Effect of Adhesive and Its Aging on the Performance of Piezoelectric Sensors in Structural Health Monitoring Systems

Xuerong Liu 1, Yuanming Xu 1, Xiangyu Wang 2, Yunmeng Ran 3 and Weifang Zhang 3,*

1 School of Aeronautic Science and Engineering, Beihang University, Beijing 100191, China; liuxuerong@buaa.edu.cn (X.L.); xuymg@sina.com (Y.X.)
2 School of Energy and Power Engineering, Beihang University, Beijing 100191, China; wangxiangyu2016@buaa.edu.cn
3 School of Reliability and Systems Engineering, Beihang University, Beijing 100191, China; rym2018@buaa.edu.cn
* Correspondence: zhangweifang@buaa.edu.cn; Tel.: +86-139-1129-1326

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Abstract: Adhesive and its aging can have influence on the Piezoelectric (PZT) elements in structural health monitoring (SHM) systems. However, the current research pays little attention to the effect of adhesives in SHM systems, and the mechanism of adhesive aging on monitoring signals is still unclear. In the present study, the relationship between types of adhesives, adhesive thickness, accelerated aging, and monitoring signal was analyzed in detail. The study was carried out with three kinds of epoxy resin AB adhesive (AW106, E-30CL, and E-120HP) and bonding thicknesses (0.01, 0.05, and 0.12 mm), and the elevated temperature was 100 °C for 45 days. The signal-based monitoring method was used to extract the characteristic parameters. The experimental results indicated that the standard shear strength and thickness of the adhesive may have a combined effect on the monitoring signal. Increasing the thickness may enhance the shear strength between PZT and the matrix. For the effectiveness of monitoring the signal propagation, however, increase in thickness may have a negative influence. Moreover, the elevated temperature will bring the signal amplitude to a peak in the first period of aging, and the highest point appears in 10 to 15 days. Nevertheless, with the increase of aging time, the adhesive will finally be degraded, resulting in the decrease of the signal amplitude. The experimental results may provide useful information for practical monitoring in the SHM field.

Keywords: adhesive; adhesive aging; PZT discs; structural health monitoring

1. Introduction

Recently, there has been growing interest in structural health monitoring (SHM) technology for online structural health monitoring and damage control, which is widely used in aerospace and civil engineering, machinery, transportation, and other fields [1,2]. The Piezoelectric (PZT) elements network in SHM technology are often applied to military equipment to monitor the safety of the structure, reduce maintenance costs, and extend the service life. Therefore, the validity of PZT elements network in SHM system has important theoretical significance and practical application value for ensuring flight safety [3].

The piezoelectric elements are usually fixed on the metal structure by the interface adhesive layer; these elements play the role of forces and strains transferring between piezoelectric components and structures [4,5]. However, in the actual service environment, the piezoelectric components are often subjected to various external loads and long-term temperature aging, which may cause the degradation of the adhesive layer between PZT elements and sensor substrate [6,7].
As such, the degradation of adhesive will affect the transmission of the piezoelectric signal in the structure. The change of signal is considered as an unreliable of monitoring result. In addition to the shear strength and thickness of the adhesive, the existing adhesive technology will have an influence on the signal transmission. The shear strength of the adhesive itself will also affect the receiving signal as it transmits stress in the structure. As a result, investigating the effect of adhesive and its aging is particularly important for the reliability of SHM systems.

There are two approaches for structural damage detection using PZT elements: one is the electromechanical impedance technique, and the other is the wave propagation method [8,9]. Research shows that the Lamb wave-based method has great potential in SHM systems [10,11].

Many research works have been carried out on the issue of adhesives and varying temperatures for the SHM system [7,12,13]. The thickness and shear strength are the two most frequently investigated factors in adhesive research, which have been discussed independently so far [14]. Mustapha [15] investigated five adhesive systems on the excitation of guided waves. The results revealed that the shear strength altered the magnitude of the excited wave signals. Bhalla and Soh [16] suggested that the PZT patch should be bonded to the structure using an adhesive of high shear modulus and smallest practicable thickness.

Raghavan et al. [7] studied the influence of interface degradation of the bonding layer on the performance of piezoelectric sensors; a series of aging tests of three types of adhesives under varying temperatures were designed, and a performance degradation model of piezoelectric sensors under high temperature was proposed. Park [17] presented a sensor diagnostics and validation process, which performed in-situ monitoring of the operational status of PZT active-sensors. The influence of sensor/structure bonding defects was studied by Lamb wave propagations and impedance methods, and the results showed a significant change of the phase and amplitude of the propagated waves and impedance spectrum.

However, few studies have comprehensively considered the influence of shear strength, thickness, and aging of adhesives between piezoelectric discs and aluminum substrate on the signal; as such, the change trend of different thickness and type of adhesive in the aging progress is not certain. Moreover, the mechanism of the influence of the adhesive and its aging on the monitoring system is not clear. A study of different kinds of adhesives and bonding thicknesses in the aging progress could reveal the effect of the adhesive and adhesive aging on the SHM system.

In this work, we performed a system experimental study to investigate the effects of adhesive and bonding thickness on the monitoring signal of the SHM system. Three kinds of epoxy resin AB adhesives (AW106, E-30CL, and E-120HF) and bonding thicknesses (0.01 mm, 0.05 mm, and 0.12 mm) were set. Then, the elevated temperature test was carried out to study the influence of adhesive aging, where the elevated temperature was 100 °C for 45 days. The excitation frequency was 100 kHz and aluminum 2024-T3 was selected as the substrate. This work considered the signal-based damage monitoring approach to extract the characteristic parameters of the Lamb wave, which are the normalized amplitude and phase difference of A0 mode. Also, the influence of adhesive and its aging on receiving signal was analyzed.

2. Lamb Waved Method

2.1. Propagation of Lamb Wave in Aluminum Plate

The concept of the Lamb wave was first proposed by Horace Lamb [18] in 1917. A Lamb wave can be defined as a two-dimensional elastic wave propagating in a free boundary and thin plate structure, also known as plate wave [19]. There are two main modes of Lamb wave propagating in the plate, symmetric mode (S) and anti-symmetric mode (A). The symmetric mode has patterns of S0, S1, ..., Sn, etc., while the anti-symmetric mode has patterns of A0, A1, ..., An, etc. [1,20]. Group velocity and phase velocity are the basis of studying dispersion characteristics of the Lamb wave, and the group velocity of the Lamb wave depends on its wavelength and plate thickness. Figure 1 is the dispersion curve of group velocity in a 2 mm thick aluminum plate [21]. The frequency–thickness product (f–s) should be limited to a low value to avoid the mode superposition of the Lamb wave,
which is set at 0.2 MHz mm. The thickness of the aluminum plate is 2 mm and the frequency of the Lamb wave is 100 kHz. Besides, the A0 mode is applied given to higher energy and noise ratio.

Figure 1. Dispersion curve of Lamb wave propagating in an aluminum alloy plate.

There are two approaches to monitoring damage in SHM systems, one is pulse-echo mode and the other is pitch-catch mode [22,23]. Compared to the pulse-echo method, the signal in the pitch-catch method travels a relatively shorter distance and may reduce the loss of substantial information for damage feature extraction [24]. Thus, the pitch-catch mode is used in this study. The schematic diagram of the monitoring system is shown in Figure 2 [21]. The Integrated Structural Health Monitoring Scanning System (SHM-ISS-4.0A) which was provided by Nanjing Smart Monitoring Technology Co., Ltd. The system is composed of the signal excitation module, PZTs group, the data acquisition module, and the structural health monitoring software. In the signal excitation module, the sinusoidal modulation wave generates a specific excitation signal through a function generator, which is amplified by a power amplifier, and then the Lamb wave is generated by the inverse piezoelectric effect of the piezoelectric actuator. The Lamb wave propagates in the structure and is received by the sensor. Finally, the data are collected by the data acquisition module.

Figure 2. Transmission process of the monitoring signal.

A five cycles sinusoidal tone burst modulated by the Hanning window is selected as the excitation pulse in this work, given the characteristics of periodicity, smoothness, and fast peak time. At present, there are two main methods to excite the Lamb wave, which are narrowband excitation and broadband excitation. The narrowband is easier to interpret than the broadband, which can be used to monitor the damage in structures [22,25]. The excitation signal is shown in Equation (1). The amplitude of the signal is 5 V, and the sampling frequency is 10 MHz.

\[
u(t) = A[H(t) - H\left(t - \frac{N}{f_c}\right)] \times (1 - \cos\frac{2\pi f_c t}{N})\sin2\pi f_c t \tag{1}\]

where \(A\) is the amplitude of the signal, \(f_c\) is the central excitation frequency, \(N\) is the number of excitation signal cycles, and \(H(t)\) is the Heaviside step function.
2.2. Extraction of Characteristic Parameters

Figure 3 shows the process of the A0 mode packet time window interception of the Lamb wave [21]. The black line represents the excitation signal and the red line represents the received signal. T0 is the duration of the excitation signal propagation, and TOF (time of flight) is the flight time of the signal from the actuator to the received sensor. The calculations of the time window are shown in Equations (2) and (3).

\[ T_{\text{start}} = T_1 + TOF - \frac{1}{2} T_0 \]  
(2)

\[ T_{\text{end}} = T_1 + TOF + \frac{1}{2} T_0 \]  
(3)

where \( T_{\text{start}} \) and \( T_{\text{end}} \) represent the beginning and end of the time window, respectively. \( T_1 \) is the time point of excitation signal and \( T_0 \) is the period of excitation wave.

Due to the complexity of the monitoring signals, the direct observation method is often met with some difficulties in the analysis process. We extract characteristic parameters to study the change trend of signals [26,27]. Under the condition of long-time accelerated temperature aging, the energy of the Lamb wave is attenuated, and the amplitude is reduced. In addition, the propagation path of the wave may also change, that is, the phase angle may shift. Therefore, the normalized amplitude and phase angle offset of the Lamb wave are often used as characteristic signals in the time domain.

In order to simplify the calculation and reduce the magnitude value, the dimensional expression is transformed into the dimensionless expression. Thus, the amplitude of the collected Lamb wave signal is normalized. The formula of normalized amplitude and relative phase angle offset are shown in Equation (4):

\[ x = \frac{A_i}{A_0} \]  
(4)

where \( x \) is the normalized amplitude, \( y \) is the relative phase angle offset. \( A_i \) denotes the amplitude of the wave packet signal in case \( i \), and \( A_0 \) is the amplitude of the reference signal (the initial state of piezoelectric element).

3. Materials and Accelerated Ageing Test

3.1. Materials

The piezoelectric elements are provided by the STEINER & MARTINS, INC (39873 Highway 27, Suite 225, Davenport, FL, USA), which are circular discs with a diameter of 7 mm and thickness of 0.5 mm. Table 1 shows the detailed performance parameters of the discs. The Al 2024-T3 plate is selected as the substrate, which has a dimension of 250 mm and is 222 mm wide and 2 mm thick. The
material parameters of Al 2024-T3 plates are shown in Table 2. The epoxy resin AB adhesive is widely used at the structure for piezoelectric sensor bonding in the field of structural health monitoring. Based on the previous research works [15,28,29], we find that the type of adhesive used has an influence on the monitoring signal in the SHM system. In this study, three kinds of epoxy resin AB adhesives were selected as, namely, AW106, E-30CL, and E-120HP. Table 3 shows the tested parameters of the three adhesives according to the ASTM D1002 standard, and the shear strength of the specimen in Table 3 is called the standard shear strength in the following description. Its standard shear strength is AW106 < E-30CL < E-120HP, where the standard shear strength of E-30CL is twice that of AW106, and the standard shear strength of E-120HP is slightly greater than E-30CL.

Table 1. Parameters of piezoelectric elements.

| Product Number       | SMD07T05R412WL |
|----------------------|----------------|
| Material             | SM412          |
| Dimensions           | 7 mm x 0.5 mm  |
| Resonant Frequency   | 4.25 MHz ± 5%  |
| Static Capacitance   | 2.5 nF ± 30%   |
| Test Condition       | 25 ± 3 °C, 40–70% R.H (Relative Humidity) |

Table 2. Material parameters of the Al 2024-T3 aluminum alloy.

| Material              | Yield Strength (MPa) | Tensile Strength (MPa) | Modulus of Elasticity (MPa) |
|-----------------------|----------------------|------------------------|-----------------------------|
| 2024-T3 aluminum alloy| ≥245                 | ≥390                   | 72,000                      |

Table 3. Performance parameters of epoxy resin AB adhesives.

| Parameters | Adhesives | Dielectric Strength, V/Mil | Tensile Strength, MPa | Standard Shear Strength, MPa | Tg, °C |
|------------|-----------|----------------------------|-----------------------|-----------------------------|--------|
|            | AW106     | 550–600                    |                      | 14                          | 45     |
|            | E-30CL    | 500                        | 55                    | 29                          | 70     |
|            | E-120HP   | 650                        | 41                    | 33                          | 90     |

The thickness of the adhesive will affect the resonance frequency and the amplitude of the sensing signal. A thin adhesive can be easily broken and even cause the piezoelectric elements to fall off, which will lead to a failure to monitor the signal. Therefore, the thickness of the adhesive must be controlled in a certain range. In this experiment, three kinds of adhesives with different thickness were designed, which were 0.01 mm, 0.05 mm, and 0.12 mm, respectively. Figure 4 shows the schematic of piezoelectric elements on Al 2024-T3 plates with three kinds of adhesive and thickness. In the figure, the piezoelectric discs are opposite each other; one is used as the excitation actuator X (X = A, B, C), and the other is used as the receiving sensor Y (Y = A’, B’, C’), and the distance between the actuator and the sensor is 162 mm. The thickness of adhesive in group I, group II, and group III were 0.01, 0.05, and 0.12 mm, respectively. Ai (i = 1, 2, 3), Bi (i = 1, 2, 3) and Ci (i = 1, 2, 3) denote the adhesives AW106, E-30CL, and E-120HP, respectively.

Figure 4. Schematic of piezoelectric elements on Al 2024-T3 plates: (a) the design drawing: the adhesive thickness of zone I is 0.01 mm, that of zone II is 0.05 mm, and that of zone III is 0.12 mm; Ai: AW106, Bi: E-30CL, Ci: E-120HP; (b) actual diagram.
A polytetrafluoroethylene (PTFE) film can be used to control the bonding thickness of piezoelectric elements on an aluminum alloy plate. Figure 5 is the schematic diagram of the adhesive thickness control method. Figure 5a is the positive view image, Figure 5b is the top view image, and Figure 5c is the actual diagram. As shown in Figure 5, the piezoelectric disc is pasted on the tape, and the thickness of the adhesive is controlled by pasting PTFE film between the tape and aluminum alloy plate. The thickness of the adhesive is equal to the thickness of the PTFE film minus the thickness of the piezoelectric discs. Because the thickness of PTFE is 0.51, 0.55, and 0.62 mm, respectively, and the thickness of PZT discs are 0.5 mm, the thickness of the adhesive is 0.01, 0.05, and 0.12 mm. Moreover, in order to maintain the appropriate adhesive properties, the bonding procedure must be done accordingly. First, the surface of the aluminum plate is cleaned with isopropyl alcohol to remove all oil, stains, and dust, and then sanded on the surface of the aluminum alloy to obtain the highest strength and durability of the bonded parts. After grinding, isopropyl alcohol is used to perform a secondary cleaning process. Next, A glue (resin) and B glue (curing agent) of epoxy resin AB are mixed at a ratio of 2:1 and stirred for 50 s, so that the color of the adhesive gradually turns to milky white. After that, the piezoelectric elements are bonded to the plate, and the thickness of adhesive is controlled by tape and PTFE. Finally, the aluminum alloy plate with piezoelectric pieces is placed at room temperature (25 °C) and cured for more than 24 h.

![Figure 5](image)

**Figure 5.** Control method of adhesive thickness: (a) positive view image; (b) top view image; (c) actual diagram.

### 3.2. Accelerated Aging Test

In the experiment, it is necessary to consider the temperature threshold of the piezoelectric sensor, namely Curie temperature. When the temperature is lower than the Curie point, the piezoelectric elements are ferromagnetic and can be used normally. However, when the temperature is higher than Curie point, the material becomes paramagnetic and the piezoelectric elements will lose their use efficiency. In order to ensure the effective use of the piezoelectric sensor, its accelerated aging temperature must be below the Curie point, which for piezoelectric elements is about 300 °C. Based on the above analysis, the temperature of the accelerated aging test is 100 °C.

The active damage monitoring method is based on the propagation of the Lamb wave in the aluminum alloy plate. As the aging time increases, the performance of the adhesive will degrade, and
the performance of the piezoelectric sensor itself may also be affected, thereby affecting the receiving signal. In the accelerated aging test, the temperature of the aging test is 100 °C, during the aging process, the sensor signal is monitored every 5 days, and the total test time is 45 days, that is, 1080 h. Three kinds of adhesives (AW106, E-30CL, and E-120HP) and three different adhesive thicknesses (0.01 mm, 0.05 mm, and 0.12 mm) are selected for the test, and the monitoring signals are analyzed. In the process of signal analysis, the A0 wave packet signal is intercepted to analyze the change trend of piezoelectric sensor signal under different aging times.

4. Results and Discussion

4.1. Effect of Adhesive Type and Thickness on Monitoring Signal

The initial signal did not undergo the accelerated aging test is analyzed. Figure 6 shows the characteristic normalized amplitude extracted from the Lamb wave signal monitoring by the SHM system with three kinds of adhesives. As can be seen from the figure, the influence of adhesive type on the monitoring signal varies according to the thickness. It can be seen from Figure 6 that when the adhesive thicknesses are 0.01 and 0.05 mm, the amplitude of adhesive E-120HP is the largest, and the minimum when the adhesive is AW106. When the thickness is 0.12 mm, the adhesive AW106 comes to the largest amplitude, and the adhesive E-120HP is the minimum. Besides, it can be seen that the extent of influence of adhesive on monitoring signal is different. When it comes to the thickness of 0.01 and 0.05 mm, the length difference between three kind s of adhesives of 0.01 mm is greater than 0.05 mm, which means that the influence of standard shear strength is much greater at the thickness of 0.01 mm compared to 0.05 mm.

![Figure 6. Amplitude extracted from original signal of three kind of adhesives at the thickness of 0.01, 0.05, and 0.12 mm. The excitation frequency is 90 kHz.](image)

Figure 7 shows the influence of thickness of adhesive on the monitoring signal; the characteristic parameter amplitude is extracted from the original signal. As can be seen from Figure 7, when it comes to the AW106 adhesive, the amplitude seems to be close at the thickness of 0.01 and 0.05 mm, while when the thickness is 0.12 mm, the amplitude value is much larger than the thickness of 0.01 and 0.05 mm. For the E-30CL adhesive, the amplitudes show little difference at the thickness of 0.01 and 0.12 mm, and the amplitude at thickness of 0.12 mm is smallest. As for the E-120HP adhesive, the increase of adhesive thickness will reduce the amplitude of the signal, and the thicker the adhesive, the smaller the signal amplitude. From the analysis, we can see that for the AW106 adhesive with low shear strength, the increase of adhesive thickness will have a positive effect on the amplitude of the signal, while for the E-120HP adhesive with relatively high standard shear strength, the increase of adhesive thickness will have a negative effect on the signal.
From the above conclusion, we can see that the magnitude of the sensing signal amplitude is mainly related to two factors: the standard shear strength of the adhesive and the adhesive thickness. On the one hand, the increase of the standard shear strength of the adhesive will lead to a rise in the amplitude, which means the increase of standard shear strength has a positive effect on the monitoring signal. On the other hand, the thickness of the adhesive has a comprehensive effect on the signal, that is, the increase of adhesive thickness will increase the shear strength between the piezoelectric sensor and the structural matrix, and the influence on the signal amplitude is positive. However, the increase of adhesive thickness will influence the effectiveness of signal transmitted in the medium. In the actual monitoring process, the influence of the adhesive standard shear strength and thickness on the signal is a coupling effect, so the effect of the two factors must be considered when selecting the type and thickness of the adhesive.

4.2. Influence of Adhesive Aging on Monitoring Signal

In order to research adhesive aging on the system, the accelerated aging test was carried out. The elevated temperature was 100 °C, and the signal collection interval was 5, 10, 15, 25, 35 and 45 days. Figure 8 shows the effect of accelerated aging of adhesive on the receiving signal, with three kinds of adhesive (AW106, E-30CL, and E-120HP) with three thicknesses (0.01, 0.05, and 0.12 mm). It can be seen from Figure 8a–c that three types of adhesives have different trends in signal amplitude as the aging time increases. Besides, the signal amplitude and change trend of the same adhesive but with different adhesive thickness are also different. Therefore, the characteristic parameter amplitude from the original signal was abstracted for a better observation of the difference.
Figure 8. Effect of accelerated aging of adhesive on the receiving signal. (a) adhesive AW106, with thickness of 0.01, 0.05, and 0.12 mm; (b) adhesive E-30CL, with thickness of 0.01, 0.05, and 0.12 mm; (c) adhesive E-120HP, with thickness of 0.01, 0.05 and 0.12 mm.

Figure 9 shows the change trend of characteristic parameter amplitude of the adhesives AW106, E-30CL, and E-120HP with the increase of aging time. Figure 9a–c correspond to adhesive AW106, E-30CL, and E-120HP, respectively, and the three different curves on each graph represent three different adhesive thicknesses, which are 0.01 mm, 0.05 mm, and 0.12 mm. Firstly, we can see from Figure 9a–c, the influence of thickness on each adhesive is different. For Figure 9a, corresponding to the adhesive AW106 and E-30CL, the signal amplitude is the largest when the adhesive is the thickest (0.12 mm), whereas for Figure 9c corresponding to the adhesive E-120HP, when the adhesive is the thinnest, the amplitude of the signal is the largest. The above conclusion is consistent with that of Section 4.1. Besides, the relationship between adhesive thickness and signal amplitude remains unchanged with aging time.

It is clear from Figure 9a that the curve shows a little rise in the first 15 days of aging, and then decreases slowly. This means that for the adhesive AW106, there is a rise of amplitude in the first period of aging, and the amplitude decreases as the aging continues. For Figure 9b which correspond to the adhesive E-30CL, it can be seen that the amplitude increases with aging time before 10 days, then slowly decrease before 15 days, followed by a slight rise before 35 days, and declines at the end. There are two vertices of the curve, probably due to the instability of the adhesive in the aging process. The highest point of curve appears about 10 days. As for the adhesive E-120HP in Figure 9c, the amplitude of the signal decreases slightly in the first 5 days and then continues to rise, and the amplitude reaches the peak at 15 days, and finally decreases slowly.

Comparing the signal amplitude of three different adhesives with aging time, we can find that for adhesive AW106 and E-30CL, there seems to be a little rise in amplitude at the beginning of the aging process, and then the signal amplitude reaches the highest point (for AW106, the highest point is at 15 days, for E-30CL, the highest point is at 10 days). Finally, the signal amplitude of AW106 slowly decreases due to the aging process, the signal amplitude of E-30CL sees a slight rise before 35 days, and in the end declines. Meanwhile, for the adhesive E-120HP, there is a slight drop in
amplitude in the first period of the aging process, then it rises and reaches its highest point at 15 days. Eventually, the signal amplitude decreases with the aging time.

![Graphs](a) (b) (c)

**Figure 9.** Variation of characteristic parameter amplitude with aging time. (a), (b), and (c) correspond to the change of amplitude with aging time for the AW106, E-30CL, and E-120H adhesives, respectively.

Figure 10 shows the thermal weight loss (TGA) curve of the epoxy resin adhesive under oxygen conditions [30]. It can be seen that the weight loss curve of the adhesive decreases slightly during the temperature of 30–254 °C, and the residual weight of adhesive decreases from 100% to 96%, which is mainly caused by the volatilization of water molecules or low molecular substances. This indicates that the accelerated aging test may cause the escape of some small molecules of the adhesive, but not the sudden degradation of the adhesive. It shows the effectiveness of our accelerated test. Therefore, in the aging process of the epoxy resin at 100 °C, there will be an unstable period in the early stage of the test. After the unstable period is over, the adhesive will remain in a relatively stable state. In this work, the accelerated test temperature is 100 °C, and the properties of epoxy resin AB adhesives will remain unchanged or degrade slowly, and not show serious aging phenomenon under this temperature. Besides, the trend of the signal will not decrease greatly because of the aging process. The slight increase of the monitoring signal in the early stage may be related to the increase of the shear strength between the adhesive and the metal plate due to the escape of small molecules in the early stage of the accelerated aging test.
Figure 10. Thermogravimetric curve of epoxy resin adhesive.

Figure 11 is the curve of the shear strength of the epoxy bonded joints with aging time at the temperature of 100 °C [30]. It can be seen from the figure that in the early stage of the aging test, the shear strength of bonded joints show an increase and reach the highest point. As the aging test continues, the shear strength gradually decreases. The reason why the shear strength of adhesive increases first and then decreases may be that in the early stage of aging, the shear strength increases with the full curing of the adhesive, but in the later stages of aging, the adhesive degrades and the shear strength decreases. There are three types of adhesives in our research, all of which are epoxy resin adhesives. In our study, we can see that the signal amplitude will reach a peak in the first period of aging and the signal will finally decrease with aging time. The shear strength change trend of epoxy resin adhesive is similar to the trend of the signal we have monitored, which illustrates the variation behavior of the amplitude of the signal.

Figure 11. Shear strength of epoxy bonded joints with aging time at the temperature of 100 °C.

In this study, three types of adhesives, AW106, E-30CL, and E-120HP, were used to research the influence of accelerated aging on the receiving signal. It can be seen from the results that the change in the signal amplitude with aging time can be divided into two stages. The first stage is mainly an overall rising process of the amplitude with aging time in the initial aging period, and then the amplitude of signal reaches the highest point. This may be due to the volatilization of water molecules or other low molecular substances in the adhesive. In the first stage, the amplitude of the adhesives AW106 and E-30CL increases with aging time. However, for the adhesive E-120HP, the amplitude shows a little decrease and then increases. The difference may be due to the unstable properties of the adhesive in the early stage of aging. Besides, the standard shear strength of E-120HP is much higher than that of AW106 and E-30CL, which may cause differences in the change trend of the three adhesives in the early stage of aging. The highest point of amplitude appears about 10 to 15 days after aging, which means that the signal amplitude will rise and reach a peak in the first period of aging. The second stage is the decrease of the signal amplitude with aging time. This stage occurs mainly
because of the continuous process of the accelerated aging test, and the performance of adhesive also decreases accordingly.

5. Conclusions

A study of different kinds of adhesives and bonding thicknesses in the aging progress was performed to reveal the effect of adhesive and its aging on the SHM system. Three kinds of epoxy resin AB adhesive (AW106, E-30CL, and E-120HP) and bonding thicknesses (0.01, 0.05, and 0.12 mm) were chosen. The elevated temperature was 100 °C for 45 days. The signal-based monitoring method was used to analyze the monitoring signals. The following results can be drawn from the analysis:

(1) The standard shear strength and thickness of adhesive may have a combined effect on the monitoring signal. Firstly, the standard shear strength of the adhesive may have a positive effect on the amplitude of the signal. However, the effect of thickness of the adhesive on signal is complicated. Increasing the thickness may enhance the shear strength between PZT and the matrix, which will lead to an increase of the monitoring signal. For the effectiveness of monitoring the signal propagation, however, the increase of thickness might have a negative influence. Therefore, both the influence of standard shear strength and thickness of adhesive should be considered in the actual service environment.

(2) An elevated temperature will bring the signal amplitude to a peak in the first period of aging, which may be due to the volatilization of water molecules or other low molecular substances in the adhesive. In this stage, the amplitude of the adhesives AW106 and E-30CL increase with aging time, while the amplitude of adhesive E-120HP shows a little decrease and then increases. The difference may be due to the unstable properties of the adhesive in the early stage of aging. Besides, the standard shear strength of E-120HP is higher than that of the adhesives AW106 and E-30CL, which may cause the difference in the change trend between the three adhesives.

(3) The peak of amplitude appears at about 10 to 15 days after aging. Nevertheless, with the increase of aging time, the adhesive will finally be degraded, resulting in the decrease of the signal amplitude.

The experimental results may provide useful information for practical monitoring in the SHM field. Firstly, in the actual monitoring process, the influence of the adhesive standard shear strength and thickness on the signal has a coupling effect, so the effect of the two factors must be considered when selecting the type and thickness of the adhesive. Secondly, the change trend of monitoring signal of SHM system with aging time means that the aging of adhesive will have an influence on the monitoring signal. Thus, is meaningful to consider the aging of adhesive in the actual monitoring process.

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