Evaluation of Ultrasonic Bonding Strength with Optoacoustic Methods

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Abstract: This study reports the application of an optoacoustic method for evaluating the bonding strength of ultrasonically bonded joints in a non-destructive and non-contact fashion. It is proposed that the bonding strength is correlated with the resonant frequency of bonded joints. The bonding strength measured with a destructive tensile test roughly increased with the vibration time, however, it varied, causing the transitional and dispersed formation of micro-bonds at the bonding interface. Scanning Electron Microscopic observation of the fractured surface suggested that the bonding strength depends on the total bonded area of micro-bonds. Frequency response of the bonded joint was examined with a non-destructive method using a piezo-electric vibrator. The experiment revealed that the resonant frequency exponentially increased with the bonding strength. In addition, this vibration behavior was dynamically visualized with electronic speckle pattern interferometry (ESPI). The correlation between the bonded area and the resonant frequency is discussed based on finite element analysis. The results indicate the possibility for in-situ evaluation of the ultrasonic bonding strength.

Keywords: ultrasonic bonding; bonding strength; nondestructive testing; resonant frequency; electronic speckle pattern interferometry (ESPI)

1. Introduction

Ultrasonic bonding is one of the solid-state bonding techniques that uses high frequency vibration to bond metal sheets. This technique is utilized in the automotive industry for joining parts such as wire bonding on a semiconductor substrate, wiring components with electrode terminals, and thin film electrodes of lithium ion batteries. The importance of the ultrasonic bonding is increasing with electrification of automobiles and the expansion of demand of electric vehicles. In addition, as the ultrasonic bonding has advantages such as short-time and low energy compared with other solid-state bonding techniques [1], the ultrasonic bonding is expected to be a promising tool in dissimilar bonding for automotive body panels. Since the industrial importance and the demand of the bonding quality increase, inspection methods for assuring the reliability of the bonding are required.

Destructive methods including a tensile testing, tensile shear testing, etc. are utilized to evaluate the bonding strength. The bonding reliability is evaluated statistically by a sampling inspection. On the other hand, nondestructive methods including ultrasonic testing or radiographic testing are conducted for evaluation of the state of the bonding. Some researchers evaluated the deterioration inside materials with ultrasonic waves [2–4], electrical methods [5], thermography [6,7], and radiography [8]. The ultrasonic testing detects the reflected waves coming from the discontinuous interfaces due to cracks and un-bonded regions. In addition, some researches [9–11] tried to detect the residual stress around the bonded area by nonlinearity of the sound wave. These methods used the acoustoelastic
effect, in which the sound velocity depends on the elasticity of materials. The bonding strength is often estimated with the bonded area. The bonded area was visualized by ultrasonic C-scan testing [12–15] and radiography [16,17]. In these studies, it was indicated that the relation between the bonded area and the bonding strength are linearly correlated. However, C-scan testing and radiography are not suitable for in-situ measurement of the bonding strength, because it needs measurement equipment outside of the production line and is time-consuming. There have been other ways to evaluate the bonding area with ultrasonic techniques including the A-scan method [18,19], resonant frequency measurement [20], cantilever test [21], electrical method [22], and thermographic test [23]. Application of an optical technique is an effective methodology for non-contact measurement. However, there are few studies that relate the optical measurement to evaluation of the bonding strength. The bonded area detected by the optical coherence tomography [24] had a correlation with the bonding strength. Furthermore, nondestructive evaluations are of technical interest, as well as fundamental interest, in the measurement of interfacial strength between dissimilar materials such as metal/polymer dissimilar joints [25] and fiber reinforced composites [26–28]. The interfacial strength is extremely important in controlling the mechanical property of joints.

In our study, we propose a new method to evaluate the bonding strength that is non-destructive and quick by analyzing the elastic behavior of the bonded materials. We expect that the elastic behavior will change depending on the bonding strength. By analyzing the elastic behavior of bonded materials, it is expected that the bonding strength can be evaluated. We focus on the optoacoustic methods to analyze the elastic behavior in a non-destructive way. The ultrasonic bonding uses acoustic vibration, so we considered that it will be possible to measure the elastic behavior in situ. In addition, the vibration behavior can be measured without contact using the optics with the acoustics.

2. Theory

First, we describe formation and enlargement of the bonded area in an ultrasonic bonding process. The ultrasonic bonding process consists of two main steps: a clamping step and a vibrating step. At the clamping step, a normal force is applied to the bonding part by the ultrasonic horn and the faying surfaces get into an intimate contact under the exertion of the normal force. During the vibrating step, the ultrasonic horn vibrates parallel to the contact area with the bonding tip at the ultrasonic frequency, causing relative motion between the plates to be bonded. At the initial phase in the bonding mechanism, oxide films on the faying surface break, and new surfaces get into contact. By achieving intermetallic bonding, micro-bonds are created. These micro-bonds create a convex contact part, so that micro-bonds are formed dispersedly at the macroscopic bonding interface. With increase in the vibration time, each micro-bond gradually enlarges, leading to an increase of the bonding strength.

In our study, we consider the bonded specimen that consists of two pieces of metal sheet as shown in Figure 1. From the bonding mechanism described above, we hypothesize an elastic modulus of the micro-bond is the same as the elastic modulus of other areas. The apparent spring constant of the total bonded area K (N/mm) is expressed by the spring constant per unit area k (N/mm · mm²) as K = k · A, where A (mm²) is the total area of micro-bonds. Since the total area of micro-bonds is small at the initial phase during bonding, the number of springs is also small. Thus, it is considered that the spring constant, K, is small if the bond is weak. The micro-bonds develop with the vibration in the latter bonding phase, resulting in an increase of the total bonded area, A, and the total spring constant, K. Considering the specimen as a spring-mass system in which two plates are connected via micro-bonds, the resonant frequency f is given as Equation (1).

$$f = \frac{1}{2\pi} \sqrt{\frac{K}{M}}$$  \hspace{1cm} (1)

where K is the apparent spring constant at the bonded part. M is the mass of the bonded specimen. As it is considered that the mass is constant during the bonding, the resonant frequency of the bonded
specimen is solely affected by the apparent spring constant \( K \). Namely, the bonding strength could be evaluated by measuring the resonant frequency.

![Diagram of an ultrasonic bonding machine and bonding tip geometry](image)

**Figure 1.** Change of apparent spring constant by enlargement of bonded area.

3. Experimental Procedure

3.1. Specimens Bonded by the Ultrasonic Bonding

Figure 2 illustrates the schematics of the ultrasonic bonding machine and bonding tip geometry. An ultrasonic bonder with an output power of 2.4 kW and a driving frequency of 14.71 kHz was used for the bonding. The amplitude of the ultrasonic horn under no load was 53 \( \mu \text{m} \) (peak-peak). An industrial aluminum alloy, AA6061-T6 sheet, was used for the bonded specimen. The sheet was cut into two metal sheets as shown in Figure 3. The upper sheet had a size of \( 50 \times 11 \times 0.5 \text{ mm} \). The lower sheet had a size of \( 50 \times 11.5 \times 0.8 \text{ mm} \). The lower sheet was placed on an anvil and clamped by a fixture to suppress slippage. The upper sheet was lapped on the lower sheet in such a way that the total length of the bonded specimen was 85 mm. Vibration was applied by the bonding tip of the ultrasonic horn under a normal force of 588 N. Bonding strength was controlled by changing the vibration time within 1000 ms. The bonding tip of the ultrasonic horn and the anvil had a knurled surface shown in Figure 2b. There were 13 \( \times \) 13 protrusions with a 0.8 mm pitch, 0.3 mm height, and 90° angle of groove. The total tip area was 10 \( \times \) 10 mm. The bonding was carried out by aligning the protrusions of the horn tip and the anvil tip with each other.

![Diagram of an ultrasonic bonding machine and bonding tip geometry](image)

**Figure 2.** (a) Ultrasonic bonder; (b) Bonding tip geometry.
The bonding strength was measured by a tensile shear test (Figure 4). The test was conducted at a cross-head speed of 0.1 mm/s. The maximum load during the tensile shear test was defined as the bonding strength in this study. The fractured surface was observed by a scanning electron microscope (SEM) and results were output to a digital image with a constant brightness and contrast. The image was binarized with a constant intensity threshold, then, the bonded area was estimated by measuring the total area of the white region. The details of the bonded area estimation are described in Section 4.1.

![Figure 3. Bonded specimen.](image)

![Figure 4. Tensile shear test.](image)

### 3.2. Measurement of Frequency Response

The experimental arrangement to detect the resonant frequency of the bonded specimen is shown in Figure 5. The 20 mm portion of the bonded specimen was fixed on a piezoelectric actuator. A sinusoidal-voltage wave generated by a function generator was input to the piezoelectric actuator through an amplifier. The amplitude of the input voltage to the piezoelectric actuator was 100 mV, which corresponded to the displacement amplitude of about 2.1 μm. A capacitance displacement gauge was placed at the other end of the specimen in order to detect the amplitude of the vibrating bonded specimen. The output voltage of the capacitance gauge was recorded into a personal computer (PC), changing the driving frequency of the piezoelectric actuator. The driving frequency was increased from 10 to 1000 Hz at the increment of 0.5 Hz, and from 1000 to 10,000 Hz in the logarithmic increment of 10^{0.1} Hz. We computed the frequency responses at each driving frequency through Fourier transformation, and the peak frequency in the amplitude spectrum was found to be ±5 Hz around the driving frequency. The maximum amplitude in the Fourier spectrum was plotted against the driving frequency to obtain the frequency response. From the frequency response, resonant frequencies of the bonded specimen were identified. Sampling frequency of output and input voltage was 100,000 Hz, the number of samples was 10,000.
Electronic speckle pattern interferometry (ESPI) was used to visualize bending motion in the above vibration test. In addition, this technique can measure the resonant frequency and vibration mode simultaneously [29–34]. Figure 6 illustrates the schematic of ESPI to measure out-of-plane displacement. A semiconductor laser with wavelength of 660 nm was used for the light source. The light was expanded by a lens and split into two paths (arm 1 and arm 2) with a beam splitter, and used to irradiate the specimen and a reference plane. An A6061-T6 sheet, which is the same material as the bonded specimen, was utilized for the reference plane. The roll direction of the reference plane was aligned with the specimen. When the laser is irradiated on a rough surface, the lights of the random phase overlap and interfere with each other due to the coherence of the laser, thereby a speckle pattern in formed. The superposed speckle pattern of the reference plane and the specimen with a photographed image before vibration from another image after deformation, and then calculating the absolute value of them, a subtract image was created to recognize the deformation of the bonded specimen. The subtracted speckle intensity changes with the phase difference of the object beam (arm 2) relative to the reference beam (arm 1). The phase difference is caused by the displacement of the specimen.
The specimen was vibrated in the same manner as the measurement of frequency response. The input voltage to the piezoelectric actuator was 5 mV, which is lower than that used in the measurement of frequency response described in the Section 3.2, because the ESPI cannot detect the large displacement owing to high sensitivity. The frame rate of the CCD camera was 30 frames per second (fps). The brightness of the subtract images was multiplied by 10 to make the images brighter.

4. Results and Discussions

4.1. Formation of Bonds under the Ultrasonic Bonding

Figure 7 shows the relation between the vibration time and the bonding strength. The vertical axis is the vibration time. The horizontal axis is the bonding strength. With vibration times shorter than 200 ms, a joint strong enough to measure the bond strength was not obtained. This time period can be considered as an incubation time to form the micro-bonds through the removal of oxide film. The bonding strength roughly increased with the vibration time of 200 ms, while it had a large variance especially in the shorter vibration time. In addition, the fracture mode changed with the vibration time. The specimen bonded with the shorter vibration time broke at the bonded interface between the two sheets as shown in Figure 8a. When the vibration time increased to over 400 ms, the fracture occurred around the bonded part as shown in Figure 8b. We call this fracture mode the base material fracture. During the vibration, the upper bonding sheet in contact with the ultrasonic horn is compressed by the normal force. This causes thinning of the bonding part. The base metal fracture is due to a decrease of the fracture strength of the specimen by the thinning.
The changes in bonding strength are associated with the development of the bonded area. In order to estimate the bonded area, the fracture surface that exhibited the interface fracture was observed. Figure 9 shows an example of an SEM image of the interface fractured surface. This specimen showed a bonding strength of 532 N at the vibration time of 200 ms. In the fracture surface, two characteristic patterns are observed in white on the fractured surface: the scratch pattern shown in Figure 9b,c, and the dimple pattern in Figure 9d,e. In the initial stage of ultrasonic bonding, the ultrasonic vibration causes friction between metal sheets forming the scratch pattern. Thus, the scratch pattern observed in the SEM image is not considered to be the “un-bonded region”. The intermetallic bond is achieved through removal of oxide films and interfacial adhesion on the scratched surface, resulting in formation of micro-bonds. In addition, these phenomena mainly occur at the stress concentration part caused by the horn and anvil tips, or uneven contact part due to rolling. Thus, the formation of micro-bonds occurs dispersedly at the bonding interface. Since the micro-bond is torn off in the tensile shear test, the resultant dimple pattern is observed in the fractured surface. The variation in the bonding strength observed in Figure 7 is considered to be due to the transient formation of micro-bonds. Figure 10 shows the relation between the bonding strength and the total area of the white region in the SEM image computed with the image binarization. The total area includes both the scratch pattern and the dimple pattern. The bonding strength increases with the calculated bonded area, indicating the development of a bonded region. However, it was difficult to identify the accurate bonded area by the image analysis, because the size of the micro-bonds, about 10 to 100 μm, was so small that it was difficult to distinguish between the scratch pattern and the dimple pattern. Actual area of the bonded region is surmised to be smaller than the values shown in Figure 10.

![Figure 9. Fracture surface observation at bonded area by SEM. (a) Bonded interface; (b) Scratch part; (c) Magnified scratch part; (d) Dimple pattern; (e) Magnified dimple pattern.](image-url)
4.2. Evaluation of Bonding Strength with Frequency Response

Figure 11 illustrates the frequency response of the bonded specimen. The horizontal axis is the driving frequency. The vertical axis is an amplitude spectrum that means the displacement of specimen. The five peaks are seen at 163, 606, 1918, 3487, and 6033 Hz in the frequency response. We interpret that these peaks are the resonant frequencies. Figure 12 shows the bonding strength plotted against the resonant frequency. The red circle plots show the interface fractures. Blue triangle plots show the base material fractures. In the interface fracture, the bonding strength exponentially increased with the resonant frequency. This tendency appeared at each of the resonant frequencies shown in Figure 11. It is noted that the bonding strength of the specimen exhibits a correlation with the resonant frequency better than the vibration time. The approach in this study is similar to the “tapping mode” in atomic force microscopy (AFM), which utilizes the forced vibration of a cantilever. In AFM, the potential energy of the object alters the resonance behavior of the cantilever. In the present case, the resonant frequency of the vibrating joint (the cantilever) changes depending on the interfacial strength between the two sheets. The results indicate usefulness of this method in the evaluation of the bonding strength in a non-destructive manner in the case of interface fractures. On the other hand, in the case of the base material fracture, the bonding strength is deviated from the relation observed in the interfacial fracture. Figure 13 shows bonding parts of specimens. Indentations on the bonding part became bigger due to penetration of the knurled edges on the ultrasonic horn tip. With the development of the micro-bonds at the bonding interface, a relative motion between the bonding sheets during the ultrasonic bonding is hindered. This may cause the relative motion between the horn tip and the upper sheet, causing the enhancement of edge penetration and the thinning of the bonding part. The resonant frequency measured in this study is affected by the second moment of the area of the bonded part, because the specimen vibrates with a bending motion. Thus, the deviation of resonant frequency in the base material fracture is considered to be due to the thinning of the bonded part.

![Figure 11. Frequency response of bonded specimen.](image)

(a) Driving frequency from 10 to 1000 Hz; (b) Driving frequency from 1000 to 10,000 Hz.
Figure 11. Frequency response of bonded specimen. (a) Driving frequency from 10 to 1000 Hz; (b) Driving frequency from 1000 to 10,000 Hz.

Figure 12. Relation between resonant frequency at each of vibration mode and bonding strength. The resonances were observed at the driving frequency of (a) 173 Hz; (b) 626 Hz; (c) 1485.9 Hz; (d) 1717.9 Hz, and (e) 2013.7 Hz.

Figure 13. Indentation at contacted area with the horn bonding tip. (a) Vibration time is 200 ms; (b) Vibration time is 1000 ms.
4.3. Evaluation of Bonding Strength with ESPI

The ESPI arrangement in this study visualizes the out-of-plane displacement distribution of the specimen surface (the out-of-plane component of the bending displacement). Since the frame rate of the CCD camera (30 fps) is much lower than the driving frequency of the vibration test, the ESPI image shows the averaged displacement during a given frame. Figure 14 shows interference fringes observed at four driving frequencies. Here, the left and right ends of the image are the clamped and oscillating (driven by the transducer) ends of the specimen, respectively. In the fringe patterns (a)–(c), it is seen that in going from the clamped to the oscillating end, the fringe interval decreases. This indicates that the out-of-plane displacement increases nonlinearly from the clamped to the oscillating end. In other words, the specimen underwent a bending motion. As the driving frequency increases from 160 Hz to 170.5 Hz (Figure 14a–c), the fringe interval becomes smaller, indicating that in this frequency range the vibration amplitude increases with the driving frequency. At the driving frequency of 173 Hz (Figure 14d), the type of fringe pattern observed in Figure 14a–c that represents a monotonic increase in the out-of-plane displacement from the clamped to oscillating end disappears. Instead, a bright region appears in the middle of the specimen. This pattern is considered to indicate an eigen mode (resonance) oscillation, and is called the characteristic pattern hereafter.

![Figure 14](image)

**Figure 14.** Increase in number of fringes as resonance is reached. (a–c) show fringe patterns at the driving frequency near the resonance, and (d) 173 Hz shows a fringe pattern at the resonance.

In a characteristic pattern, the bright region is interpreted as representing a node of the oscillation. Since dark fringes generally represent null displacement and at a node of eigen mode oscillation the oscillation is null, this interpretation may sound counterintuitive. However, we believe this is a correct interpretation. The ground for this argument is as follows. When the specimen is oscillated at resonance, the vibration is close to null in the vicinity of nodal points and much larger in the other areas. In the present experimental arrangement, it is expected that the oscillation in non-nodal areas is so large that the speckle pattern loses correlation between the subtracted (after deformation) frame and the subtracted-from (before deformation) frame. (See Section 3.3, Electronic Speckle Pattern Interferometry (ESPI) for the image subtraction.) Consequently, the gray scale level of the captured image tends to be saturated in both the after-deformation and before-deformation frames, converging to the maximum level of 255 (in the 8-bit format). Therefore, when the image subtraction is made, the gray-scale values of the before and after deformation images are close to each other in the vicinity of 255. This makes these areas appear to be dark. On the other hand, the gray-scale value in the area near a nodal point
tends to be a low value that fluctuates from subtraction to subtraction. Consequently, in the subtracted image the nodal area appears to be whiter.

Figure 15 shows the frequency response of the bonded specimen detected by ESPI. The total intensity of the specimen was plotted against the driving frequency. Original data was smoothed with the 10-point moving average method. The averaged total intensity shows a rapid decrease at certain frequencies, which appears as sharp minima in Figure 15. Based on the above argument, we interpret that these minima represent resonant frequencies.

![Figure 15. Frequency response of bonded specimen detected by ESPI.](image)

Characteristic patterns were observed at other frequencies as shown in Figure 16. Figure 16a,b,e–g show the similar bending motion to Figure 14d. The nodes appeared bright. The number of nodes increased with the increase in driving frequency, as expected. In Figure 16c,d,h, the fringes appear in the transverse direction. These patterns can be interpreted as representing torsional vibration modes.

![Figure 16. Visualized vibration modes by ESPI.](image)

(a) 173 Hz  (b) 626 Hz  
(c) 1485.9 Hz  (d) 1717.9 Hz  
(e) 2013.7 Hz  (f) 3758.3 Hz  
(g) 6165.9 Hz  (h) 6493.8 Hz
In this fashion, the ESPI method allowed us to find several resonant patterns and frequencies. Accordingly, we compared the bonding strength with the resonant frequency. Figure 17 plots the bonding strength as a function of the resonant frequency determined by the above-mentioned method. Yellow rhombus plots show the interface fracture detected by EPSI. Red circle plots show the interface fracture detected by the capacitance displacement gauge (Figure 12). Similarly, blue triangle plots show the base material fracture detected by the capacitance displacement gauge. Notice that the results from the capacitance displacement gauge and those from the ESPI measurement show the same general dependence on the resonant frequency. The two data sets clearly indicate that the bonding strength exponentially increases with the resonant frequency. This result demonstrates that the optoacoustic method can evaluate the bonding strength in a non-destructive and non-contact fashion. It also indicates that the resonant frequency can be detected by monitoring the total intensity of speckles in the observing surface.

![Figure 17. Relation between resonant frequency detected by ESPI and bonding strength. (a) 1st resonant frequency (173Hz), and (b) 2nd resonant frequency (626Hz).](image)

5. Finite Element Analysis

5.1. Model

We carried out eigenvalue analysis using the commercial finite element analysis (FEA) solver LS-DYNA (R 7.1, Livermore Software Technology Corp., Livermore, CA, USA). Figure 18 shows the specimen model in FEA. The size of the upper and lower plates was commonly 50.0 mm in length, 11.5 mm in width, and 0.8 mm in thickness. Two sheets were lapped in such a way that the total length of the bonded specimen was 85 mm. The 8-node hexahedron element was employed. The element size was 0.125 × 0.125 × 0.1 mm. The numbers of nodes and elements were 671,142 to 670,313 depending on the bonded area and 588,800, respectively. The specimen was modeled as an elastic material. Physical properties of A6061-T6 are shown in Table 1. The 10 mm edge of the lower plate was fixed. Because the specimen was fixed by the screw of a jig at a point 10 mm away from the edge in the experiment, it was considered that the clamp force was applied at this area. The other side of the specimen was a free edge. Assuming that the contact area with the bonding tip was 10 × 10 mm and the micro-bond was preferentially formed in the bonding interface under the knurled edges on the bonding tip, 13 × 13 bonded areas were arranged on the bonded interface. As shown in Figure 19, the bonded area was expressed by merging nodes on the contact surfaces of two plates. In addition, enlargement of the bonded area was modeled by an increase in number of the merged nodes shown as black points in Figure 19b–d. The total bonded area was set to five conditions: 2.06 mm², 2.64 mm², 5.90 mm², 6.89 mm², and 12.51 mm².
5.2. Results

Figure 20 illustrates the relation between the bonded area and the resonant frequency at each vibration mode obtained by FEA. The results show that the resonant frequency goes up as the bonded area increases. The relation between them is exponential. The bonded area increased as the resonant frequency increased, similar to the experimental results indicated in Figures 12 and 17. This fact supports the claim that the resonant frequency of the bonded part increases with the bonded area. The vibration modes and the resonant frequency analyzed by FEA are illustrated in Figure 21. The colors of the pattern presented in Figure 21 represent the relative magnitude of the displacement vector. The red means the larger displacement, and the blue means the smaller displacement. Figure 21a,b,e,f,h showed the bending vibration modes. The nodes of vibration were seen as a blue area. Figure 21c,d,g illustrated the torsional vibration modes. These vibration modes are consistent with the experimental result observed in the ESPI measurement, except for the eighth vibration mode. The seventh mode shown in Figure 21g coincides with the eighth mode observed in ESPI (Figure 16h). The resonant frequency obtained by FEA was plotted against the experimental result in ESPI in Figure 22. The result indicates that the FEA result is correlated with the ESPI result, and the vibration mode can be visualized using ESPI.

![Figure 18. Bonded specimen model by finite element analysis (FEA).](image)

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**Table 1. Physical properties of A6061-T6.**

| Material        | Density (Kg/mm$^3$) | Young’s Modulus (GPa) | Poison’s Ratio |
|-----------------|---------------------|-----------------------|----------------|
| A6061-T6        | $2.7 \times 10^{-6}$ | 68.9                  | 0.33           |

![Figure 19. Enlargement of bonded area.](image)
5.2. Results

Figure 20 illustrates the relation between the bonded area and the resonant frequency at each vibration mode obtained by FEA. The results show that the resonant frequency goes up as the bonded area increases. The relation between them is exponential. The bonded area increased as the resonant frequency increased, similar to the experimental results indicated in Figure 12 and 17. This fact supports the claim that the resonant frequency of the bonded part increases with the bonded area.

The vibration modes and the resonant frequency analyzed by FEA are illustrated in Figure 21. The colors of the pattern presented in Figure 21 represent the relative magnitude of the displacement vector. The red means the larger displacement, and the blue means the smaller displacement. Figure 21 a, b, e, f, h showed the bending vibration modes. The nodes of vibration were seen as a blue area. Figure 21 c, d, g illustrated the torsional vibration modes. These vibration modes are consistent with the experimental result observed in the ESPI measurement, except for the eighth vibration mode. The seventh mode shown in Figure 21g coincides with the eighth mode observed in ESPI (Figure 16h).

The resonant frequency obtained by FEA was plotted against the experimental result in ESPI in Figure 22. The result indicates that the FEA result is correlated with the ESPI result, and the vibration mode can be visualized using ESPI.

Figure 21. Composite displacements in the x, y, z directions. (a) First mode: 118.03 Hz, (b) Second mode: 701.60 Hz, (c) Third mode: 1426.74 Hz, (d) Fourth mode: 1659.86 Hz, (e) Fifth mode: 1994.54 Hz, (f) Sixth mode: 4002.46 Hz, (g) Seventh mode: 4019.39 Hz, (h) Eighth mode: 6747.37 Hz.

Figure 22. Resonance detected by ESPI vs. resonance by FEA.
6. Conclusions

We applied the optoacoustic method to evaluate the bonding strength in a non-destructive and non-contact fashion. The experiment showed that the bonding strength of an ultrasonically bonded joint increased with the enlargement of the bonded area. The increase in the bonded area led to the higher resonant frequency of the joint in the vibration test: the resonant frequency increased exponentially with the bonding strength. It was indicated that the joint strength is correlated with the resonant frequency of the joint better than with the vibration time. In addition, the resonant frequency and the vibration modes were visualized by ESPI. The exponential correlation between the bonded area and the resonant frequency was confirmed by FEA. The vibration modes obtained by FEA were consistent with the experimental results in ESPI.

This study indicated that it is possible to evaluate the ultrasonic bonding strength by obtaining the correlation curve beforehand between the bonding strength measured by the tensile shear test and the resonant frequency with a non-destructive method.

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