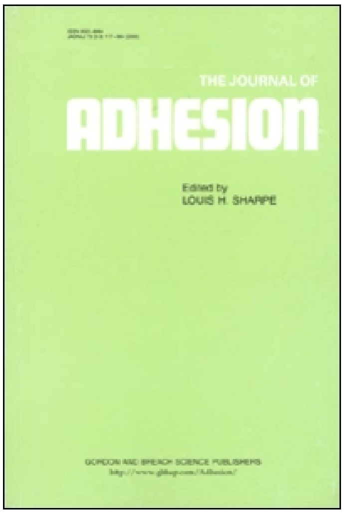

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Effect of Flaws in the Adhering Interface on the Strength of Adhesive-bonded Butt Joints

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This paper presents the strength of metal-to-metal bonded joints with a flaw in the interface between the adhesive layer and the adhering surface of adherend. The test specimens of butt joints are prepared by bonding two thin-wall metal tubes. The materials are carbon steel, aluminum alloy, brass and copper. The adhesive is epoxy resin. The tensile and shear strength of the joints are experimentally determined by subjecting the specimens to axial load and torsion for various flaw sizes and thickness of adhesive layers. Linear elastic fracture mechanics is applied to the experimental results. The stress intensity factors for a layered composite with a flaw in the interface are numerically calculated in terms of flaw size and loading by using Erdogan's formulas. The fracture stresses of joints with a flaw are predicted at the critical values of the stress intensity factors. The strength of joints without a flaw is also correlated with the stress intensity factors by use of a concept of "effective flaw size".

1. INTRODUCTION

Adhesive joints generally involve flaws in the interface between the adhering surface and adhesive layer because of abrasive particles or incomplete wetting by the adhesive resin. These flaws cause stress concentrations in the adhering interface and reduce the strength of bonded joints. From the standpoint of structural design, it is important to comprehend qualitatively the effect of flaws on the strength of adhesive bonded joints.

There are many research works[1–13] on the fracture toughness and propagation of cracks in bonded joints, which are conducted by using single-edge-notch specimens or double-cantilever-beam specimens. Few papers,[14,15]

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however, are found on the qualitative effect of flaws on the strength of bonded joints.

In this paper, the tensile and shear strength of joints with an interfacial flaw are experimentally investigated by subjecting butt joint specimens of thin wall tubes to axial load and torsion. The experimental results of the tensile and shear strength are predicted at the critical values of Erdogan's stress intensity factors for layered materials. The strength of joints without a flaw is also correlated with the stress intensity factors by use of the concept of "effective flaw size".

2. EXPERIMENTAL PROCEDURE

Two types of cylindrical specimens shown in Figure 1 are used as adherends. Type I specimens of carbon steel with carbon content of 45% and aluminum alloy with copper content of 4% were prepared, and those of brass with zinc content of 40% and copper were type II. The adhering surface of the specimen is the edge of the cylindrical part indicated by the arrow A in Figure 1. This

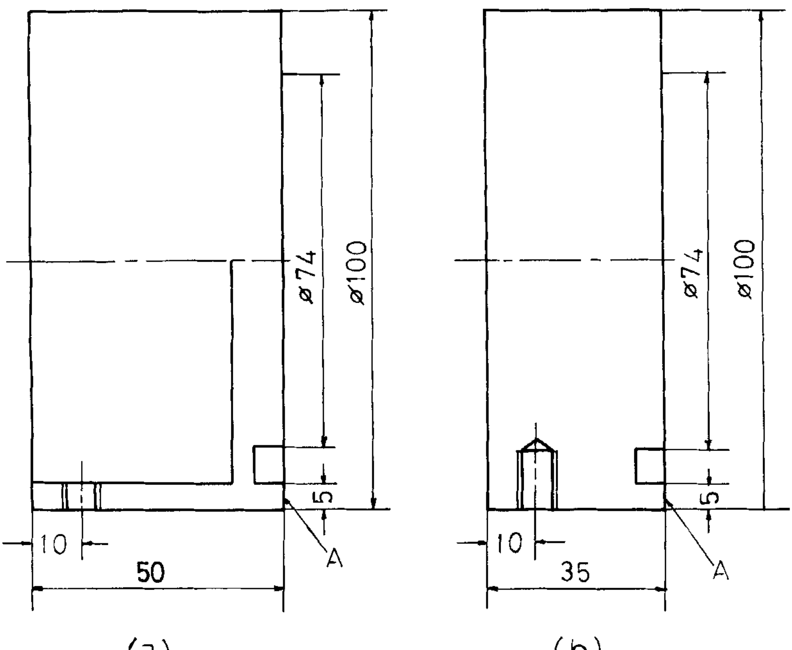

FIGURE 1 Dimensions of thin-wall tubes for butt joints. Units: mm.

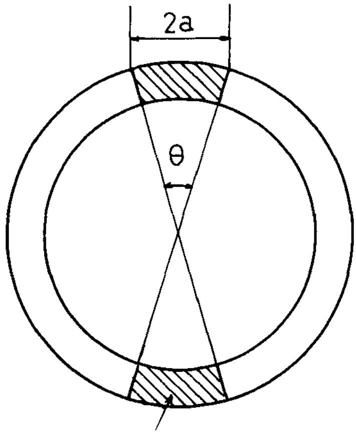

FIGURE 2 Interfacial crack dimensions in butt joints of tubular specimens.

surface was abraded by abrasive papers, and then washed in a solution of ethyl alcohol and a chlorofluorocarbon agitated ultrasonically. To make an artificial crack in the interface between the adhering surface of the adherend and the adhesive layer, mold release agent was applied to one adhering surface in the certain range (angle θ in Figure 2) before bonding. The mold release agent prevented bonding and thus formed an interfacial crack. To cancel a bending effect in the tensile tests, the crack is symmetrically formed as shown in Figure 2. The thickness of adhesive layer can be set to a given value by using the thickness gauge inserted between the circular region of two cylindrical adherends.

The adhesive was epoxy resin (R-802 of Showa Kobunshi Co. Ltd.) with the hardener system of cumene hydroperoxide and cobalt naphthenate. For the copper adherends, the curing system without cobalt naphthenate was used. The specimens were bonded under the weight of 15 kg for 2 hours at room temperature, cured for 2 hours at 70°C, and cooled to room temperature at the rate of 5°C/hour.

The bonded cylindrical specimens were subjected to axial and torsional load (shear) by a combined stress testing machine.[16] The stress rate applied to specimens was 2.35 MPa/minute with tension and 4.71 MPa/minute with shear. The loads at fracture of the specimens were measured. From those load values, the axial and shear stresses at fracture were calculated on the basis of the original dimensions of the specimen. The detailed testing procedure is given in a previous paper.[16]

The mechanical properties of the adhesive resin are examined by tensile, compressive and shear test of thin-wall tube specimens molded from the adhesive resin. The thickness of the tube specimen is 2.5 mm in the gauge length.

3. EXPERIMENTAL RESULTS

3.1 Stress-strain relations of the adhesive resin

Figure 3 shows the stress-strain curves of the adhesive resin for tensile, compressive and shear tests. The result of the shear test is represented by an equivalent stress-strain curve of the von Mises type. The deformation behavior of the adhesive resin is similar to a brittle material in which plastic deformation is small to fracture. The compressive strength is a little higher than the tensile strength.

3.2 Effect of a crack on the strength of joints

Figures 4 and 5 show the effect of crack length on the adhesive strength. The crack length is indicated by the angle θ in Figure 2. In Figure 4, the results of tensile fracture stress of carbon steel joints are shown. The thickness (h) of adhesive layer is 200 μm and the surface roughness (R_a) 0.30 μm. The tensile strength for large crack angles is reduced to about half that for small crack angles. Figure 5 shows the tensile and shear fracture stresses of aluminum alloy joints. The thickness of adhesive layer was 200 μm and the surface roughness (R_a) was 1.18 μm. Similar to Figure 4, the large crack angles reduce the strength of joints. Comparing the strength for the same crack angle, the shear strength is higher than the tensile one.

Figures 6 to 9 present the effect of the thickness of adhesive layer on the tensile and shear strength of specimens having a crack of constant length ($2a = 1$ mm in Figure 2). The roughness (R_a) of the adhered surface is 0.30 μm. The adherend materials are carbon steel, aluminum alloy, brass and copper. In the results of Figures 6 to 9, the shear strength is higher than the tensile one, and the fracture stresses decrease with increasing thickness of adhesive layers.

3.3 The strength of joints without a crack

Figures 10 and 11 show the tensile and shear strength of specimens without a crack. The roughness (R_a) of the adhered surface is 0.30 μm. Comparing the results of Figures 10 and 11 with those of Figure 6, the strength of joints with a crack becomes half that without a crack in the case of thin adhesive layers. But the presence of a crack does not have a large effect on the strength of joints for thick adhesive layers.

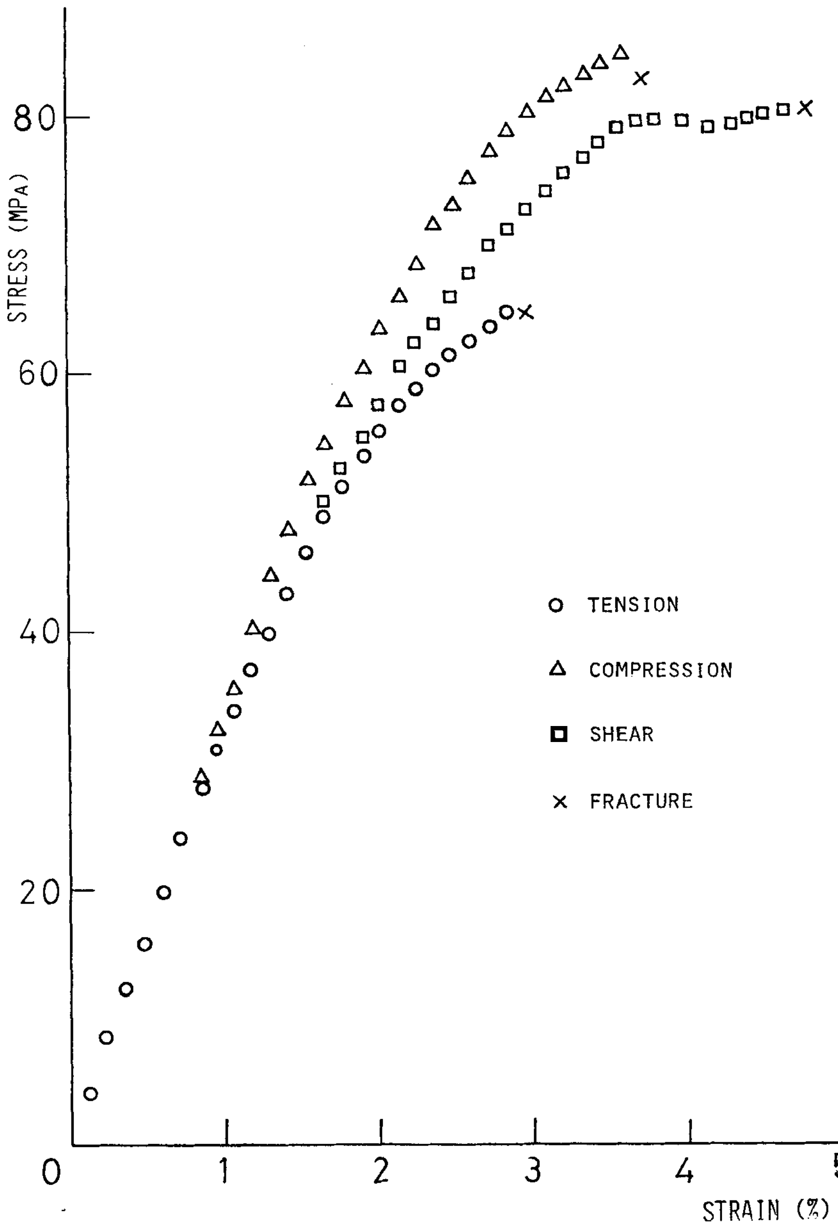

FIGURE 3 Stress-strain relations of epoxy resin.

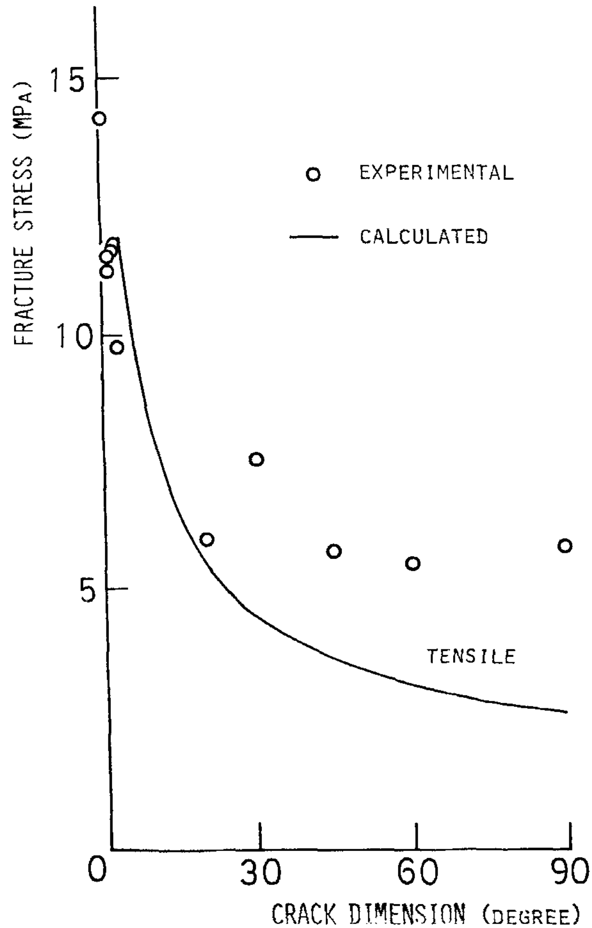

FIGURE 4 Effect of the interfacial crack length on the strength of butt joints (adherend : carbon steel, $h = 200\ \mu m$, $R_a = 0.30\ \mu m$).

4. APPLICATION OF FRACTURE MECHANICS

Linear elastic fracture mechanics is a useful method to predict the failure of brittle materials containing cracks.

The adhesive resin used in the experiments has similar properties to a brittle material as shown in Figure 2. The specimens bonded with this resin fracture suddenly under increasing loads. In addition, it is found by visual observations that the fracture in the broken specimens are initiated from the crack introduced by the method previously described. Those facts offer the possibility of predicting the strength of the joint specimens with a crack by using linear elastic fracture mechanics.

In fracture mechanics, the quantity most used to estimate the fracture by crack growth is the stress intensity factor, denoted by K. There are many calculated results[17–26] on the stress intensity factors for an interfacial crack between two bonded materials. Among such results, the formulas for stress intensity factor derived by Erdogan *et al.*[20] are adequate to predict the fracture of adhesive joints, because they are given in terms of a thickness of adhesive layer as well as crack dimensions. Figure 12 shows the model of an adhesive joint, in which the thickness of adhesive layer and length of an interfacial crack

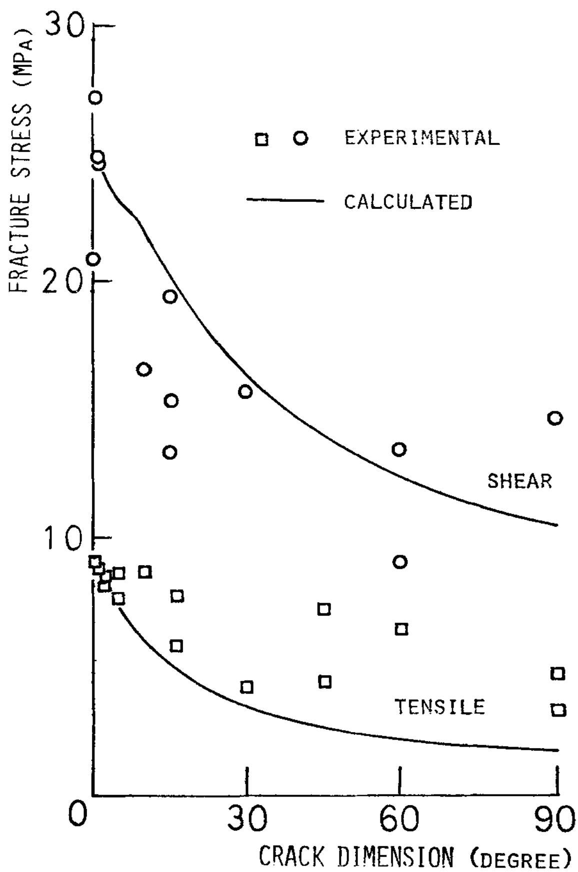

FIGURE 5 Effect of the interfacial crack length on the strength of butt joints (adherend: aluminum alloy, $h = 200\ \mu m$, $R_a = 1.18\ \mu m$).

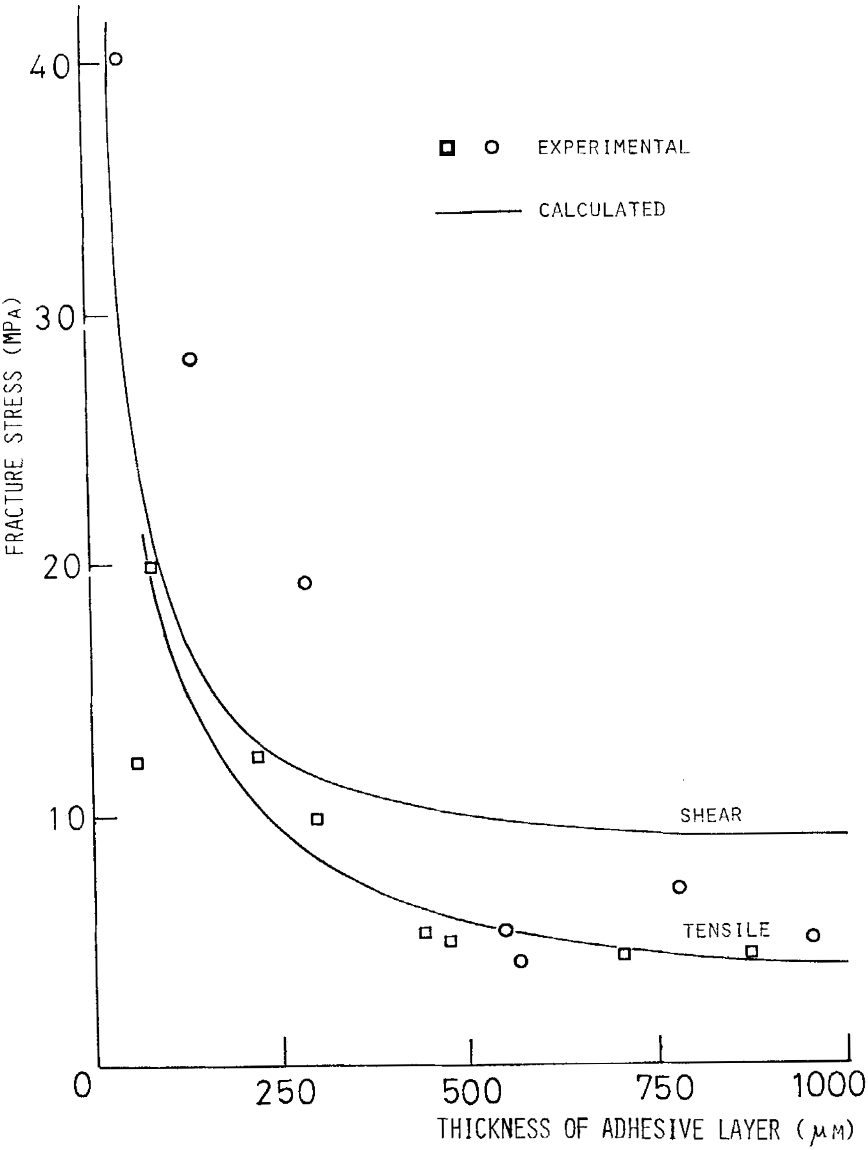

FIGURE 6 Effect of the thickness of adhesive layers on the strength of butt joints with interfacial crack (adherend: carbon steel, $2a = 1$ mm, $R_a = 0.30$ μm).

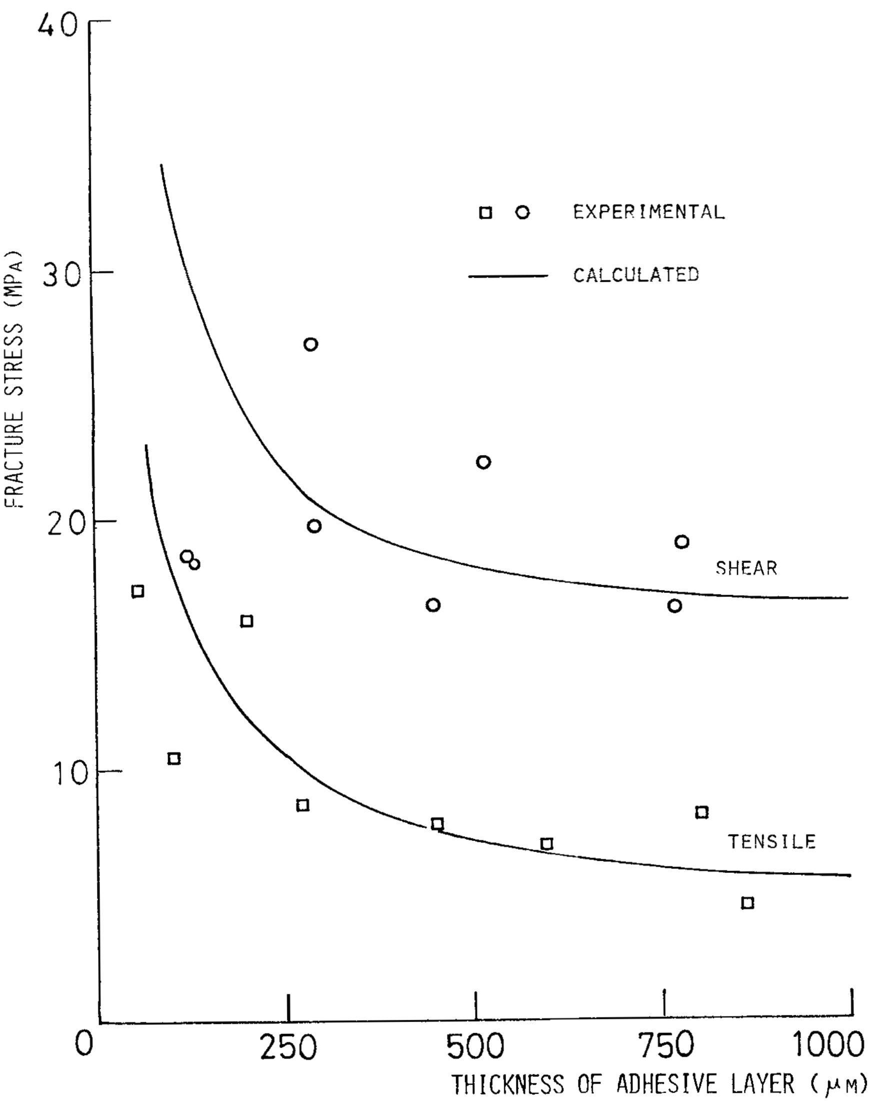

FIGURE 7 Effect of the thickness of adhesive layers on the strength of butt joints with interfacial crack (adherend: aluminum alloy, $2a = 1$ mm, $R_a = 1.18$ μm).

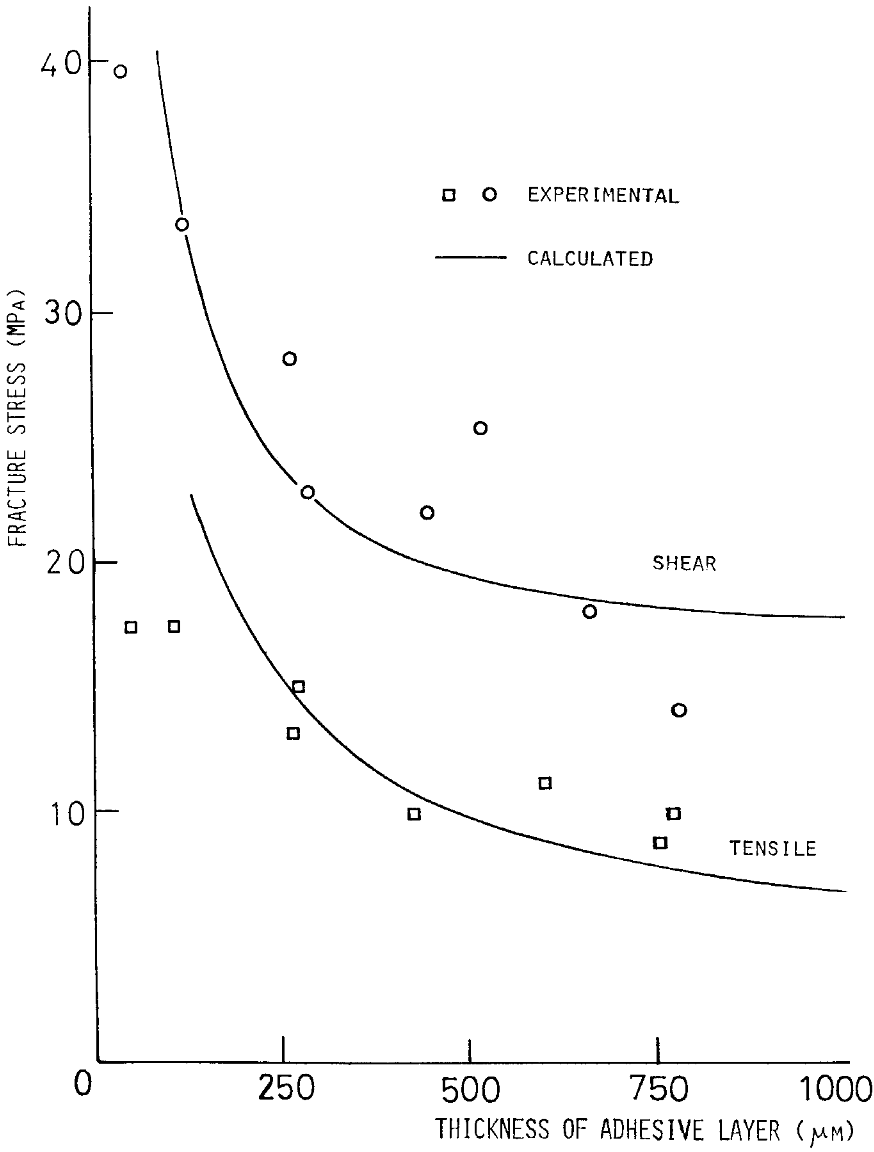

FIGURE 8 Effect of the thickness of adhesive layers on the strength of butt joints with interfacial crack (adherend: brass, $2a = 1$ mm, $R_a = 1.07$ μm).

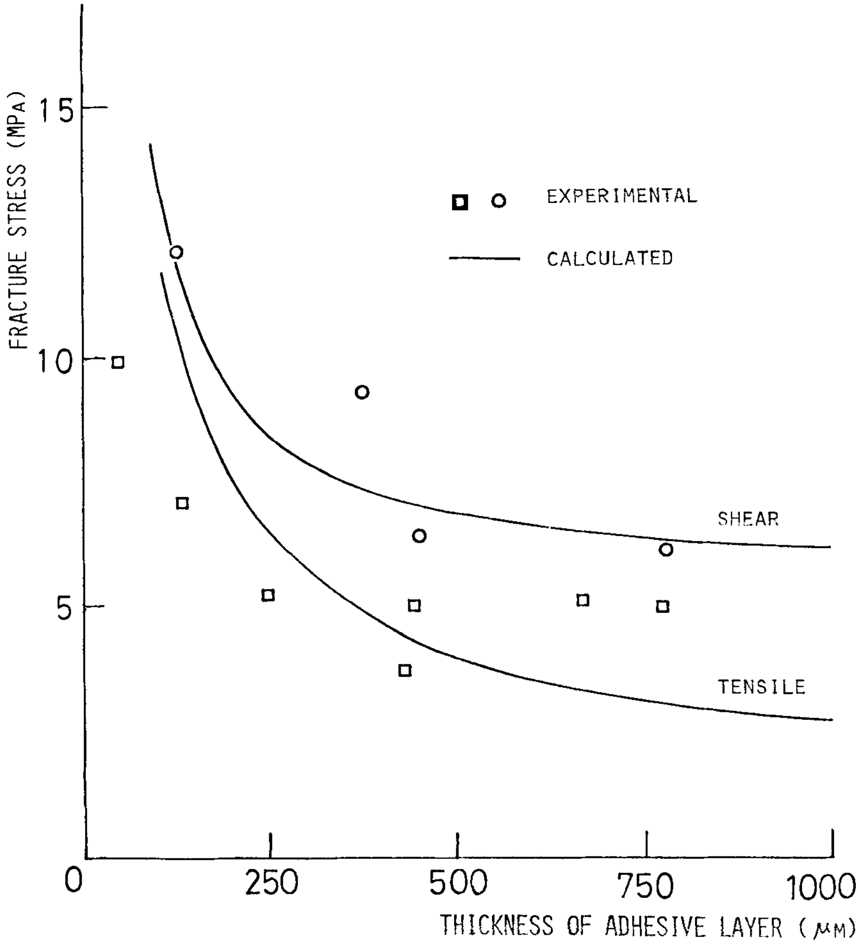

FIGURE 9 Effect of the thickness of adhesive layers on the strength of butt joints with interfacial crack (adherend: copper, $2a = 1$ *mm*, $R_a = 1.24$ μm).

are denoted by h and $2a$, respectively. For this model, the stress intensity factors are calculated as shown in Figure 13. This is the result for carbon steel adherends. Similar figures are obtained for the cases of aluminum alloy, brass and copper. The material constants used in this calculation are given in Table I. In the calculation, an interaction effect of cracks in the specimens is neglected.

A fracture criterion is necessary to correlate the stress intensity factors to the unstable crack growth stress. As seen in Figure 13, mixed fracture modes arise

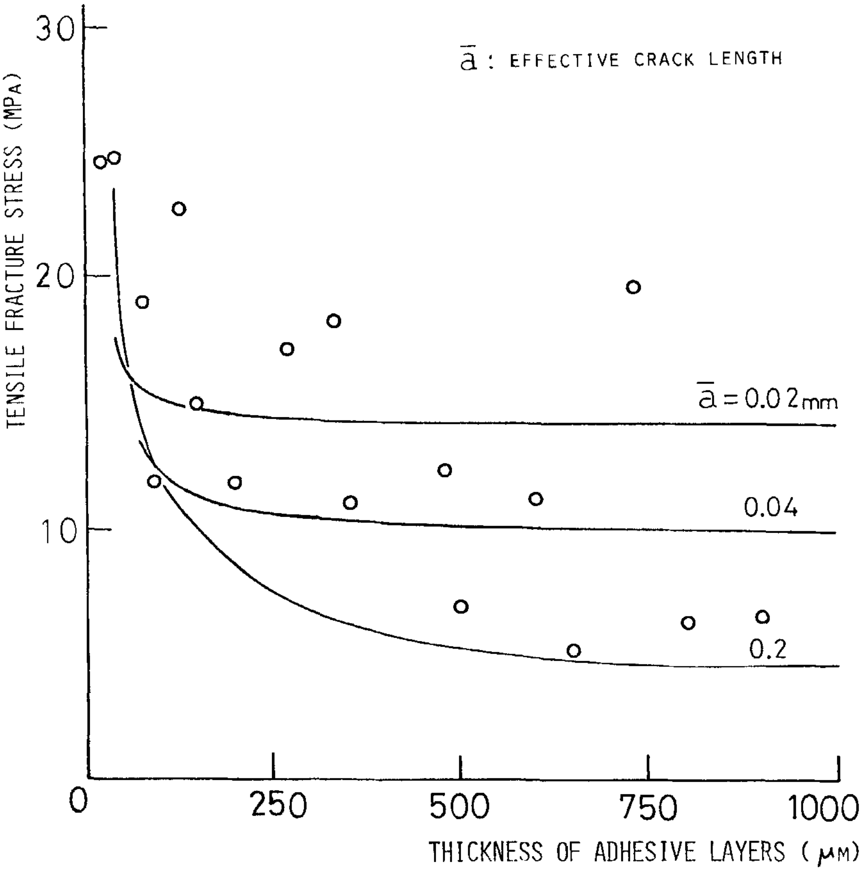

FIGURE 10 Correlation of tensile adhesive strength of butt joints without interfacial crack with the concept of effective crack (adherend : carbon steel, $R_a = 0.30\ \mu m$).

under a single applied stress condition of either tension or torsion. Therefore, precisely speaking, a mixed fracture criterion involving both K_I and K_{II} should be used to predict an unstable stress condition of the crack in joints. But the components of K_{II} under tensile stress and K_I under shear stress are small compared with K_I for tension and K_{II} for shear, respectively. Under such situations, a simplified single mode criterion will be assumed as follows,

$$\begin{aligned} K_{IC} &= \text{const., for tensile stress,} \\ K_{IIC} &= \text{const., for shear stress.} \end{aligned} \tag{1}$$

The notations K_{IC} and K_{IIC} are the critical values of the stress intensity factors

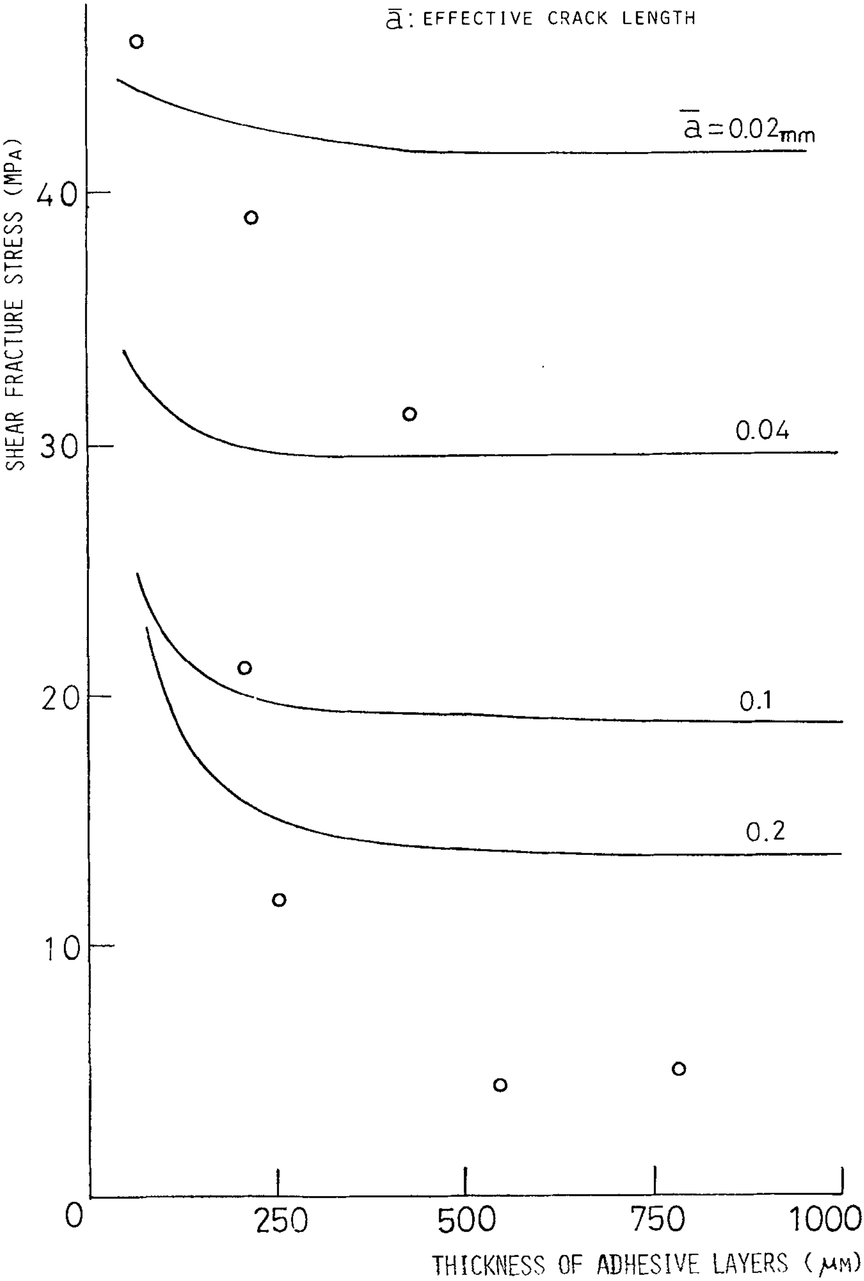

FIGURE 11 Correlation of shear adhesive strength of butt joints without interfacial crack with the concept of effective crack (adherend: carbon steel, $R_a = 0.30$ μm).

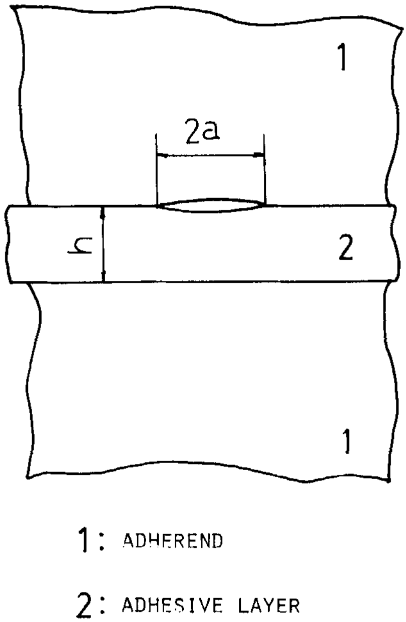

FIGURE 12 Crack in the interface of butt joints.

for the modes I and II, respectively. Those critical values are determined as follows. For a given crack length and a thickness of adhesive layer, the values of $K_I/(\sigma a^{1/2})$ and $K_{II}/(\tau a^{1/2})$ to the adherend of carbon steel can be obtained from Figure 13. The corresponding stress value by tension and torsion in Figure 6 is substituted into the value of σ and τ in $K_I/(\sigma a^{1/2})$ and $K_{II}/(\tau a^{1/2})$, respectively. The values thus obtained are used as K_{IC} and K_{IIC}. After obtaining K_{IC} or K_{IIC} for each experimental fracture stress point, the values are averaged with the results shown in Table II. For other adherends, a similar

TABLE I

Material constants of adhesive resin and adherend

	Tensile modulus GPa	Shear modulus GPa	Poisson's ratio
Epoxy resin	34.3	12.5	0.35
Carbon steel	2060	792	0.30
Aluminum alloy	687	265	0.30
Brass	932	258	0.30
Copper	1226	472	0.30

TABLE II

Critical values of stress intensity factors for the butt joints with interfacial crack

	K_{IC} MPa·m$^{1/2}$	K_{IIC} MPa·m$^{1/2}$	K_{IIC}/K_{IC}
Carbon steel	0.0636×10^{-1}	1.89×10^{-1}	3.0
Aluminum alloy	0.921	3.50	3.8
Brass	1.19	3.72	3.2
Copper	0.484	1.31	2.7

method is applied. The values of K_{IC} and K_{IIC} depend on the adherend materials. The ratio of K_{IIC} to K_{IC} also varied according to the kind of adhered metals.

By using the values in Table II and the criteria of Eqs (1), the fracture stress of joints can be predicted in terms of the crack size and the thickness of adhesive layer for various adherends and loadings. The predicted results for a crack of constant length in various thicknesses of adhesive layer are indicated by solid lines in Figures 6 to 9, and those for various crack lengths in a adhesive

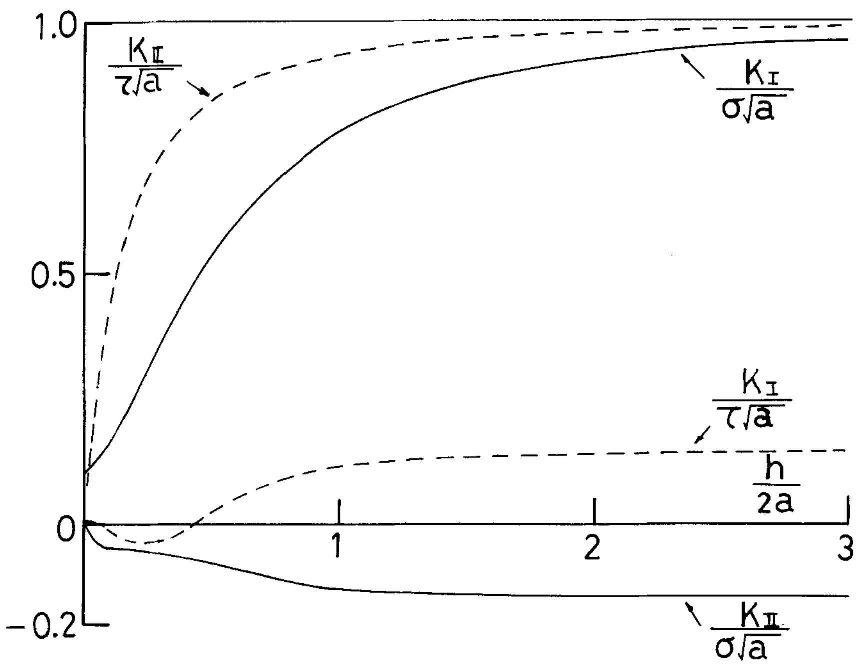

FIGURE 13 Stress intensity factors for the models of butt joints with interfacial crack (adherend: carbon steel).

layer of a constant thickness are shown in Figures 4 and 5. The predicted curves fit approximately the experimental points.

There are many possibilities of existing interfacial flaws in adhesive joints. Their dimensions, however, are impossible to know. This is a difficult problem in applying fracture mechanics to predict the strength of bonded joints. One way of overcoming this difficulty is to represent many unknown flaws in a joint by use of one imaginary effective crack. The solid lines in Figures 10 and 11 are calculated curves relating the fracture stress of joints having unknown cracks to the strength of joints with an effective interfacial crack of the length shown on the figures. As seen in these results, the experimental values can not be represented by one effective crack length. For thicker adhesive layers, a long effective crack predicts the experimental results well, and for thin layers, a short effective crack is suitable. This suggests that the thicker adhesive layer has many flaws.

5. CONCLUSIONS

The effect of an interfacial crack on the strength of butt joints is experimentally investigated. The experimental program was conducted by subjecting butt joints of thin wall tubes to axial load and torsion. The materials of adhered tubes are carbon steel, aluminum alloy, brass and copper, and the adhesive is epoxy resin. Linear elastic fracture mechanics were applied to the experimental results and the strength of joints with a interfacial crack is qualitatively related to a crack size and thickness of the adhesive layer. The following results are obtained.

1) For a given thickness of adhesive layer, the joint strength is greater with shear loading than tensile loading.

2) The tensile and shear strength are sensitive to the crack length as well as the thickness of adhesive layer.

3) The fracture stress of joints with an interfacial precrack is approximately predicted by the critical values of the stress intensity factors for layered materials.

4) The strength of joints without a precrack is interpreted in terms of an imaginary effective crack which is representative of unknown microcracks in the adhesive layer. For the joints with thick adhesive layers, long effective cracks predict the strength well and, for thin adhesive layers, short effective cracks are preferable.

References

1. S. Mostovoy and E. J. Ripling, *J. Appl. Polymer Sci.* **10**, 1351 (1966).
2. S. Mostovoy, E. J. Ripling and C. F. Bersch, *J. Adhesion* **3**, 125 (1971).

3. E. J. Ripling, S. Mostovoy and H. T. Corten, *J. Adhesion* **3,** 107 (1971).
4. S. Mostovoy and E. J. Ripling, *J. Appl. Polymer Sci.* **15,** 641 (1971).
5. G. G. Trantina, *J. Composite Materials* **6,** 192 (1972).
6. G. G. Trantina, *ibid.* **6,** 371 (1972).
7. Y. W. Mai, *J. Adhesion* **7,** 141 (1975).
8. F. Farhad, R. Muki and R. A. Westmann, *Int. J. Solids Structures* **13,** 561 (1977).
9. S. S. Wang, J. F. Mandell and F. J. McGarry, *Int. J. Fracture* **14,** 39 (1978).
10. H. Sasaki and P. F. Walsh, *J. Soc. Materials Sci.* **26,** 453 (1977) (in Japanese).
11. C. L. Chow, C. W. Woo and J. L. Sykes, *J. Strain Analysis* **14,** 37 (1979).
12. C. L. Chow and K. M. Ngan, *J. Strain Analysis* **15,** 97 (1980).
13. A. Saxena, *Fibre Sci. Tech.* **12,** 111 (1979).
14. K. Kawata and T. Takeda, *Trans. JSCM* **3,** 26 (1976).
16. K. Ikegami *et al., J. Adhesion* **10,** 25 (1979).
17. F. Erdogan, *J. Appl. Mech.* **87,** 232 (1965).
18. F. Erdogan, *ibid.* **89,** 829 (1965).
19. J. R. Rice, *ibid.* **87,** 418 (1963).
20 F. Erdogan and G. Gupta, *Int. J. Solids Structures* **7,** 39 (1971).
21. F. Erdogan and G. Gupta, *ibid.* **7,** 1089 (1971).
22. F. Erdogan and K. Arin, *Int. J. Engng. Sci.* **10,** 115 (1972).
23. P. S. Theocaris, *Acta Mech.* **24,** 99 (1976).
24. D. R. Mulville and P. W. Mast, *Engng. Fracture Mech.* **8,** 555 (1976).
25. R. Calhoun and M. Lowengrub, *Int. J. Engng. Sci.* **16,** 423 (1978).
26. A. Piva and E. Viola, *Engng. Fracture Mech.* **13,** 143 (1980).