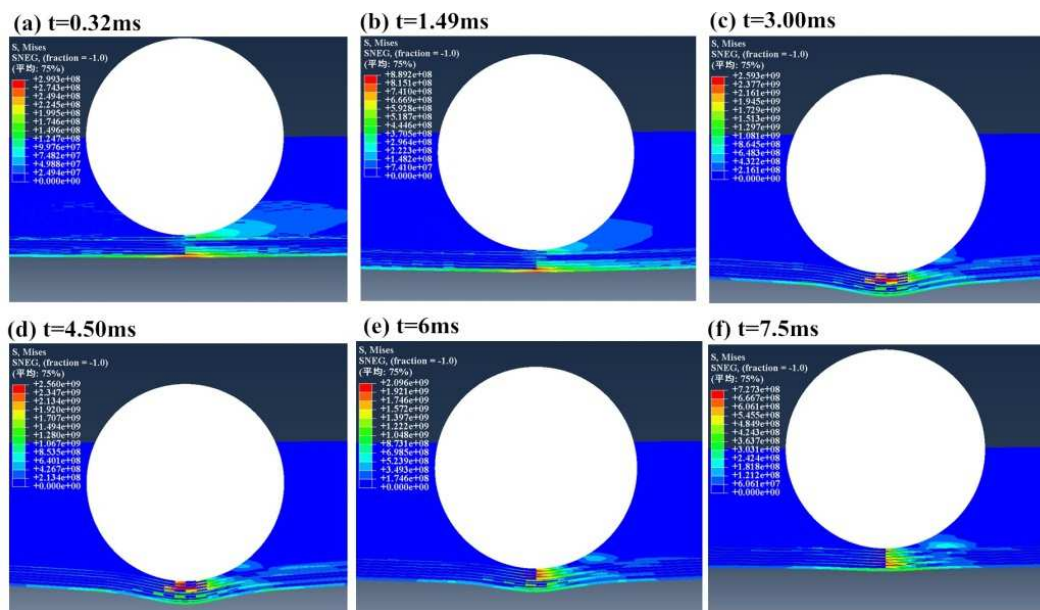


Figure 3. LVI process of composites.

The damage evolution law of composite plates was analyzed by extracting damage diagrams with impact energy of 1, 3, 5, 7J. Figure 4 shows fiber damage in about 7.5 milliseconds. The finite element analysis shows that the fiber

damage occurs at impact energy above 5J and 7J. Most fiber damage occurs first on the upper layer of the composite because the upper layer produces great compressive stress due to plastic deformation.

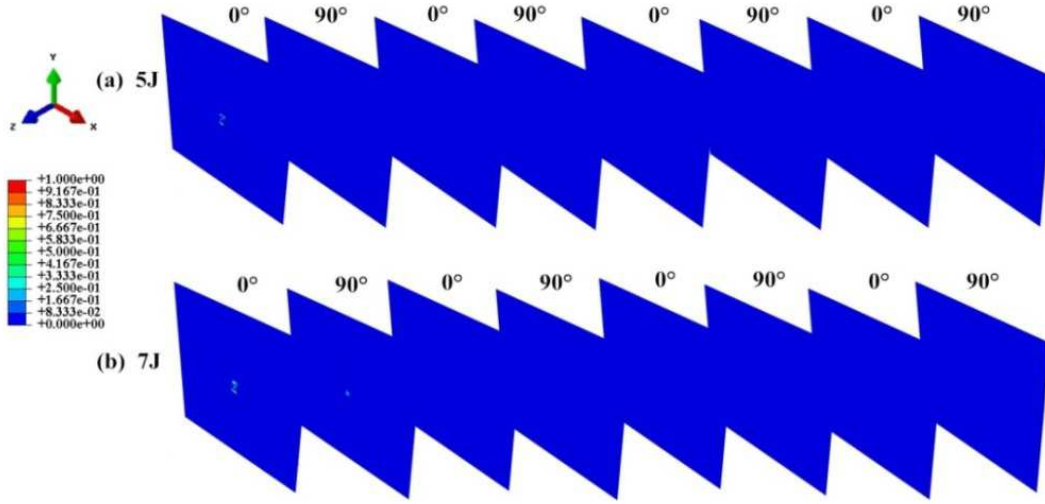


Figure 4. Fiber damage evolution at the impact energies. (a) 5J, (b) 7 J.

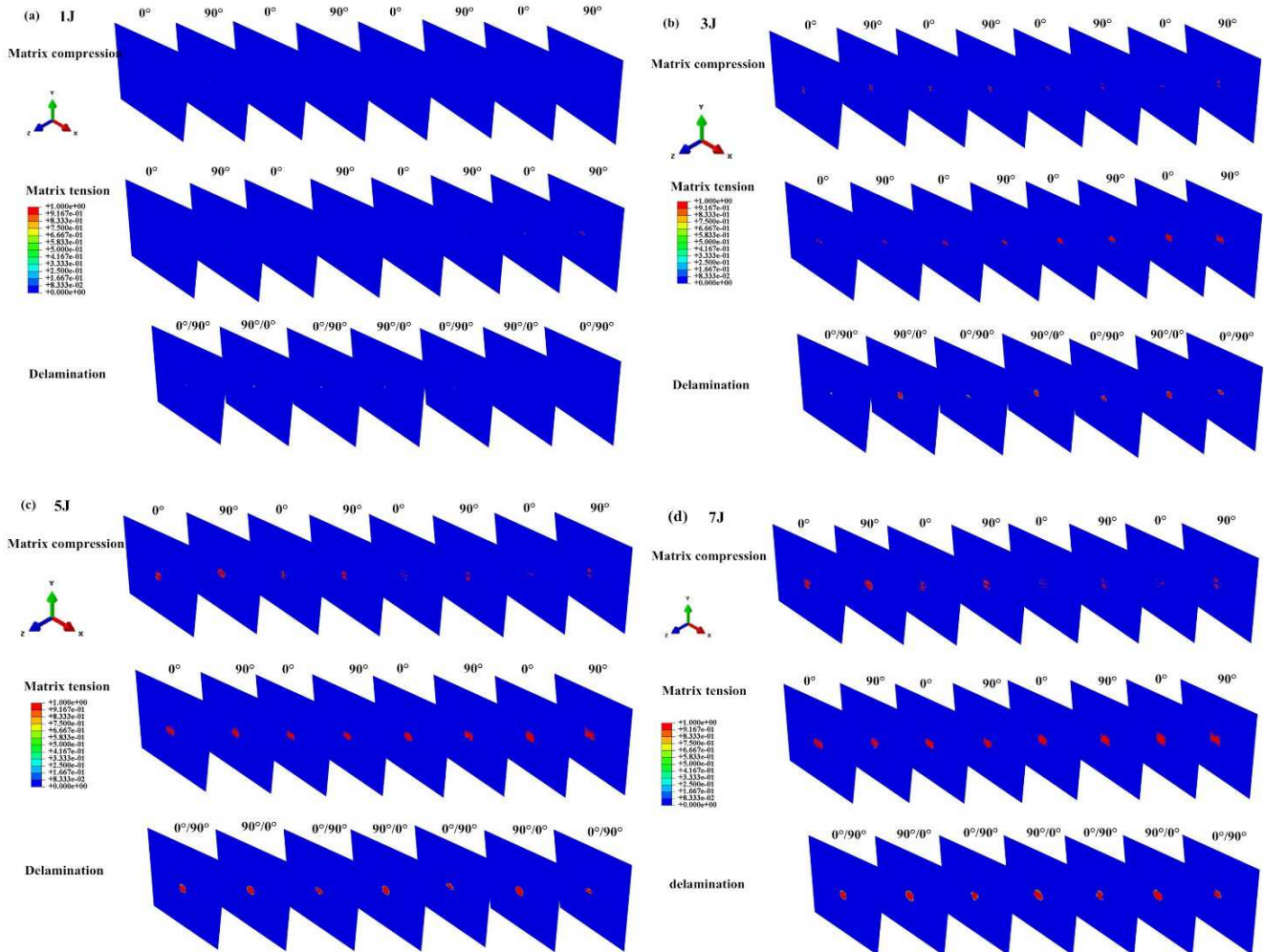


Figure 5. Matrix compression, matrix tension and delamination damage evolution for composite at the impact energies. (a) 1 J, (b) 3 J (c) 5J and (d) 7 J.

Figure 5 exhibits matrix damage and delamination. Several aspects of conclusions are obtained. The tensile damage of matrix first appeared at the bottom and spread upward. However the matrix compression appears in the front layers. The delamination first appeared on the upper interface of the composite and soon appeared at each bonding interface. As the impact continues, the matrix cracking and delamination continue to expand. Matrix damage always develops along the main direction of fiber. These conclusions are consistent with the results of Kim et al. [23] and Faggiani and Falzon [24]. In general, the tensile damage of matrix and delamination is dominant than that of matrix compression.

4. Lamb Response and Result Analysis

4.1. Lamb Wave Loading

The dynamic simulation of lamb wave activation and propagation was accomplished in composite plates damaged by LVI. The position of an actuator and three sensors on the composites are shown in the Figure 6(a). The four sensors

are surrounded by laminate center with symmetrical diamond distribution. The Lamb wave is produced by equation (2) [20]:

$$A = \frac{1}{2} \left[1 - \cos \left(\frac{2\pi f_c t}{n} \right) \sin(2\pi f_c t) \right] \quad (2)$$

where, f_c is the frequency; n is the number of cycles ($n = 5$). In this paper, the signal response under three central frequencies is discussed: 100kHz, 150 kHz and 200 kHz. As an example, Figure 6(b) is a time domain diagram of the 100 kHz excitation signal.

We also have to mention that after the LVI is completed, the laminate will remain vibrant, where the amplitude of the lamb signal generated by the actuator is smaller than the amplitude generated by the vibration. In general, the damping eliminates the vibration of composite. However, this method will increase the computation time of simulation. So, this paper proposes a technology which is viscous pressure to eliminate this vibration by introducing loading steps after the LVI step.

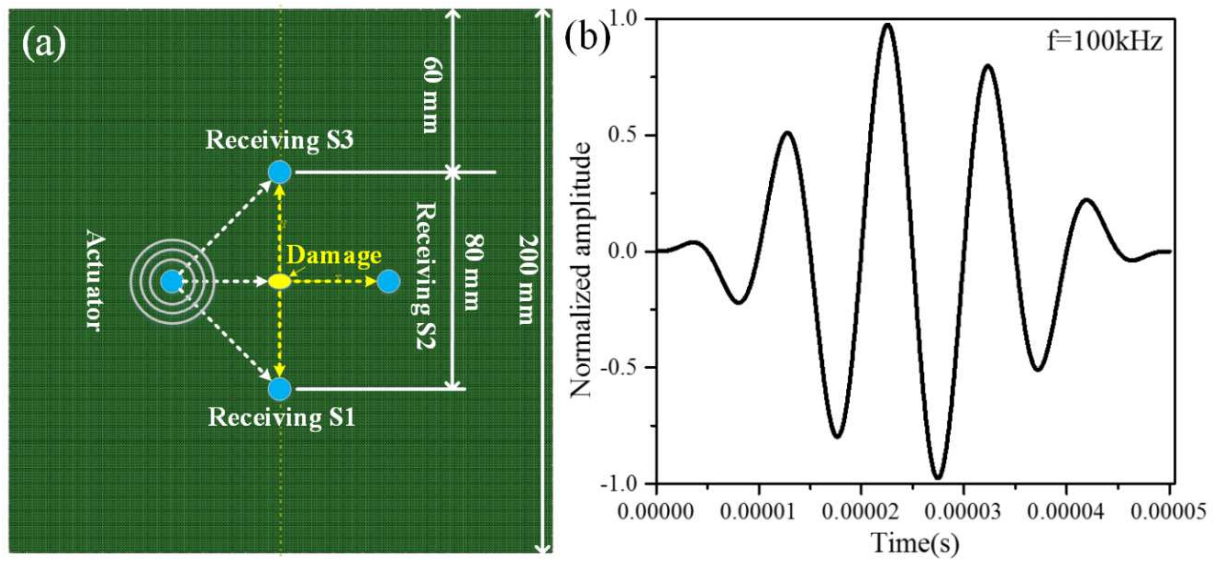


Figure 6. (a) Sensors location, (b) Excitation signal: $f = 100$ kHz.

Viscous pressure loads can be expressed by $p = -c_v(v - v_{ref}) \cdot n$, c_v is viscosity; v is velocity of the point on the surface; v_{ref} is velocity of the reference node. The c_v is given by ρc_d . ρ is the density of the material, c_d can be obtained by Equation (3).

$$c_d = \sqrt{\frac{\lambda + 2\mu}{\rho}} = \sqrt{\frac{E(1-\nu)}{\rho(1+\nu)(1-2\nu)}} \quad (3)$$

Where E is Young's modulus, λ and μ are Lamé's constants, ν is Poisson's ratio.

A comparison of the displacement of one point on the impact surface with viscous pressure and without viscous

pressure is shown in Figure 7(a). It can be seen the vibration of the plate can be attenuated. The calculation costs 92 h for damping method, but 44 h for this method under the same computer.

In the case of cutting the vibration of the plate, the wave response of composites excited at frequencies of 100 kHz and impact energy of 7J is shown in Figure 7(b), (c) and (d). The wave is excited by actuator and received by sensor S1, S2 and S3, respectively. Among them, the sensor S2 mainly receive the direct wave signal which through damage, the sensor S1 and S3 mainly receive the direct wave signal which did not through damage and scattering signal of damage.

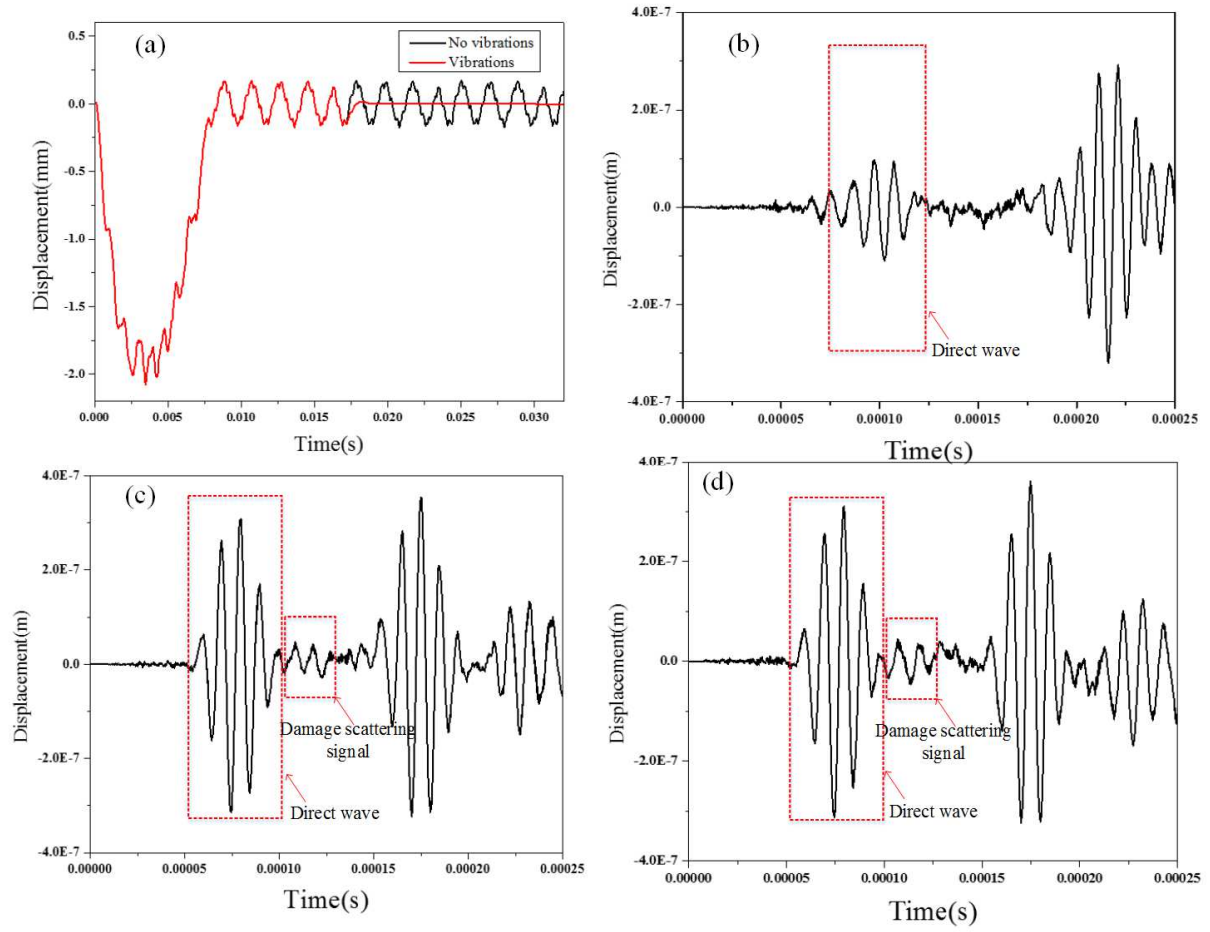


Figure 7. (a) Comparison of the numerical displacement of one point on the impact surface of the composite subjected to a 4 J impact event with and without vibrations; (b) Signal received by sensor S2; (c) Signal received by sensor S1; (d) Signal received by sensor S3.

4.2. Result Analysis

We extract the direct wave signals of sensor S2 and the damage scattering signals of sensors S1 and S3 for analysis, as shown in Figure 8 and Figure 9.

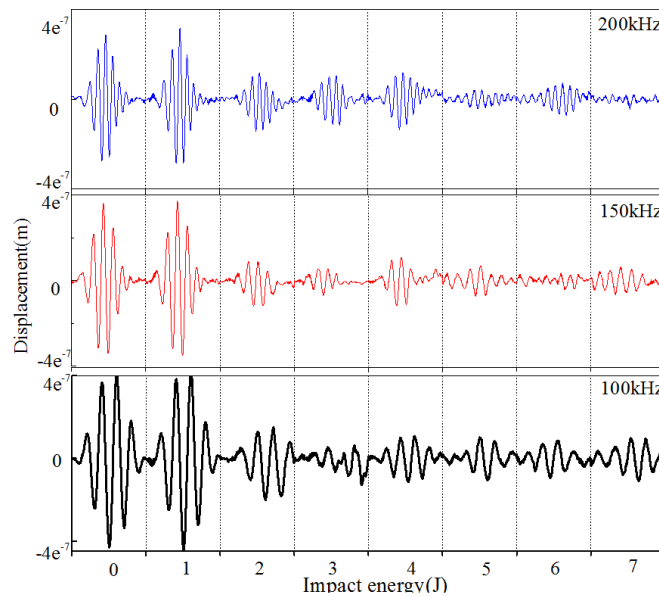


Figure 8. The relationship between the signals received by sensor S2 and the different impact energy under different excitation frequency.

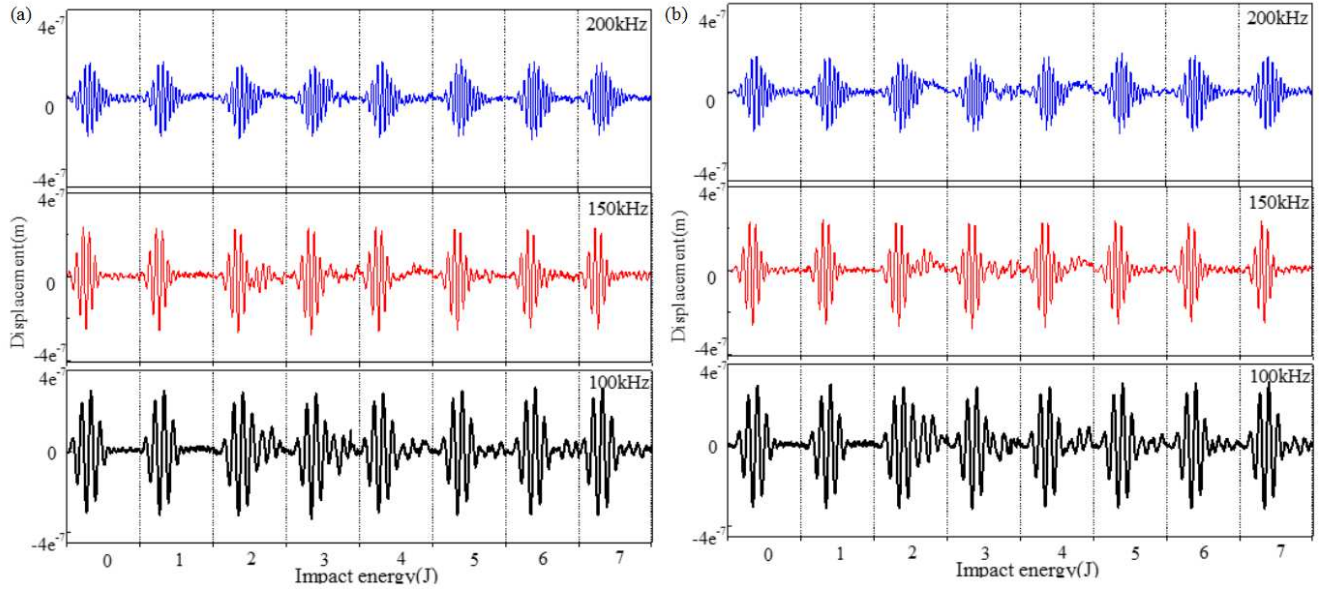


Figure 9. The relationship between the signals received by sensor and the different impact energy under different excitation frequency. (a) sensor S1 (b) sensor S3.

In Figure 8, we can see that the amplitude of direct wave signal decreases with the increase of impact energy. However, it is difficult for us to observe any obvious changes in the damage scattering signals from Figure 9. For this reason, the PSD is introduced to discriminate the damage signal [25].

The PSD can be used to reflect the relationship between the signal energy feature changes with frequency, the interaction between Lamb wave and damage can be analyzed based on this.

Assuming that the signal is $x(t)$, its Fourier transform is $X(e^{j\omega})$. According to Parseval's theorem, the energy of the signal can be calculated by Equation (4).

$$W = \int_0^T x^2(t)dt = \frac{1}{2\pi} \int_0^\infty |X(j\omega)|^2 d\omega \quad (4)$$

The PSD is:

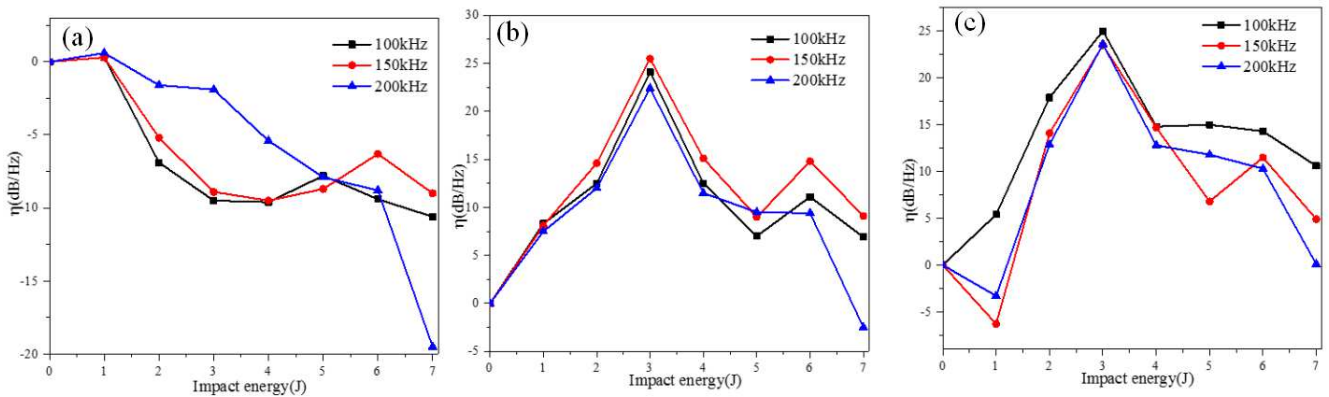


Figure 10. Damage factor vs. impact energy: (a) Sensor S2; (b) Sensor S1; (c) Sensor S3.

Figure 10(a) indicates the variation of the PSD of the S2 received signal with the impact energy at different frequencies. It can be obtained from it that the PSD decreases with the

$$P(\omega) = \int_0^T |X(e^{j\omega})|^2 d\omega \quad (5)$$

Define a damage factor, as shown in Equation (6). The greater the damage factor represents the more serious damage, and vice versa. The smaller the damage factor is, the smaller the damage is.

$$\eta = P_{\text{damage}} - P_{\text{health}} \quad (6)$$

Where P_{damage} and P_{health} represent the PSD of the laminate under the condition of damage and no damage, respectively.

Damage factors of three sensors shown in Figure 10(a) (b) and (c), under three different excitation frequencies: 100 kHz, 150 kHz and 200 kHz, respectively.

increase of impact energy. Because, according to Figure 6(a), the damage is on the propagation path. Directly affects the propagation of waves. The Lamb wave is scattered and

absorbed some energy when it meets damage.

Figure 10(b) and 10(c) show the relationship between the PSD of the damage scattering signal received by sensor S1 and sensor S3, under the different impact energy at different excitation frequencies. It can be obtained that the PSD increases with the increase of impact energy, when the impact energy is less than 3J. However, when the impact power is greater than 3J, the PSD gradually decreases. This is due to the composite is slightly damaged when the impact energy is small, which mainly scatters the lamb signal. On the contrary, when the impact energy is large, the composite plate is seriously damaged, which mainly absorbs the lamb signal. In addition, the power spectral density changes are almost the same under different excitation frequencies. It can be seen in Figure 10(a), when the central frequency of 100 kHz and 150 kHz, the PSD tends to be stable after the impact energy reaches 3J. However, the power spectral density is more sensitive to the impact of different energy with excitation frequency of 200 kHz.

5. Conclusions

In this work, the relationship between lamb waves and damage of composite plate under different energy levels is studied by numerical. 3D finite element simulations are used to obtain various types of damage that include matrix damage, delamination damage and fiber damage of composite plates. The interaction between Lamb wave and damage is studied under three central frequencies of actuation signal. The conclusions are summarized as follows:

- (1) For various types of damage caused by low velocity impact, the law of damage evolution coincides with the theory, which proved the correctness of the 3D finite element model.
- (2) For different detection paths, the PSD has different characteristics. The PSD proposed in this paper can reflect the interaction between Lamb wave and damages of LVI.
- (3) When the excitation frequency is 200 kHz, the PSD method introduced in this paper shows a better regularity.
- (4) This simulation can better guide the experiment. The excitation frequency is reasonably selected according to the specific conditions.

Highlights

- 1) A 3D finite element model for accurately simulating lamb response to the multiple types of damages is built.
- 2) The power spectrum density is introduced to characterize the relationship between lamb and damage.
- 3) The response of Lamb wave to damage under different excitation frequencies and variety impact energy is explored.

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