Dynamic Deformation of Tapered Lap Adhesive Joint under Impact Loading*

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The propagation of stress waves and the concentration of dynamic stress in tapered lap adhesive joints with impact loading were investigated analytically and experimentally. Stress distribution and time variation of stress and strain in the joints under tensile impact loading were calculated using FEM, considering viscoelastic properties of the adhesive resin. Impact tests on the adhesive joints of aluminum alloy were conducted. Calculated results agreed with experimental results. The effects of taper length on the concentration of stress and strain were examined by comparing the calculated results with the experimental results. An increase in taper length is an effective way to reduce the concentration of stress and strain in adhesive lap joints under impact loading.

Key Words: Adhesive Joint, Stress Wave, Viscoelasticity, Finite Element Method, Tapered Lap Joint

1. Introduction

In recent years, the strength of adhesive joints under impact loading has become important because of their use in the aircraft and automobile industries. For these applications, the crash worthiness of structures should be proved in terms of dynamic adhesive strength as well as the precise technique of dynamic stress evaluation.

The dynamic strength of adhesives was investigated intensively by Kinloch and Kodokian⁽¹⁾, and Lataillade and Keisler⁽²⁾. Jingu and Nagakura presented methods for evaluating the dynamic strength of an adhesive layer⁽³⁾. A few investigations concerned with dynamic stress evaluation in adhesive joints have been performed^{(4),(5)}. Our previous work addressed the theoretical analysis and experimental examination of

dynamic stress concentration in single lap adhesive joints⁽⁵⁾. However, the single lap joints have stress concentrations on both edges of the joint under static and dynamic loading conditions. Thus, it is necessary to reduce the stress concentration by means of changing the configurations of adherends at the edges of the joints.

In this paper, the dynamic deformation and stress concentration in tapered lap joints were investigated analytically and experimentally. The deformation and stress distribution in these joints under impact loading were simulated using FEM. Impact examination was conducted on these joints in order to measure the deformations and strain variations with respect to time. Through comparison of these obtained results, effects which the tapered lap joints show to reduce the stress concentration were evaluated.

2. Analytical Model

2.1 Configurations of specimens

The tapered lap joints used for the studies were configured as shown in Fig. 1. The adherends were made of aluminum alloy, and were 4 mm thick, 20 mm wide and 1 000 mm long. These adherends were bonded

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using epoxy adhesive (Scotch Weld 1838, 3 M). The thickness of the adhesive layer was 100 μm . In Fig. 1, L , L_t and C refer to the lap length, taper length and sound velocity of the adherend, respectively.

In the analysis, the adherend was regarded as a linear elastic material. The adhesive used in the experiment, however, has viscoelastic properties which depend on stress rates. The viscoelastic relations of the adhesive were formulated using Voigt's model which has five elements as shown in Fig. 2. Viscoelastic parameters of the five-elements model were obtained from the impact examinations of the adhesive using Hopkinson bar technique⁽⁷⁾. These mechanical constants of the adherend and adhesive are shown in Table 1.

2.2 Analytical method

The deformation and stress distribution in the tapered lap joints under impact loading were calculated using the finite element method (FEM). In this study, two dimensional analysis was performed assuming in-plane strain conditions. Isoparametric elements with eight points were used for the element's configuration. Figure 3 shows the boundary and meshing conditions for this analysis.

The dimensions of each finite elements in both the

Fig. 1 Configurations of single lap joint and tapered lap joint

Fig. 2 Viscoelastic model of five elements

adherend and the adhesive were 1 mm in the loading direction. The element thickness of the adherends was changed gradually in the tapered part so that the acute angle of the adherend could be described. The other part of the adherend was 1 mm thick. The adhesive was not divided in the thickness direction because the adhesive layer was very thin.

In this analysis, Hilber-Hughes-Taylor scheme was employed for time integration in order to reduce the influence of high-frequency noise which is included in the experimentally measured stress. The viscoelastic stress in the adhesive was calculated from the nodal speed and nodal displacement of the element obtained in previous steps. A discrete unit of time is critical for calculating transient responses along a continuum. The time-step size should be smaller than the period within which a stress wave travels in one element. Thus, the finite element analysis was executed with a time step of 0.1 μs .

3. Analytical Results

The deformations and the stress distributions when the step load was applied to the tapered lap

Table 1 Mechanical constants of materials for adhesive joint

Adhesive		Scotch Weld 1838
Young's modulus (static)		3.44 GPa
Poisson's ratio		0.40
Density		$1.26 \times 10^3 \text{ kg/m}^3$
Adherend		6063
Young's modulus		72.0 GPa
Poisson's ratio		0.3
Density		$2.80 \times 10^3 \text{ kg/m}^3$
Five element model		
Suffix	$E_a (\text{Pa})$	$\eta_a (\text{Pa}\cdot\text{s})$
0	4.44×10^9	
1	4.33×10^{10}	
2	9.80×10^{10}

Fig. 3 Meshing and boundary conditions for FEM

joints were calculated using the analytical method shown previously. It is difficult to calculate the ideal step response of structures because the step function includes spectra of infinite frequency which induce vibration in the calculated results. In this analysis, step-like load shown in Fig. 4 was used instead of an ideal step load. This step-like load was obtained by reducing of the high-frequency spectrum of the ideal step load. The cut-off frequency of the low pass filtering was 300 kHz, which is the same as that of the strain amplifiers used for the experiment.

Figure 5 shows the deformations of a tapered lap joint which has a lap length of 100 mm and a taper length of 25 mm. The step-like load was applied to the joints. The deformations are described by images magnified by 20 000 times in this figure. Two central lines in the adherends of a lap joint are not colinear, so that a bending moment occurs at the lap part when a stress wave travels in the adherends. This bending moment induces a flexural wave in the joint. The transmission of the flexural wave can be seen in Fig. 5. Bending moments generated when a step-like load is applied to the lap joint, did not change during loading. The flexural displacement of the joint continues increased until reflected stress waves at both sides of the adherends reach the joint part again.

The distributions and time variation of stresses in

Fig. 4 Applied stress wave for calculating step response

Fig. 5 Deformation of tapered lap joint under step loading

the adhesive layer of the joint are shown in Fig. 6. In this figure, the lateral axis shows the position in the adhesive layer and the skew axis shows time. The stresses in this figure are described by non-dimensional numbers divided by the applied stress. There were stress concentrations at both edges of the adhesive layer. The time variation of the stress concentrated at the edges was not monotonous. The stress increased, and showed a peak at the initial stage of loading. After the peak, the stress decreased. Stress waves traveled and were reflected in the bonded part of the joint during this period, and this caused fluctuation of the stress. The stress values at the edges increased again after this period because of flexural waves induced by the bending moment.

Figure 7 shows the stress variations of a tapered lap joint which has a lap length of 100 mm and a taper length of 50 mm. The step-like load was applied to the joints too. This joint has taper sides longer than those of the joint shown in Figs. 5 and 6. The tendency of stress variation is similar to that mentioned previously. The stress values and the stress concentration, however, became smaller.

Fig. 6 Variation and distribution of stress in adhesive layer of tapered lap joint under step loading ($L = 100$ mm, $L_t = 25$ mm)

Fig. 7 Variation and distribution of stress in adhesive layer of tapered lap joint under step loading ($L=100$ mm, $L_t=50$ mm)

4. Experiment

4.1 Experimental procedure

Impact tests were carried out so as to verify the analytical method described in the previous section. The experimental procedure is shown in Fig. 8. Tapered lap joints made of aluminium alloy, with the same cross section as in the analysis, were used as specimens. The length of the adherends was 1300 mm so that reflected waves of stress could not reach the bonded part within the measurement time. The bonding procedure for the joints is as follows:

1. polishing by abrasive paper (# 600)
2. degreasing of the surfaces of the adherends with acetone
3. bonding of the adherends with a 100 μm spacer as shown in Fig. 9
4. curing for 24 hours at room temperature
5. postcuring for 2 hours at 65°C.

Impact loads were applied to these specimens using an impactor which consists of an impact bar, a cam mechanism and a DC motor. The placement of the impact bar at the edge of the specimen caused a

Fig. 8 Schematic diagram of experimental equipment

Fig. 9 Bonding procedure for tapered lap joint

compressive stress wave in the upper adherend. The specimens were suspended horizontally in a frame structure via a rubber block connector. The compliance of the rubber block was small, so, the stress wave generated by the impactor passed across the connector. The strain wave arrived at the joint, and was measured with semiconductor strain gages set at half the distance from the impact point to the joint. The intensity of stress wave was calculated by applying elastic constants of the adherend to the strain variation measured by the gages. Variations in strain in the joints with respect to time were measured using six sheets of semiconductor strain gages set at several points on the surface of the joints.

4.2 Experimental results

The strain variations with time are shown in Figs. 11 and 12. In these experiments, the stress waves shown in Fig. 10 were applied. Figure 11 shows the measured results for a tapered lap joint with a lap

length of 100 mm and a taper length of 25 mm. Figure 12 shows the results for a joint with a 50 mm taper length. The strains on the joints exhibit complicated changes which the inputted stress does not exhibit. The changes are attributed to the reflections of the stress waves and the flexural wave within the joints.

4.3 Comparing analytical and experimental results

The analytical and experimental results of strain variation of the joints are shown in Figs. 11 and 12. The analytical results agree with the experimental results. Therefore, the actual strain and stress of the joints can be predicted.

Fig. 10 Dynamic load applied to tapered lap joints

(a) Input side

(b) Output side

Fig. 11 Variation of strain in adherend of tapered lap joint with respect to time under impact loading ($L=100$ mm, $L_t=25$ mm)

(a) Input side

(b) Output side

Fig. 12 Variation of strain in adherend of tapered lap joint with respect to time under impact loading ($L=100$ mm, $L_t=50$ mm)

(a) Input edge

(b) Output edge

Fig. 13 Stress variations at both edges of adhesive layer for several geometries of joints with respect to time

5. Influences of Configurations of Tapered Lap Joints on Stress Distributions

Figure 13 shows the variation in calculated stress at the edge of the adhesive layer of tapered lap joints and a single lap joint⁽⁶⁾. These joints have a lap length of 100 mm. The tapered lap joints have taper lengths of 25 mm and 50 mm respectively. A step-like load of 1 MPa was applied to these joints. Stresses of the single lap joint showed peak values when the stress wave arrived at the edges of the adhesive layer. This tendency can be seen in the stress variation of the tapered lap joint with a taper length of 25 mm. The peak, however, decreased with increasing taper length. Stress values at the adhesive edges of the single lap joint are greater than that in tapered lap joint with the same lap length. Thus, stress concentration in lap joints can be reduced by adding taper parts and increasing the taper length.

6. Conclusion

Propagation of stress waves and concentration of dynamic stress in tapered lap joints and single lap joints under impact loading were investigated analytically and experimentally. The joints consisted of aluminum alloy and epoxy resin. Stress distribution and time variation of stress and strain in the joints under tensile impact loading were calculated using FEM. Impact tests on the adhesive joints were conducted. Calculated results agreed with experimental results. The effects of taper length on the concentration of stress and strain were examined by comparing the calculated results with the experimental results. The main conclusions are summarized as follows.

(1) There are stress concentrations at both edges of the adhesive layers when a step load is applied to

tapered lap joints. The stress in the adhesive layer peaks at the initial stage of the loading.

(2) The stress generated in the adhesive layers of tapered lap joints is smaller than that for single lap joints with the same lap length.

(3) Increasing the taper length is an effective means to reduce the stress concentration in the adhesive layer.

References

- (1) Kinloch, A. J. and Kodokian, G. A., The Impact Resistance of Structural Adhesive Joints, *J. Adhesion*, Vol. 24, No. 1 (1987), p. 109.
- (2) Lataillade, J. L. and Keisler, C., Charobonnet ph., Effect of the Substrate on the Adhesion in Adhesive Bonds Loading at High Strain Rate, Preprint EURADH'92, (1992), p. 584.
- (3) Jingu, T. and Nagakura, K., The Effect of Acting Period of Stress Wave and Alternating Modes on the Fracture Strength of Adhesive Butt Joint, *Trans. Jpn. Soc. Mech. Eng.*, (in Japanese), Vol. 57, No. 544, A (1991), p. 2924.
- (4) Zachary, L. W. and Burger, C. P., Dynamic Wave Propagation in a Single Lap Joint, *Experimental Mechanics*, Vol. 20, May (1980), p. 162.
- (5) Amijima, S., Fujii, T. and Nishida, H., A Simple Numerical Methods for Dynamic Analysis of Adhesive Bonded Sandwich Beams, *J. Adhesion Society of Japan* (in Japanese), Vol. 23, No. 4 (1987), p. 131.
- (6) Sato, C., Ito, T. and Ikegami, K., Dynamic Deformation of Single Lap Adhesive Joint under Impact Loading, *Trans. Jpn. Soc. Mech. Eng.* (in Japanese), Vol. 61, No. 590, A (1995), p. 2235.
- (7) Sato, C., Ito, T. and Ikegami, K., Dynamic Viscoelastic Properties of Cured Epoxy Resin for Adhesive, *J. Adhesion Society of Japan* (in Japanese), Vol. 30, No. 8 (1994), p. 345.