Effect of Temperature on Damping Capacity of an Adhesively Bonded Beam

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The damping characteristics of an adhesively bonded beam in which two steel strips are joined by an adhesive are investigated. In particular, we focused on the effect of temperature on the damping characteristics. In the analysis, vibration modes of the bonded beam and strain energies distributed in each strip and the adhesive in motion are analyzed by the finite element method. Then the damping capacity of the bonded beam is estimated using the strain energies and damping ratios of the steel strips and the adhesive, which were obtained independently beforehand by experiments. The temperature dependence of Young’s modulus, Poisson’s ratio and the damping ratio of the adhesive are considered in the analysis. The estimated values of the damping capacity are in good agreement with the experimental results. Thus, the effects of temperature, vibration modes and the thickness of the adhesive layer on the damping capacity of a bonded beam are clarified.

Key Words: Damping Property, Adhesive Joint, Finite Element Method, Strain Energy, Dissipated Energy, Vibration Mode, Temperature Dependence

1. Introduction

Because adhesives generally possess a high damping capacity, machine structures fabricated using adhesives are thus also expected to have a high damping capacity. Chang et al.(1), and Sakata and Usui(2) reported that the cutting performance of a milling machine, the structure of which was fabricated by adhesive bonding, was markedly improved due to the high damping capacity arising from the bonded structure. It has also been reported that the stiffness of joints can be improved using adhesives(3). There are some studies concerning the damping capacity of composite laminates. Hwang and Gibson(4) developed a three-dimensional finite element technique for the characterization of damping in composite laminates. Johnson and Kienholz(5) estimated modal damping ratios from undamped normal mode results by the modal strain energy method. However, the damping capacity of practical adhesively bonded structures has not been investigated, except for the work by Nakano and Kobayashi(6). They proposed an estimation method for the damping capacity of practical adhesively bonded structures and clarified the effect of the thickness of the adhesive on the damping capacity. As adhesives generally show a strong temperature dependence, this effect should be clarified in the estimation of damping capacity. Thus, further studies are necessary for determining the damping capacity of bonded structures.

In this study, the damping characteristics of a beam in which two steel strips are partially joined by an adhesive have been investigated. Strain energies in the steel strips and in the adhesive in motion are analyzed analytically by the finite element method. Then the damping capacity of the adhesively bonded beam is calculated using the strain energies and damping ratios of the steel strip and the adhesive which were measured independently beforehand. The effects of the thickness of the adhesive and the mode configurations on the damping capacity of the beam are examined. Furthermore, the temperature dependence of the damping capacity is also examined while considering the strong temperature dependence of the material properties of the adhesive.

The validity of the proposed estimation method for the damping capacity was examined experimentally. Ad-
Adhesively bonded beams with different adhesive thicknesses were fabricated and the damping capacities were measured by an impact excitation method. Thus, the effects of the thickness of the adhesive and the mode configurations of the beam on the damping capacity were clarified experimentally and compared with those obtained from the estimation method. Two different adhesives were used in the experiment to examine the effects of material properties.

Nomenclature

- \( A_a \) : cross-sectional area of the bulk specimen of the adhesive
- \( D \) : total energy dissipated
- \( D_a \) : energy dissipated in the adhesive
- \( D_b \) : energy dissipated in the steel strip
- \( E_a \) : Young’s modulus of the adhesive
- \( I_a \) : area moment of inertia of the bulk specimen of the adhesive
- \( L \) : length of the steel strip
- \( T \) : room temperature
- \( U \) : total strain energy
- \( U_a \) : strain energy dissipated in the adhesive
- \( U_b \) : strain energy stored in the steel strip
- \( f \) : natural frequency of the adhesively bonded beam
- \( f_a \) : natural frequency of the bulk specimen of the adhesive
- \( h \) : thickness of the adhesive
- \( l_o \) : overlap length
- \( I_o \) : overhang length of the bulk specimen of the adhesive
- \( \nu_a \) : Poisson’s ratio of the adhesive
- \( \rho \) : mass per unit volume of the adhesive
- \( \zeta \) : damping ratio of the adhesively bonded beam
- \( \zeta_a \) : damping ratio of the adhesive
- \( \zeta_b \) : damping ratio of the steel strip

2. Analysis

Figure 1 shows a model for the analysis in which two steel strips are partially joined by an adhesive. The thickness, length, and width of the strip are denoted by \( H \), \( L \), and \( B \), respectively, and the lap length and thickness of the adhesive as \( l \) and \( h \), respectively. The damping capacity of the bonded beam for the \( n \)-th mode is analyzed here. Let us consider a situation in which the bonded beam is put in motion at the \( n \)-th mode of bending. When focused on one cycle of a free vibration, the damping ratio \( \zeta_n \) of the beam is expressed as

\[
\zeta_n = \frac{D_n}{4\pi U_n},
\]

where \( U_n \) and \( D_n \) are the total strain energy and the energy dissipated in the beam per cycle, respectively. The subscript \( n \) designates the \( n \)-th mode.

The strain energy \( U_a \) and the energy \( D_a \) dissipated per cycle are divided into two parts: those in the two steel strips and those in the adhesive. Hence, \( U_n \) and \( D_n \) can be written as

\[
\begin{align*}
U_n &= U_{na} + U_{ab} \\
D_n &= D_{na} + D_{ab} 
\end{align*}
\]

where the subscripts \( a \) and \( b \) designate the adhesive and steel strips, respectively.

Because the damping ratios of the steel strips and the adhesive are defined in the same manner as in Eq. (1), the energies dissipated in each part are expressed as

\[
\begin{align*}
D_{na} &= 4\pi \zeta_a U_{na} \\
D_{ab} &= 4\pi \zeta_b U_{ab} 
\end{align*}
\]

By substituting Eqs. (2) and (3) into Eq. (1), the damping ratio \( \zeta_n \) of the bonded beam shown in Fig. 1 can be written as

\[
\zeta_n = \frac{U_{na}}{U_n} \zeta_a + \frac{U_{ab}}{U_n} \zeta_b.
\]

The damping ratio of the adhesively bonded beam can be obtained by analyzing the strain energies \( U_{na} \) and \( U_{ab} \) because the damping ratios \( \zeta_a \) and \( \zeta_b \) are known material properties. As can be understood from Eq. (4), it is effective to increase the ratio of strain energy of the adhesive layer to total strain energy to take advantage of the high damping capacity of the adhesive. Namely, the damping capacity is effectively increased if the bending stiffness of the steel strips is high because the strain energy decreases in this case.

To estimate the strain energy distributions in the bonded beam, a two-dimensional vibration analysis is carried out using the finite element code Marc/Mentat II. In the analysis, quadrilateral isoparametric elements are used and the numbers of elements are 622 for the steel strips and 640 for the adhesive layer, respectively. The thickness of the adhesive was varied from 0.2 mm to 2.5 mm to examine the effect of the thickness on the damping ratio of the beam. The material properties of the adhesive shown in Section 3, in which the temperature dependence is considered, are used. Thus, the strain energies \( U_{na} \) and \( U_{ab} \) can be calculated from the stress and strain distributions in the beam numerically obtained by the finite element analysis. Finally, the damping ratios of the bonded beam can be calculated using Eq. (4).

![Fig. 1 Analytical model of adhesively bonded beam](image)
3. Experimental

3.1 Material properties

To measure the material properties of the adhesive, bulk specimens, the width, thickness, and length of which are 12.5, 6, and 120 mm, respectively, were fabricated. Two epoxy resin adhesives (Scotch-Weld 1838B/A and 2216B/A, Sumitomo 3M Co. Ltd.) were used in the experiment. The former is called adhesive A and the latter adhesive B below. One end of the specimen was fixed rigidly to a base with an overhang length $l_a$ and a deflection which can cause an adequate amplitude of free vibration was applied to the other free end as shown in Fig. 2. By quickly releasing the deflection, the specimen was put in motion and the natural frequency $f_a$ and the free vibration were measured by strain gages attached to the surface of the specimen. The decay of the free vibration of the bulk specimen was recorded by a fast Fourier transform (FFT) frequency analyzer. Then Young’s modulus $E_a$ is obtained based on the formula of natural frequency of a cantilever beam(7).

$$E_a = \frac{(2\pi)^2 f_a^2 \rho_a A_a}{1.875 l_a^4}$$  \hspace{1cm} (5)

Poisson’s ratio $\nu_a$ was also calculated directly as the ratio of the transverse strains to the longitudinal ones measured by the biaxial strain gages. The damping ratios of the adhesive were determined using the peak values of the longitudinal strain and the corresponding time interval, which were detected from the records.

To investigate the temperature dependence of the damping ratio, the above tests were carried out on the bulk specimen in a temperature-controlled room by varying the temperature from 288 K to 303 K. The specimen was allowed sufficient time to be close to room temperature before measurement. The material properties of the steel strips (SS400, JIS) were also measured.

3.2 Measurement of damping ratio of bonded beam

A schematic of the experimental apparatus used for measuring the damping characteristics of the adhesively bonded beam is shown in Fig. 3. Two strips of mild steel (SS400, JIS), the length, width, and height of which are 300, 38 and 8 mm, respectively, were joined by the adhesive with an overlap length of 40 mm; the total length of the adhesively bonded beam was 560 mm. The thickness of the adhesive was varied from 0.2 mm to 2.5 mm to examine the effect of the thickness on the damping ratio of the beam. The adhesively bonded beam was cured at room temperature and no additional heat treatment was carried out. A one-body model of the beam made of the same mild steel, which was almost identical to the adhesively bonded beam except for the bond line, was also studied for comparison.

4. Results and Discussion

4.1 Temperature dependence of the material properties of the adhesive

Figure 4 shows the experimental results on the effects of temperature on the material properties of adhesives A and B. Figure 4 (a), (b) and (c) show the temperature dependence of Young’s modulus, Poisson’s ratio, and damping ratio, respectively. Approximated results by the least squares method are also indicated in those figures. Because the experimental results on the damping ratio did
not show any apparent amplitude dependences, it could be concluded that the adhesive used in this study was viscous in nature. Furthermore, it was observed that the damping ratio of the adhesive did not depend on the natural frequency up to 1 kHz.

Young’s modulus decreases and Poisson’s ratio increases slightly with increasing temperature while the damping ratio is almost constant at approximately 2.3% in the case of adhesive A. Although the Young’s modulus and Poisson’s ratio of adhesive B are close to those of adhesive A at the temperature of 288 K, the decreasing rate of Young’s modulus and the increasing rate of the Poisson’s ratio become significant compared with those of adhesive A with increasing temperature. The damping ratio of adhesive B markedly increases with increasing temperature and becomes threefold when the temperature is increased by just 15 K. The damping ratio of adhesive B is 6 to 7 times as high as that of adhesive A in the temperature range above 300 K. It can be said that adhesive A is not sensitive to temperature but adhesive B has a strong temperature dependence even in the tested temperature range between 288 K and 303 K. The material properties of the beam and the adhesive are summarized in Table 1. The material properties are expressed by regression functions determined by the least squares method. Those material properties are utilized in the finite element analysis.

### 4.2 Mode configurations

Figure 5 shows comparisons of the mode configurations between the experimental results and the numerical ones obtained by the finite element analysis in the case of the one-body model. The solid line in the figure indicates the calculated mode configuration and the open circles, the measured results. Configurations of the first, second, and third modes are indicated together with their natural frequencies. From this figure, it can be seen that the numerical results of the mode configuration and the natural frequency are in fairly good agreement with the experimental results for all modes. It is noted that the bonded part, which is located at the center of the beam, is subjected to a bending moment in the cases of the first and third modes. Accordingly, a large amount of strain energy is stored in the adhesive. While in the case of the second mode, the bonded part is simply rotated and less strain energy is stored in the adhesive.
4.3 Natural frequency

Figure 6 shows the relationship between the natural frequency $f$ of the bonded beam and the adhesive thickness. They are the results for adhesive A at about 293 K. With increasing adhesive thickness, the natural frequencies slightly decrease in all three modes. This is because the stiffness of the bonded part becomes low due to the increased adhesive thickness. The numerical results of the natural frequency are in fairly good agreement with the experimental results in all modes.

The effect of temperature on the natural frequency of the bonded beam was also examined. According to the results shown in Fig. 4, it is predicted that the natural frequency becomes low with increasing temperature because the Young's modulus of the adhesive is largely affected by temperature. However, the natural frequencies did not change much in all of the modes for adhesives A and B.

This is because the adhesive layer is thin and Young’s modulus has little effect on the stiffness of the bonded part.

4.4 Temperature dependence of the damping ratio of the bonded beam

Figure 7 shows the effects of temperature on the damping ratios of the adhesively bonded beam for the first three modes. Figure 7 (a) and (b) are the results for adhesives A and B, respectively, in the case where the thickness of the adhesive is about 1 mm. When focusing on the effect of the vibration mode, the damping ratios of the first and third modes are slightly higher than that of the second mode in the case of adhesive A. This tendency is marked in the case of adhesive B. The damping ratios for the second mode are almost the same as that of the steel strip itself. Namely, the damping ratio of the second mode is not improved by the adhesive in the case of the second mode. This is because the strain energy of the bonded
part is small in the case of the second mode as discussed in section 4.2. In the case of vibration modes in which the deformation of the bonded part is small, the damping capacity cannot be improved by the adhesive even if the damping capacity of the adhesive itself is high. In other words, the adhesive joints can effectively increase the damping capacity of a machine structure only when they are positioned in such a way that the strain energies become high.

The damping capacities of the first and third modes are approximately 3 to 10 times higher than that of the second mode. However, the high damping capacity of the adhesives is not reflected sufficiently in the damping capacity of the bonded beam considering that the damping capacity of the adhesives itself is 60 times higher in adhesive A and 400 times higher in adhesive B than that of the steel strips. This is because the steel strips used in the experiment are rather flexible and the amount of strain energy in these strips is very large compared to that of the adhesive. The amount of strain energy in the adhesive is only approximately 1% of the total strain energy. It is understood from Eq. (4) that the adhesive should store a large amount of strain energy to realize a higher damping capacity of an adhesively bonded beam.

Attention is paid to the temperature dependence of the damping capacity of the bonded beam in Fig. 7. Although significant temperature dependences are not observed for all three modes in the case of adhesive A, a marked effect of temperature is seen in the case of adhesive B. This is because the damping ratio of adhesive B has a strong temperature dependence and this characteristic is reflected in the damping characteristics of the bonded beam.

Figure 8 shows the variations of the damping ratio with temperature change for the first mode and comparisons between the experimentally and numerically obtained damping ratios. The numerical results are obtained by considering the temperature dependences of the material properties of the adhesives shown in Table 1. The temperature dependence in adhesive B is well estimated by the analysis proposed in this study.

Analytical results concerning the effect of the thickness of the adhesive on the damping ratio of the adhesively bonded beam are shown in Fig. 9 (a) and (b) along with experimental results. These are the results for the case where the room temperature is almost 293 K. With increasing thickness of the adhesive layer, the damping ratios for the first and third modes increase sharply in the range where the adhesive is thin and are almost saturated in the range where the adhesive is thicker than about 0.5 mm. The reason for this is considered to be as follows: in the range of thin adhesive, the strain energy stored in the adhesive increases markedly with a small increase in the thickness because the change in the volume of the adhesive is

![Fig. 8 Comparison of damping ratios between analytical results and experimental results (h = 1.0 mm)](image)

![Fig. 9 Effect of thickness of the adhesive layer (where temperature T is approximately 293 K)](image)
large. However, when the thickness reaches a certain value (0.5 mm in this case), the change in strain energy becomes relatively smaller because the stress distribution in the adhesive becomes moderate. This means that it is not sufficient to improve the damping capacity solely by increasing the thickness of the adhesive. To obtain a higher damping capacity of an adhesively bonded structure, an adhesive with a high damping capacity should be employed. The analytical values indicated by the solid lines in Fig. 9 are slightly larger than the experimental ones; however, good consistency is obtained between the analytical and experimental results.

5. Conclusions

This study was carried out as part of fundamental work to clarify the damping characteristics of adhesively bonded structures and to estimate their damping capacity. By using a simple adhesively bonded beam in which two steel strips were partially joined by an adhesive, the damping characteristics and an estimation method were investigated. The results obtained were as follows:

(1) It has been shown that the material properties of adhesives generally exhibit a temperature dependence and that this characteristic is reflected in machine structure fabricated by bonding.

(2) An estimation method for the damping capacity of an adhesively bonded beam was proposed and the results obtained by the analysis were in good agreement with the experimental results.

(3) The damping capacity of the adhesively bonded beam is closely related to mode configurations. The damping capacity becomes high only when the bonded part of the beam is subjected to a large bending moment.

(4) The damping capacity increases with increasing thickness of the adhesive in a relatively thin adhesive range. However, when the adhesive is thicker than a certain critical value, the damping capacity does not increase significantly with increasing thickness of the adhesive.

References


