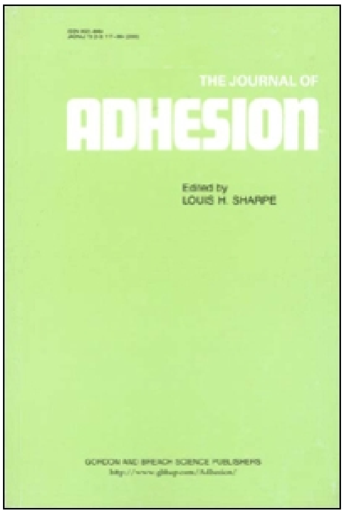

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A Method of Estimating the Strength of Adhesive Bonded Joints of Metals†

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The strength of adhesive bonded joints is investigated both analytically and experimentally. The deformed states of lap joints under tensile shear loading are analysed by the finite element method on the assumption of elastic deformation. A method of using the adhesive strength law is proposed to estimate the joint strength. The adhesive strength law is experimentally determined by subjecting butt joints of two thin-walled tubes to combined axial load and torsion. The strength of lap joints is determined by adopting the adhesive strength law to the adhering interface as well as the strength law of adherend and adhesive resin. The calculated strain distribution and strength of the joints are compared with the experimental results. The effects of the joint configurations on the deformation and strength are discussed. It is shown that the proposed method is useful to predict the joint strength.

KEY WORDS Adhesive joint strength; adhesive strength laws; lap-shear joints; metal adherends; strength prediction; stress distribution.

1 INTRODUCTION

Adhesive bonded joints have many advantages for structural usages compared with mechanical fastenings such as bolts, nuts and rivets. However, they do not always have enough reliability as to joint strength. This is caused by the fact that the strength of adhesive

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joints is difficult to evaluate. A rational method is necessary for the estimation of the joint strength.

Adhesive joints deform under loading conditions in a complicated manner, as they are composite structures consisting of different materials in the adherends and in the adhesive layer. Such joint deformation has been investigated by many researchers within the framework of the theory of elasticity and and plasticity and by numerical methods such as the finite element method. Some of the research results are found in a recently published book.[1] The prediction of the joint strength is more complicated than the stress analysis. The fracture of the joints is related to the interfacial strength as well as the strength of the adherend and adhesive layer. To evaluate the joint strength, it is necessary to correlate the stress distribution with the interfacial strength. In this paper, the adhesive strength law, which is determined by subjecting butt joints of thin-walled tubes to combined axial load and torsion, is proposed as the reference value for the correlation of the interfacial strength and stress distribution. The proposed method is applied to the stress distribution of various lap joints of metal. The predicted strength is compared with the experimental value.

2 STRAIN ANALYSIS

2.1 Lap joints under tensile shear load

(1) *Analytical model* The coordinates, dimensions and boundary conditions are given in Fig. 1(a, b). The joint length, the length of upper and lower adherends and the adhesive length are represented by notations l, l_1 and l_2, respectively. The thickness of both adherend and adhesive are represented by notations t_1 and t_2, respectively. The position in the x-direction and the adhesive length are shown by non-dimensional notations $\bar{X}(\bar{X} = x/l_2)$ and $\overline{L_O}(L_O = l_2/l)$, respectively. The boundary conditions are assumed that all nodal points on the left edge of the upper adherend are fixed in x and z directions, and the uppermost nodal point on the right edge of the lower adherend is free in the x direction and fixed in the z direction. The load per unit width, f, is applied to all nodal points on the right edge of the lower adherend. The material constants of adherends (carbon steel) and adhesive resin (epoxy resin) used in this research are given in Table I.

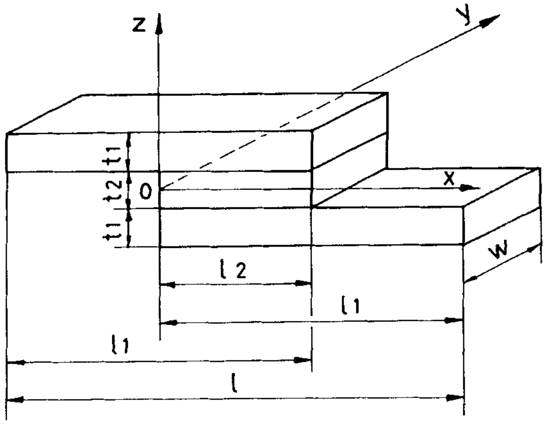

FIGURE 1(a) Coordinate system and dimensions of single lap joint.

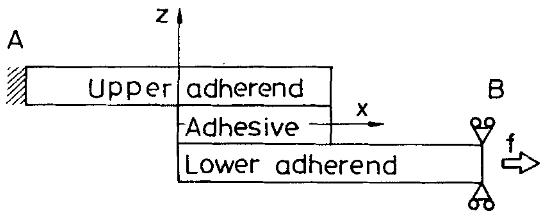

FIGURE 1(b) Boundary conditions of single lap joint.

(2) *Strain distributions* The strain and stress distributions were computed by the elastic finite element method under the assumption of the plane strain condition. The finite element mesh divided the joint triangularly into 89 layers of elements in the x direction and into 12 layers of elements in the z direction and they formed 8 layers in the adherends and 4 layers in the adhesive layer.

The joint for strain analysis is 178 mm in length and 0.05 mm in

TABLE I
Material constants for the joint

	Adherend (carbon steel)	Adhesive (epoxy resin)
Young's modulus GPa	206	3.33
Poisson's ratio	0.33	0.34

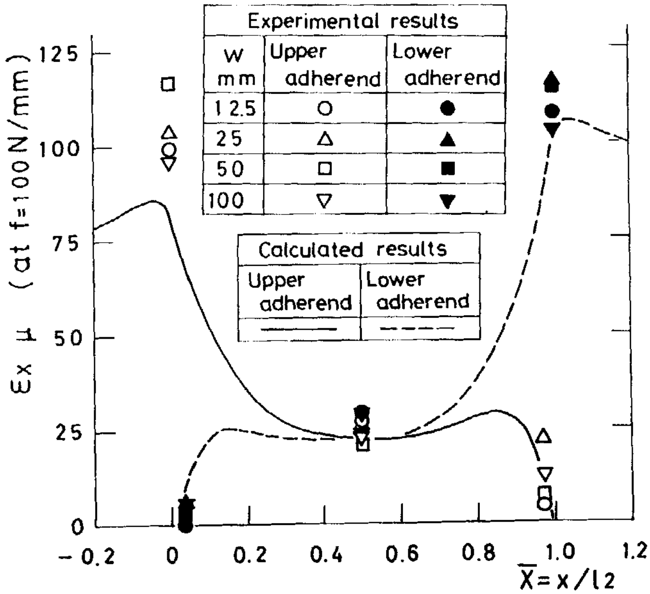

FIGURE 2 Distributions of the strain ε_x in adherends of single lap joint.

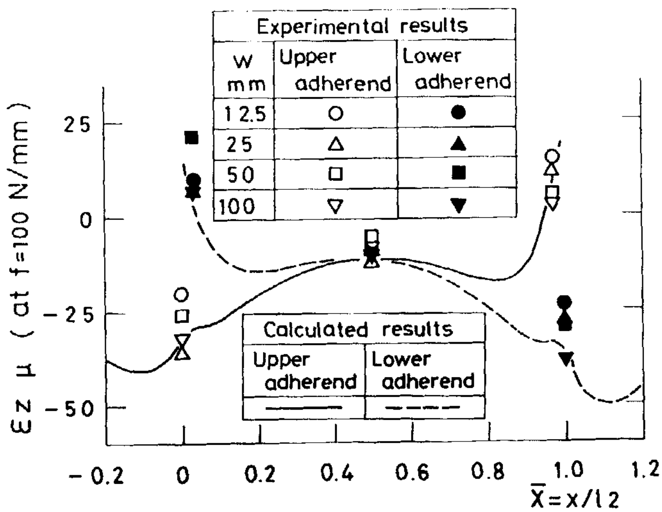

FIGURE 3 Distributions of the strain ε_z in adherends of single lap joint.

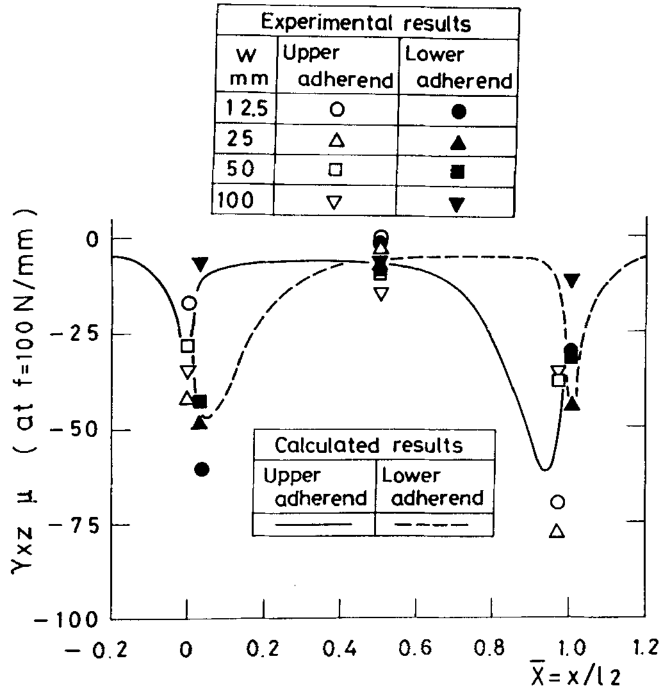

FIGURE 4 Distributions of the strain γ_{xz} in adherends of single lap joint.

adhesive thickness. The results in Figures 2 to 4 correspond to the case of $l_1 = 114$ mm, $l_2 = 50$ mm, $t_1 = 10$ mm, $t_2 = 0.05$ mm and $\overline{L_O} = 0.281$. These figures show the strain distributions εx, εz and γxz of the adherends in the x direction at $z = t_1/8 + t_2/2(z = 1.275$ mm) in the upper adherend and $z = -t_1/8 - t_2/2(z = -1.275$ mm) in the lower adherend. The range of $\bar{X}$ from zero to unity corresponds to the overlapping length of the joint. The strains ε_x, ε_z and γ_{xz} vary significantly in the vicinity of $\bar{X} = 0$ and 1.0, *i.e.* on the edges of adhesive layer, while they are approximately constant in the region near to $\bar{X} = 0.5$. Figure 5 shows the strain distributions ε_z of adherends in z direction at $\bar{X} = 0.01$, $\bar{X} = 0.05$ and $\bar{X} = 0.99$. The range of $\bar{Z}$ from zero to unity corresponds to the adherend thickness. The strains ε_z on $\bar{X} = 0.01$ and $\bar{X} = 0.99$ increase in the vicinity of $\bar{Z} = 0$, *i.e.* on both layers of the adhesive

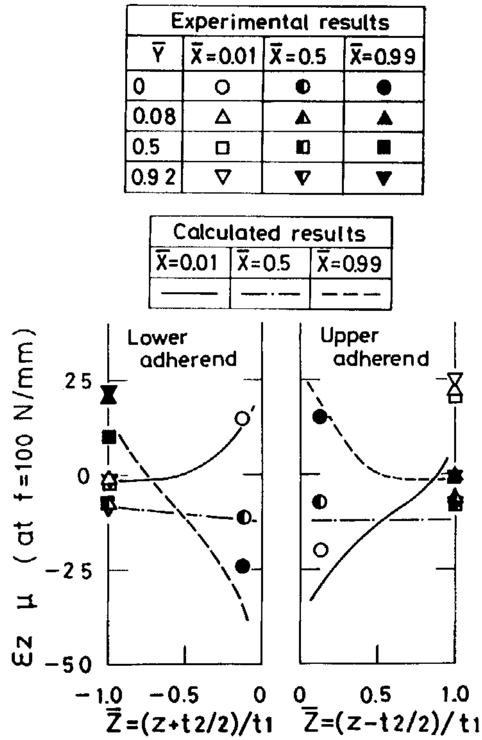

FIGURE 5 Distributions of the strain ε_z in adherends of single lap joint along the thickness.

interface; while the value at $\bar{X} = 0.5$ is approximately constant in the ranges of $\bar{Z}$ from 0 to 1.0 and from 0 to −1.0.

The strain distributions of joints under tensile shear loading were measured by the use of the tensile loading equipment.[2] The experimental results for a load $f = 100$ N/mm are also shown in Figures 2 to 5. The experimental strain distributions coincide with the analytical ones.

2.2 Tapered lap joints under tensile shear load

(1) *Analytical model* The coordinates, dimensions and boundary conditions of the tapered lap joint are given in Figure 6. The length

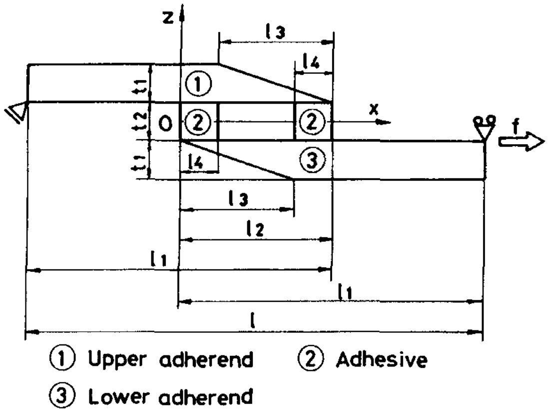

FIGURE 6 Coordinate system, dimensions and boundary conditions of tapered lap joint.

of the joint, adherend overlap, taper and adhesive layer are represented by notations l, l_1, l_2, l_3 and l_4, respectively. The thickness of adherends and adhesive layer are shown by notations t_1, and t_2, respectively. The non-dimensional length of the overlap, the adhesive and the taper are given in Table II.

The assumed boundary conditions are that the lowermost nodal point on the left edge of upper adherend is fixed in the x and z directions and that the uppermost nodal point on the right edge of the lower adherend is free in the x direction and fixed in the z direction. The load per unit width, f, is applied to the uppermost nodal point on the right edge of the lower adherend. The analytical method and the material constants are the same as the previous section.

TABLE II
Non-dimensional length of tapered lap joint

Overlap length	$\overline{L_O}$	l_2/l
Adhesive band length to joint length	$\overline{L_A}$	$2 \times l_4/l$
Adhesive band length to overlap length	$\overline{L_B}$	$2 \times l_4/l_2$
Tapered length	$\overline{L_T}$	l_3/l_2

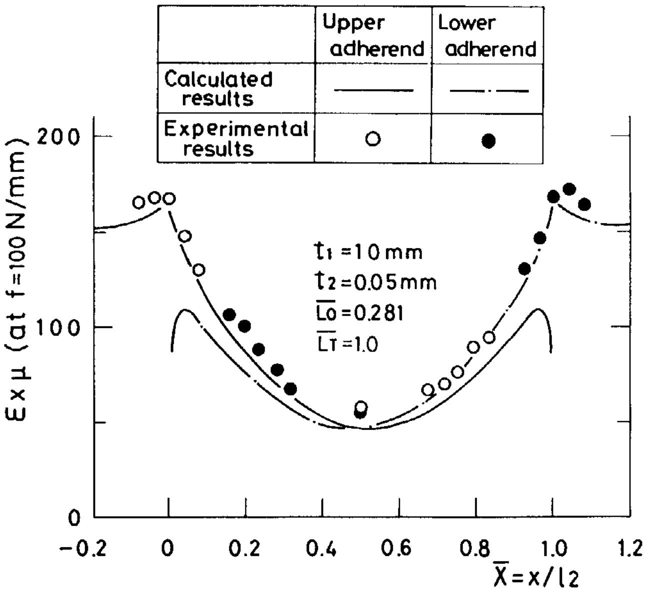

FIGURE 7 Distributions of strain ε_x in adherends of tapered lap joint.

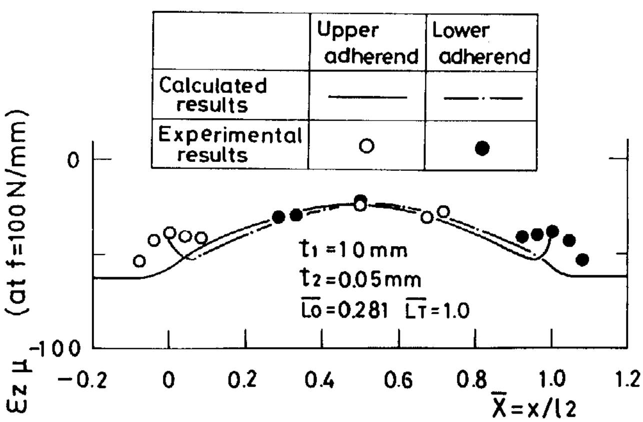

FIGURE 8 Distributions of strain ε_z in adherends of tapered lap joint.

(2) *Strain distributions* The analysed joint was 178 mm in length, $t_2 = 0.05$ mm in adhesive thickness, $t_1 = 10$ mm in thickness of adherends and $l_3 = 50$ mm in tapered length.

Figures 6 to 8 show the strain distributions ε_x, ε_z and γ_{xz}, respectively. The joint dimensions are $l_1 = 114$ mm, $l_2 = 50$ mm and $l_3 = 50$ mm and $\bar{L}_B = 1.0$. The strain ε_x changes remarkably in the vicinity of $\bar{X} = 0$ and 1.0, *i.e.* near both edges of adhesive layer, and it varies parabolically in the range of $\bar{X}$ from zero to unity. The strain ε_z becomes maximum near the center in the overlapped length. The strain γ_{xz} increases in the vicinity of $\bar{X} = 0$ and $\bar{X} = 1.0$.

Comparing the single lap joints with the tapered lap joints, the strain distributions in the single lap joint vary uniformly in a wide range of the overlap length, while the distributions in the tapered lap joint change parabolically in the overlap region. The maxima of the ε_x, ε_z and γ_{xz} in the tapered lap joint are reduced to about one-half of the values for the lap joint without tapering. This suggests that the tapering of the adherends improves the joint strength.

Tensile shear loading tests were carried out by a method similar to that in the previous section. The measured strain distributions for the load $f = 100$ N/mm are shown in Figs. 7 to 9. The experimental

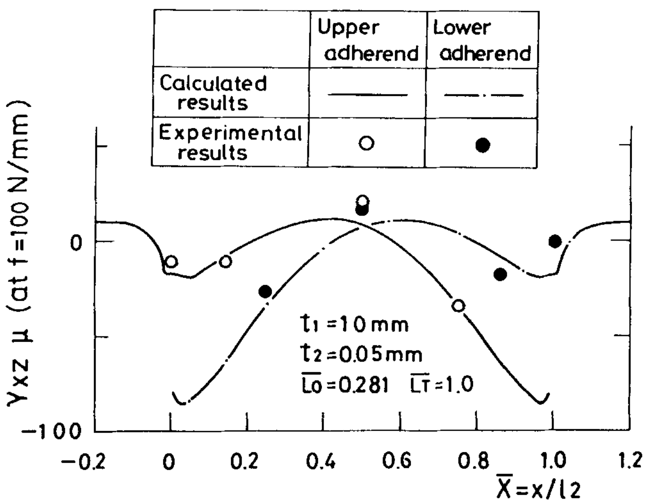

FIGURE 9 Distributions of strain γ_{xz} in adherends of tapered lap joint.

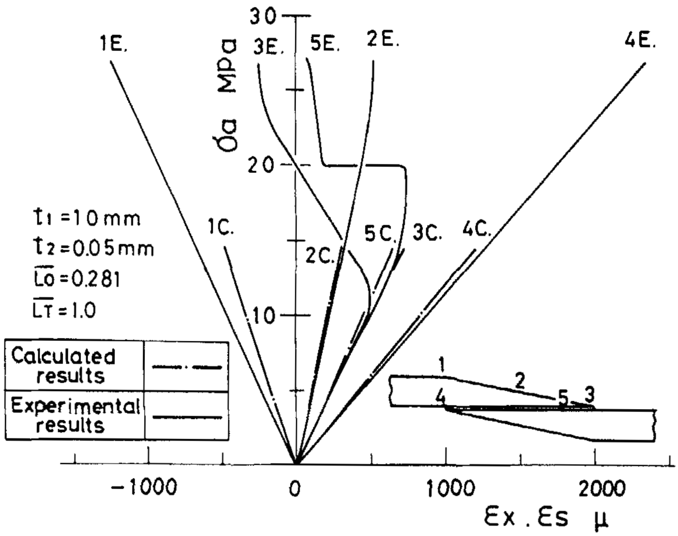

FIGURE 10 Variations of the strains ε_x and ε_s in the tapered lap joint.

results are in good agreement with the computed distributions. The variations of ε_x and ε_s (the strain on the adherend surface in the direction x) under the tensile load are illustrated in Fig. 10. The measured points are shown in the inserted figure. The ordinate indicates the average stress $\sigma\alpha$ which is defined as the applied load divided by the whole cross section of adhesive. The strain ε_s at the position 3 decreases abruptly in the vicinity of $\sigma\,\mathrm{a} = 10\,\mathrm{MPa}$, and then it approaches nearly to zero due to cracking on the edge of the adherend. With the increase of the applied stress, the strain ε_x at the position 5 varies greatly according to the crack propagation.

3 STRENGTH EVALUATION BY USE OF AN ADHESIVE STRENGTH LAW

To evaluate the strength of structures or machine elements, the strength laws of their constituted materials are adopted to the stress distributions and the critical loads are estimated. A similar method may be applied to predict the strength of adhesive joints. The strength of a joint can be obtained by using the strength laws of the adherend and adhesive resin. But the thus-obtained strength is higher than the actual strength. This is due to the lack of consideration of the strength of the adhering interface which is generally weaker than the adherend and adhesive resin. To include the strength of the interface in the estimation of joint strength, what kind of strength law is used for the interface becomes a subject of discussion. The authors proposed[3] that the adhesive strength law determined by subjecting a butt joint of two thin-walled tubes to combined loads is useful as the reference value in the strength design of the adhesive joints, as the strength is obtained under combined uniform stress states. The adhesive strength law, as well as the strength laws of the adherend and adhesive resin, are used to evaluate the joint strength. Those three strength laws are adopted to the adhering interface, adherends and adhesive layer. The critical loads of each part of the joint are calculated. The joint strength is decided by using the minimum value among the calculated critical loads.[4]

4 STRENGTH OF LAP JOINTS

4.1 Strength laws

Von Mises criteria were applied to the adherends and adhesive layer. They were represented as follows.

For the adherend,

$$F_1 = (\sigma_x^2 - \sigma_x\sigma_z + \sigma_z^2 + 3\tau_{xz}^2)^{1/2}/\sigma_{01} = 1 \tag{1}$$

For the adhesive layer,

$$F_2 = (\sigma_x^2 - \sigma_x\sigma_z + \sigma_z^2 + 3\tau_{xz}^2)^{1/2}/\sigma_{02} = 1 \tag{2}$$

where σ_{01} and σ_{02} correspond to the yield stresses of adherend and adhesive resin, respectively. For the material in this research, $\sigma_{01} = 343$ MPa and $\sigma_{02} = 64$ MPa. Figure 11 are adhesive strength laws which were determined by using butt joints of thin-walled tubes subjected to combined axial load and torsion. The adhesive strength law is represented in the form of the expression,

$$F_3 = |\sigma_z/\sigma_{04}|^m + |\tau_{xz}/\tau_{01}|^m = 1 \tag{3}$$

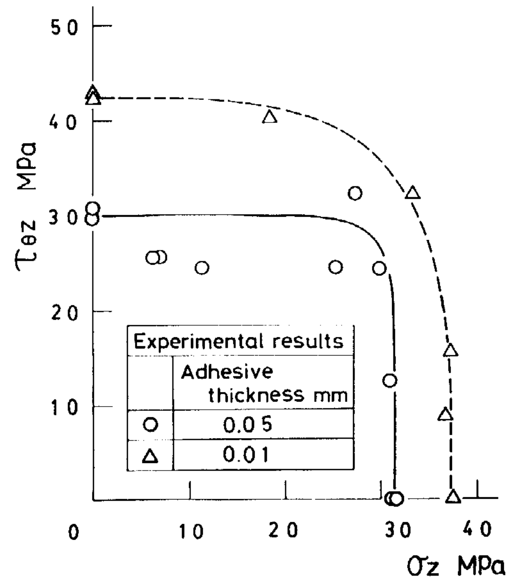

FIGURE 11 Adhesive strength law in $\sigma_z - \tau_{\theta z}$ stress state.

In Eq. (3), the stress component along the adhesive layer (σ_x) can be neglected because of the small effect on the adhesive strength.[2] From Figure 11 the constants σ_{04}, τ_{01} and m in Eq. (3) are obtained as follows; for the adhesive thickness 0.05 mm, $\sigma_{04} = 31.5$ MPa, $\tau_{01} = 30.8$ MPa, $m = 8.66$, and for adhesive thickness 0.01 mm, $\sigma_{04} = 37.2$ MPa, $\tau_{01} = 42.4$ MPa, $m = 3.54$.

4.2 Strength prediction and comparison with experimental results

The joint strength is calculated by applying strength laws of Eqs. (1), (2) and (3) to the stress distributions of corresponding parts in the joint. Figure 12 shows the strength distributions in the joint for which strain distributions are given in Figure 2 to 4. The notation f indicates the force per unit width for the initial failure of the part. The values f are small at both edges of adhesive layer and adhesive interfaces. This suggests that the initial failure occurs at those points in the joint.

The effect of the tapered length on the joint strength is shown in

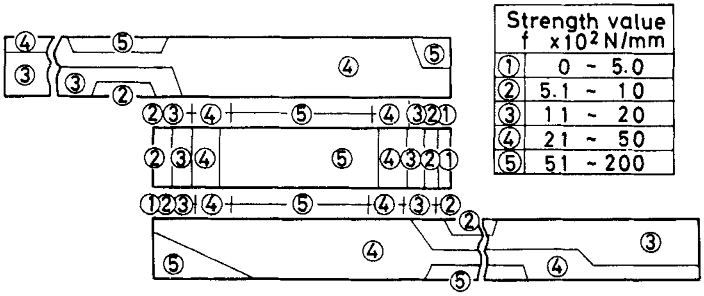

FIGURE 12 Strength distributions in the single lap joint.

Figure 13. The ordinate shows the average failure stress σ_b which is given by the failure load divided by the whole adhesive area of the joint. The abscissa shows the non-dimensional tapered length $\overline{L_O}$, which is given by the overlap length l_2 divided by the joint length l. In this figure, the average failure strength σ_b saturates above $\overline{L_T}1.0$. The calculated results for the tapered lap joint ($\overline{L_T} = 1.0$) are about twice as large as those for the single lap joint ($\overline{L_T} = 0$). The predicted results for the single lap joint are illustrated in Figure 14. The strength of the tapered lap joint ($\overline{L_T}1.0$) coincides approximately with that of the single lap joint ($\overline{L_T} = 0$) below $\overline{L_O} = 0.2$. But

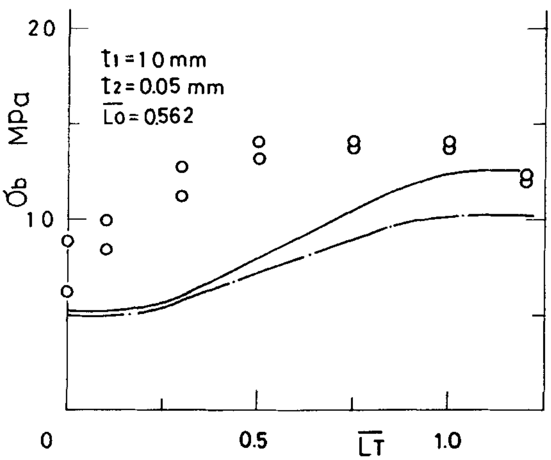

FIGURE 13 Effect of tapered length on the joint strength.

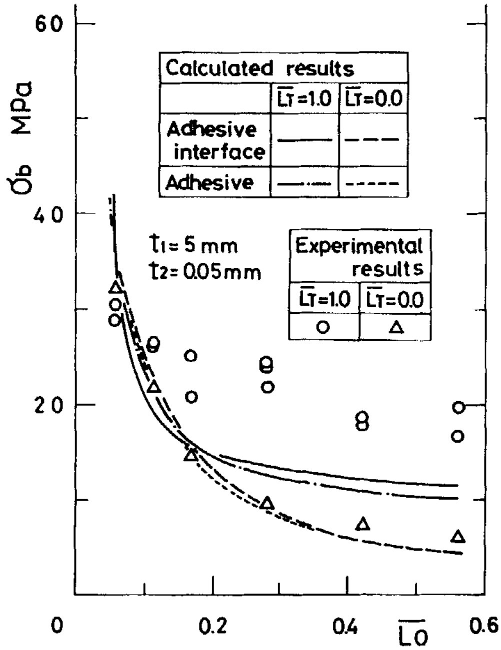

FIGURE 14 Effect of adhesive length on the joint strength.

the strength with tapering is about twice as large as the strength without tapering above $\overline{L_O} = 0.2$. In the single lap joint, as shown by the two broken lines in Fig. 14, the strength of the adhesive interface is approximately consistent with that of the adhesive layer above $\overline{L_O} = 0.2$. In the case of the tapered lap joint, the strength of the adhesive interface is greater than that of the adhesive. Therefore, the strength of the tapered lap joint above $\overline{L_O} = 0.2$ is dominated by the strength of the adhesive layer.

The effects of the band adhesive length on the joint strength are shown in Figure 15. The overlap length and the tapered length of the tapered lap joints are constant. The left and right ordinates show the average failure stress σ_b and the load for unit width, f, respectively. The abscissa shows the non-dimensional adhesive band length $\overline{L_B}$. The joint strength f saturates above $\overline{L_B} = 0.5$. This means that the tapered lap joint, which is bonded for half of the whole overlap length ($\overline{L_B} = 0.5$) from both adhesive edges, has the

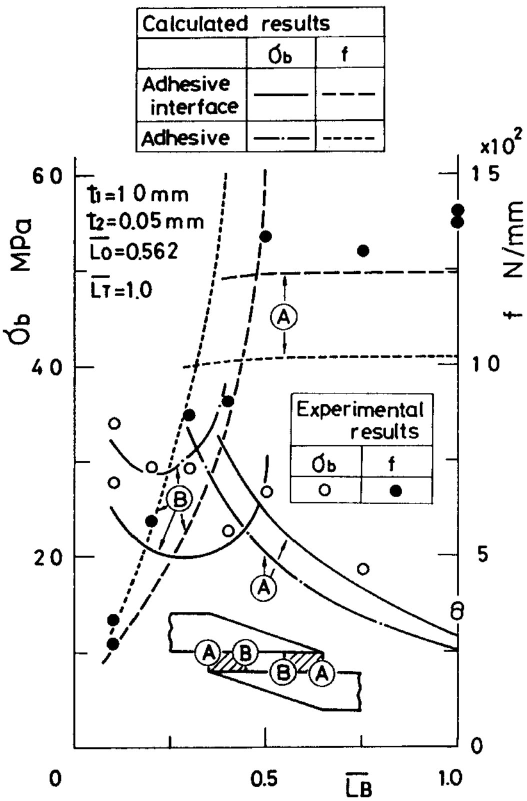

FIGURE 15 Effect of adhesive band length on the joint strength for tapered lap joint.

same strength as the tapered lap joint bonded with the whole overlap length $\bar{L}_B = 1.0$.

Figure 16 shows the effect of the band adhesive length on the strength of the single lap joints. The joint strength f saturates above $\bar{L}_B = 0.25$ with the adherend thickness $t_1 = 10$ mm. This shows that a quarter of the bonding length of the whole overlap ($\bar{L}_B = 0.25$) is enough to obtain the strength of the single lap joint.

The experimental results of the joint strength are indicated in Figs. 13 to 16. The experimental values coincide approximately with the analytical results for the small values of $\bar{L}_O$, $\bar{L}_T$ and $\bar{L}_B$, but

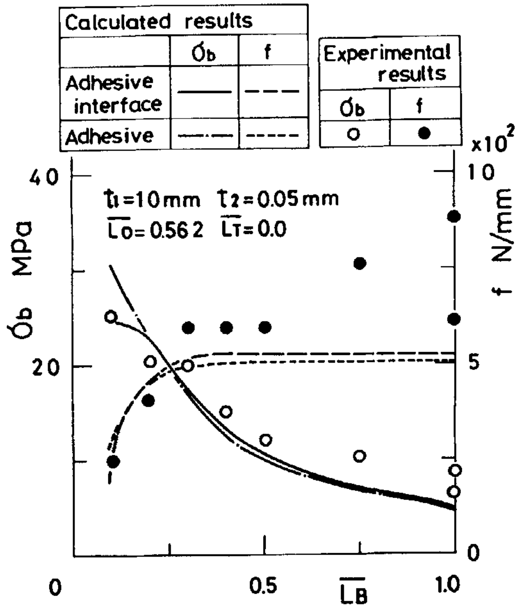

FIGURE 16 Effect of adhesive band length on the joint strength for single lap joint.

they are larger than the analytical results for the large values of $\overline{L_O}$, $\overline{L_T}$ and $\overline{L_B}$. The experimental strength is obtained by the final fracture load, while the analytical strength corresponds to the initial fracture load. As shown in Figure 10, the joint does not fracture after the initial failure and the joint can bear the increasing load. This is one reason for the discrepancy between experimental strength and predicted strength. The process to the final fracture from the initial cracking should be investigated in future.

5 CONCLUSIONS

A method of estimating the strength of adhesive bonded joints was proposed. The adhesive strength law which was determined under combined stress states was used to decide the joint strength as well as the strength law of adherends and of the adhesive resin. Those three strength laws were adopted to the stress distributions in the adhering interface, adherends and adhesive layer, and the critical loads in each part of the joint were calculated. The minimum load among them was taken as the joint strength. The proposed method was applied to predict the strength of lap joints.

The lap joints used in this research consisted of carbon-steel adherends bonded with epoxy resin. The deformed states under tensile shear loading were analysed by the elastic finite element method. The calculated strain distributions were compared with the experimental results. The joint geometry influenced the strain distributions remarkably. The adhesive strength law was experimentally determined by subjecting a butt joint of carbon-steel cylinders to combined axial load and torsion. The strength of lap joints with various configurations was predicted by the proposed method. The effects of overlap length, tapering length and adhering length on the strength were obtained. The predicted strength was compared with the experimental value. It was shown that the method of using the adhesive strength law was useful for the prediction of joint strength.

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