Adhesive Tensile Strengths of Scarf and Butt Joints of Steel Plates*

(1st Report, A Case of Brittle Adhesive)

By Yasuaki SUZUKI**

Adhesive tensile strengths of scarf joints with various scarf angles and butt joints with various adhesive layer thicknesses have been measured to establish fracture criterion for joints of steel plates bonded by brittle epoxy adhesive. A three-dimensional elastic stress analysis of these joints was performed by FEM. Fractures of both joints were explained quantitatively by introducing a boundary layer depth of 0.035 mm at free surfaces of adhesive layers and obeying maximum principal stress criterion. In adhesive layers of scarf joints with 0.1 mm layer thickness, the boundary layer depth of 0.035 mm included most of stress concentrated area at free surfaces. Locations of fracture initiation and fracture modes of adhesive layers observed with an optical microscope and a scanning electron microscope agreed with those expected from stress distributions and boundary layer conception.

Key Word: Strength, Elasticity, Fracture Criterion, Adhesive Joint, Scarf Joint, Butt Joint, Non-Uniform Stress Distribution, Brittle Fracture, Three-Dimension, FEM.

1. Introduction

Establishment of fracture criterion is indispensable for designing safe and efficient adhesive joints. Numerous studies on stress analyses of adhesive joints have been performed, but research for fracture criterion is scarce. In the case of scarf joints, Lubkin⁽¹⁾ considered the fracture criterion, and Yamaguchi et al.⁽²⁾ experimentally examined the adhesive strength. Masuoka et al.⁽³⁾ and Sugibayashi and Ikegami⁽⁴⁾ studied butt joints, the former discussing the case of fracture condition under which plastic deformation had sufficiently proceeded in the adhesive layer, and the latter setting up equations on the adhesive strength of cylindrical joints under combined stresses.

Scarf joints are useful in the investigation of joint-fracture criterion, since combined stress state of vertical stress and shear stress is obtainable and their combination ratio is easily varied by simply changing the scarf angle. The author⁽⁵⁾ previously measured the adhesive strength of epoxy resin adhesive joints of steel plates and discussed the fracture criterion, but the explanation of the experimental results was not fully successful because the results were those of approximate two-dimen-

sional stress analysis of the joints.

On the other hand, Lubkin discussed the fracture criterion on the conception that the stresses are uniformly distributed and in plane stress condition, but a three-dimensional finite element analysis⁽⁶⁾ by the present author revealed a considerable stress concentration in the vicinity of free end of the adhesive layer, while most parts of the layer were in plane strain condition.

The present study was performed for a more detailed examination of fracture criterion of scarf and butt joints. Firstly, in addition to the previous results⁽⁵⁾ obtained through experiments on scarf joints, the adhesive strengths of butt joints using the previously employed adhesive were measured varying adhesive layer thickness. Secondly, a more detailed three-dimensional finite element analysis than in the previous report⁽⁶⁾ was performed in the vicinity of free end of the adhesive layer of the joints. The results obtained were employed to theoretically relate the scarf angle and adhesive layer thickness to the adhesive layer, taking the boundary layer⁽⁷⁾ of the adhesive into account. Finally, the influence of non-uniform stress distribution on adhesive strengths was investigated by comparing the theoretical results with the experimental results.

2. Experimental Procedures

2.1 Adhesives

Eleven parts equivalent of Diethylenetriamine was added as hardener to hundred parts of Epikote 828 (Shell Chemicals

* Received 25th May, 1983.

** Manager,
Nippon Sharyo Seizo Kaisha, Ltd.,
1-1, Sanbonmatsu-cho, Atsuta-ku,
Nagoya, 456.

Co.) and the blending was used as the adhesive. The stress-strain curves and Poisson's ratio of the adhesive cast were obtained by the previously described method⁽⁵⁾.

2.2 Adhesive Joints

Figure 1 shows a schematically the scarf and butt joint specimens used in the measurements of adhesive tensile strengths. Low carbon steel (SS 41) was used as the adherend. Scarf angle was varied in six values, namely, 15°, 30°, 45°, 60°, 75°, and 90° (butt joint), and 12.7 mm square interface was uniformly taken. The adhesive layer thickness h was 0.1 mm in the case of scarf joint, whereas various thicknesses of 0.1, 0.3, 0.6, 1.0, and 5.0 mm were taken for butt joints. Adhesion was done by vacuum impregnation method⁽⁵⁾. The elongation of the adhesive layer and a part of adherend was measured with two pieces of 5 mm-long strain gauges attached at the center of the specimen, as shown schematically in Fig.1. The unreferred manufacturing procedure of butt joint specimen and tensile test procedure were the same as the previously reported method⁽⁵⁾.

3. Experimental Results

3.1 Adhesives

Figure 2 is a typical stress-strain curve obtained on the adhesive. The linear relation up to fracture is characteristic of brittle materials, Table 1 gives Young's modulus and Poisson's ratio, which are the mean values obtained from five specimens.

3.2 Adhesive tensile strength of scarf joints

Adhesive tensile strength σ_y was calculated by dividing the experimentally obtained fracture load by the cross section-

Fig. 1 Adhesive joint specimens ($\theta=15^\circ$ to 90°)

Fig. 2 Stress-strain curves for adhesive bulk specimens

al area vertical to the longitudinal direction at each angle θ .

The corresponding values are marked with a small circle $\circ$ in Fig. 3, and each value is an average of the data measured from ten specimens. Minimum σ_y is indicated at $\theta=60^\circ$ and it remains approximately constant up to $\theta=90^\circ$, whereas it abruptly increases with a decreasing θ in the range lower than 60° . This phenomenon will be discussed later. Figure 4 shows a tensile load-strain curve of the joint. The proportion of the adhesive layer is estimated to make up about tens percent of the total strain observed, considering the adherend to adhesive layer ratios of Young's modulus and lengths in strain gauge, but, the stress-strain curve exhibits a linear relation.

Table 1 Mechanical properties of adhesive

Young's modulus	Poisson's ratio
3.14 GPa {320 kgf/mm ² }	0.37

Fig. 3 Relations between adhesive tensile strengths and scarf angles on scarf joints

Fig. 4 Load-strain curves for scarf joint specimens

3.3 Adhesive tensile strength of butt joints

The mean value for 10 specimens is marked with a small circle $\circ$ in Fig. 5 as the experimentally obtained σ_y at each adhesive layer thickness h . Weibull deduced the following relation between

Fig. 5 Relations between adhesive tensile strengths and adhesive layer thicknesses on butt joints

Fig. 6 Load-strain curves for butt joint specimens

Fig. 7 Three-dimensional finite element analysis models

the total crack number n and the strength of the specimen S_m , on the basis of the probability discussion of fracture according to Griffith's theory(8)(9).

$$S_m = \frac{(1-1/m)^{1/m}}{(an)^{1/m}} \quad (1)$$

Where a and m are constants depending on the material used. Since n is proportional to the sample volume V , Eq. (1) is simplified as follows (8)(9).

$$S_m \propto V^{-1/m} \quad (2)$$

This indicates the linear relation between $\log S_m$ and $\log V$. σ_y is plotted against h , both on logarithmic scales in Fig. 5, since the adhesive layer volume V is proportional to h . Their relation is represented by straight lines changing the slope at $h=0.6$ mm. Further discussion on these relations will be given later.

Figure 6 is a load-strain curve of the joint, from which the linear relation is indicated to the point of fracture.

4. Stress Analysis

4.1 Process

The same model as well as process described in the previous report(6) was applied. Three-dimensional elastic analysis was performed on the 1/2-model of $\theta=15^\circ \sim 75^\circ$ (Fig. 7(a)) and 1/8-model of $\theta=90^\circ$ (Fig. 7(b)), by dividing the sample into approximately 1100 nodes and 800 elements using eight-nodes isoparametric elements of hexahedron.

The length ratio of the adhesive layer l to the thickness h was varied from approx. 10 to 127, by magnification or reduction of the coordinates (changing k values in Fig. 7), where $l/h=127$ corresponds to the $h=0.1$ mm specimen. The thickness t (x -coordinate) of the model was varied by modifying θ as shown in Fig. 7 (a). Both (a) and (b) models were divided as the element in the same number as in the previous report in

the x-, y-, and z-directions, but the coordinates were modified so that it would be divided into finer parts in the vicinity of the corner of the free end (Point A' shown in Fig. 7 (c) of the adhesive layer. In addition, it was so designed that the centroid of the element on the diagonal A'L in the xz plane should match A'L.

The case of completely uniform stress distribution on the whole joint at $\theta=52.47^\circ$ was also analyzed, based on the results⁽¹⁰⁾ obtained of finite element analysis of joints in plane strain condition.

4.2 Results of the analysis

Stresses in the lower adhesive interface near the free end which yields maximum stress in the range of $\theta=15^\circ\sim 90^\circ$ are given in Fig. 8. The stresses are expressed with dimensionless values of maximum principal stress, σ_1 and the equivalent stress of von Mises, σ_{eq} , by normalizing with σ_a . Maximum stress occurred on BB' (Fig. 7(c)) in the range of $\theta=15^\circ\sim 52.47^\circ$, while it occurred on AA' in the range of $\theta=60^\circ\sim 90^\circ$. The maximum stress at the constant length in the x- or z-direction from the free end

of the adhesive layer occurred on the diagonals A'Q'L and B'R'L, or on the b-wide center line AQLRB. A larger stress is adopted in Fig. 8. The abscissa is the dimensionless distance from the free end in the x-direction normalized by h. Each stress for respective values of l/h was almost on one curve, and similarity was observed.

In addition, the stresses of the center element (in the area of constant stress) in the s-, n-, and z-directions of the adhesive layer shown in Fig. 7(c) were expressed with σ_{1c} and σ_{eqc} , and their σ_a -normalized dimensionless values at $l/h=127$ are shown with straight lines in Fig. 8. Ratios of the maximum values of σ_{1c} and σ_{eqc} in the free end to σ_{1c} and σ_{eqc} are a kind of stress concentration coefficient. Their values are at the minimum in the range of $\theta=52.47^\circ\sim 60^\circ$,

(a) $\theta=15^\circ$

(b) $\theta=30^\circ$

(c) $\theta=45^\circ$

(d) $\theta=52.47^\circ$

(e) $\theta=60^\circ$

Fig. 8 Stress distributions in the vicinity of the adhesive layer free end with stress maxima (1)

and they increase as θ deviates from this range. Especially, both stresses yield higher values than 3 at $\theta=15^\circ$ and 30° . Nevertheless, internal stresses σ_1 and σ_{eq} at $0.8h$ depth from the free end are approximately equal to σ_{1c} and σ_{eqc} , respectively.

Figure 9 relates σ_1/σ_a to x at $\theta=90^\circ$, where each l/h value corresponds to h of each butt joint specimen. The stresses on the diagonal A'Q'L are larger than those on the b-wide center line AQL in the very vicinity of the free end with an exception in the case of $l/h=2.54$, but the relations in the inside parts are reserved.

5. Discussions

5.1 Application of the boundary layer theory to the adhesive layer

Sato et al.⁽¹¹⁾⁽¹²⁾ and Noguchi⁽¹³⁾ reported that fractures under non-uniform stresses of brittle materials such as marbles, glass ceramics, etc., and of cast iron, etc. are well explainable considering a boundary layer⁽⁷⁾ on the material surfaces analogous to the case of ductile materials. Accordingly, an adhesive layer was similarly hypothesized in this study.

The broken line in Fig. 10 represents the analytically obtained stress in the vicinity of the free end in the adhesive interface, according to Fig. 8. As Nakanishi et al.⁽⁷⁾ pointed out, δ -thick boundary layer taken into account yields the solid line with the maximum σ_δ at $x=\delta$. This σ_δ is presumed to correspond to the elastic analysis stress. The following equation is suggested as the fracture criterion of the adhesive layer.

$$\sigma_s = A\sigma_0 \quad (3)$$

Where, σ_0 is the tensile strength of the adhesive itself. The reported A values are 1.5 by Sato et al.⁽¹¹⁾⁽¹²⁾ and 1.0 by Noguchi⁽¹³⁾. Since the bulk adhesive specimen used in section 2.1 is several hundred times larger than adhesive layer in volume, the adhesive layer is expected to yield a larger value of σ_0 than the former according to Eq.(1). On the other hand, the incorporation of moistures, gas, etc., adsorbed on the adherend surface into the small adhesive layer volume raises the moisture content and the number of defects per unit volume. They reduce σ_0 of the adhesive layer. As a result, in the present case of brittle adhesives which are sensitive to defects, the tensile

Fig. 8 Stress distributions in the vicinity of the adhesive layer free end with stress maxima (2)

Fig. 9 Maximum principal stress distributions at the interfaces of adhesive layers of butt joints

Fig.10 Stress distributions in the vicinity of the free end based on the boundary layer theory

strengths obtained with above tensile specimens are not appropriate ones to be used as σ_0 in Eq. (3) in a strict sense.

Accordingly, the calculated ratio of adhesive strength σ_y at any θ or h to the standard adhesive strength σ_{ys} , that is, $(\sigma_y/\sigma_{ys})_{cal}$ was employed instead of calculated value of adhesive strength $(\sigma_y)_{cal}$ based on Eq. (3), following the equation given below:

$$\left(\frac{\sigma_y}{\sigma_{ys}}\right)_{cal} = \left(\frac{\sigma_{ss}}{\sigma_a}\right) / \left(\frac{\sigma_s}{\sigma_a}\right) \dots\dots\dots (4)$$

Where, σ_{ys} is the adhesive strength at a standard angle in the cases of scarf joints, and that at a standard thickness in the case of butt joints. Similarly, σ_{ss} is σ_s at the standard θ or h . $(\sigma_y)_{cal}$ values were obtained by multiplying the observed σ_{ys} values $(\sigma_{ys})_{exp}$ by Eq. (4), given as Eq. (5).

$$(\sigma_y)_{cal} = \left(\frac{\sigma_y}{\sigma_{ys}}\right)_{cal} (\sigma_{ys})_{exp} \dots\dots\dots (5)$$

5.2 Adhesive strengths of scarf joints

σ_s values for σ_1 and σ_{eq} were obtained in the following three cases of $\delta = 0.001$ mm (the vicinity of the maximum stress point), 0.035 mm, and around $t/2$ (the area of uniform stress), using the results on the analysis given in Fig. 8. $\theta = 52.47^\circ$ was taken as the standard. The calculated $(\sigma_y)_{cal}$ values based on Eqs. (4) and (5) are shown in Fig. 3. σ_{1c} and σ_{eqc} values of Fig. 8 were adopted for σ_s at $\delta = t/2$. Since σ_1 values at $\theta = 90^\circ$ was smaller than σ_{1c} in the case of $\delta = 0.035$ mm, σ_{1c} was used in place of σ_s . The mean of the experimental values at $\theta = 45^\circ$ and 60° was taken for the $(\sigma_{ys})_{exp}$ at $\theta = 52.47^\circ$.

Figure 3 shows good agreement between

experimentally obtained and calculated values at $\delta = 0.035$ mm in the case of maximum principal stress (σ_1) criterion. The σ_1 values at $\delta = 0.035$ mm and at $\delta = t/2$ agree at most of the θ values except at $\theta = 15^\circ$ and 30° , showing a slight deviation. Therefore, calculated σ_y values have similar tendencies. That is to say, strongly stressed area are essentially included in the 0.035 mm-thick boundary layer. That is the reason why the calculated σ_y values in the case of $\delta = 0.001$ mm completely disagree with those experimentally obtained.

Similarly, the calculated σ_y values based on von Mises equivalent stress σ_{eq} , completely disagree with the experimental results.

5.3 Adhesive strengths of butt joints

σ_y was calculated with consideration of the boundary layer, employing the larger stress, i.e., either the stress on the body diagonal A'Q'L or that on the b-wide center line AQL shown in Fig. 9. Figure 9 suggests that non-uniform stress distribution effects become more pronounced at larger h values. Accordingly, δ was obtained such that calculated values best agree with the observed adhesive strengths in the cases of $h = 0.6, 1.0$, and 5.0 mm, by using $h = 1.0$ mm as the standard. It resulted in $\delta = 0.035$ mm, which is equal to the value of scarf joints. The calculated σ_y values are given in Fig. 5. The broken lines in the figure represent the calculated σ_y employing σ_{1c} , since stresses at $\delta = 0.035$ mm were smaller than σ_{1c} in the cases of $h = 0.1$ and 0.3 mm. The slope of the experimentally obtained line is slightly steeper than that of the calculated. This might be due to strength reduction

Fig. 11 Fracture surfaces of adhesive layers in scarf joints (12.7mm x 12.7mm, $h = 0.1$ mm)

induced in the experiment by the cracks in the adhesive layer represented with Eq.(1).

The boundary layer thickness of $\delta=0.035$ mm is smaller compared to those of mild steels⁽⁷⁾, marbles⁽¹¹⁾, glass ceramics⁽¹²⁾, and cast iron⁽¹³⁾, which are 0.30, 0.27, 0.11, and 2~4 mm, respectively. The amorphous nature of the epoxy resin with the three-dimensional network molecular structure might account for this discrepancy. Size of internal defects, lengths of branched molecular chains with free ends, etc., are considered determinative factors of δ values in the case of epoxy resin.

5.4 Observation of the fracture surfaces of the adhesive layer

Figure 11 is a representative adhesive layer fracture surface of scarf joints. Characteristic feather-like fracture surfaces are observed in the range of $\theta=15\sim75^\circ$. Microcracks⁽¹⁴⁾ account for this phenomenon as previously reported⁽¹⁰⁾. A crack forming vertical to the load direction (horizontal in Fig. 11) crossing the adhesion plane (denoted main crack hereinafter) is considered to initiate the fracture, and it occurred at the vicinity of free end (noted BB' in Fig. 7(c)) in most of the specimens at $\theta=15$ and 30° as shown in Fig 11. On the contrary, the cracks formed between the free ends in $\theta=45\sim75^\circ$ -specimens. This can be explained by the results

Fig. 12 Fracture surface of adhesive layer ($\theta=90^\circ$, 12.7mm x 12.7mm, h=0.1mm)

shown in Fig. 8. That is to say, the stress concentration ($\sigma_{1\max}/\sigma_{1c}$) at the free ends and proportions of the area in which stress is larger than σ_{1c} at $\theta=15$ and 30° are larger than those at $\theta=45\sim75^\circ$. In the cases of joints at $\theta=45\sim90^\circ$, σ_1 values at $\delta=0.035$ mm from the free end are mostly equivalent to σ_{1c} . Joints at $\theta=45\sim75^\circ$ partly exhibit parabolic fracture figures⁽¹⁵⁾⁽¹⁶⁾.

Figure 11(f) shows a fracture initiating miller region⁽¹⁵⁾⁽¹⁶⁾ close to the interface near the corner of adhesion plane (lower left) in most of the $\theta=90^\circ$ -specimens. Irregular lines⁽¹⁵⁾⁻⁽¹⁷⁾ radially spread out from the miller region, which leads to rough planes. Small roundshaped fracture nuclei⁽¹⁸⁾ are observed not only in the free ends, but also many in the inside. Particular samples, such as those shown in Fig. 12, formed the main fracture nucleus⁽¹⁸⁾ near the center of the adhesion plane.

Figure 13 illustrates scanning electron microscope observations of scarf joint-fracture surfaces. 15° ① and ② correspond to feather-like fracture region of Fig. 11(a). Fine particles of adhesive remain on the steel surface, which were yielded by microcracks. 45° ① shows the vicinity of main crack in Fig. 11(c). Dark parts correspond to adhesive layers, where the crosssectional plane in the thickness direction is observed. Islands and particles of adhesive layers produced by fractures spread out from the plane. 45° ② exhibits a white, obscure part in the lower-right of Fig. 11(c), which indicates an intrusion of the adhesives into the polished streaks, showing fine particles of adhesive attached on the surface. Dark island-like adhesive layer is shown in 90° ①, with round fracture nucleus at the center and surrounded by many smaller nuclei scattered. 90° ② is a magnification of the right end of 90° ①. Adhesives penetrated well and remain in the polish streaks of the steel.

Fig. 13 SEM photographs of fracture surfaces of adhesive layers in scarf joints

Fig. 14 Fracture surfaces of adhesive layers in butt joints (12.7mm x 12.7mm)

Figure 14 exhibits the fracture surfaces of butt joints in the range of $h=0.3\sim 5.0$ mm. In analogy with the case of $h=0.1$ mm shown in Fig. 11(f), fracture initiates close to the interface near the corner of adhesion plane in either cases and irregular lines follow miller region, but, fracture initiation occurs only in the vicinity of the corner.

The above results testify that fracture points and morphologies approximately agree with the predicted results when applying the boundary layer theory to the stress analysis.

6. Conclusions

The adhesive tensile strengths of scarf angle-varied scarf joints and adhesive layer thickness-varied butt joints were measured for the investigation of fracture criterion for adhesive joints using a brittle adhesive. Three-dimensional finite element analysis was further performed on the joints, and the adhesive strengths were calculated by applying the boundary layer theory. Following conclusions are derived by comparison of calculated and observed values.

(1) Quantitative explanation of experimentally obtained results was nearly successful by taking the 0.035mm-thick boundary layer δ in the adhesive layer free end into account, in both cases of scarf and butt joints.

(2) Fractures in the adhesive layers of both joints occur under the maximum principal stress condition.

(3) Most of the stress concentrated areas in the vicinity of adhesive layer free end are included in the $\delta=0.035$ mm-boundary layer in the case of scarf joint (with 0.1 mm-thick adhesive layer).

(4) Microscope and SEM observations of fracture regions and of their morphologies verified the results predicted from stress analysis and boundary layer theory.

Finally, the author deeply thanks Professor Masaichiro Seika of the Faculty of Engineering, Nagoya University, who encouraged him to carry out this study. The author also wishes to express his gratitude to Mr. Ikuo Iwase, General Manager, Mr. Toshihiko Taniguchi, General Manager, and Dr. Ren Obata, General Manager of Research and Development Department, Nippon Sharyo Seizo Co. who supported and leaded him in this study, and as well as to Mr. Tsutomu Matsumoto,

Manager of the same Dept. for cooperation to take SEM photographs of fracture surfaces and to the members of Computer Center of the same company for the calculation by ACOS 77 Model 550.

References

- (1) Lubkin, J.L., Trans. ASME, J. Appl. Mech., Vol. 24(1957), P.255.
- (2) Yamaguchi, Y., et al., Res. Rep. Kogakuin Univ. (in Japanese), No.30(1971), p.66.
- (3) Masuoka, M. and Nakao, K., J. Adhesion Soc. Jpn. (in Japanese), Vol.14, NO.4 (1978-4), P.125.
- (4) Sugibayashi, T., et al., J. Adhesion Soc. Jpn. (in Japanese), Vol.14, No.5(1978-5), p.167.
- (5) Matsumoto, J., et al., J. Adhesion Soc. Jpn. (in Japanese), Vol.14, No.8(1978-8), p.288.
- (6) Suzuki, Y., Trans. Jpn. Soc. Mech. Eng. (in Japanese), Vol.50, A, No.449 (1984-1), p.67.
- (7) Nakanishi, F., et al., Jpn. Soc. Mech. Eng. (in Japanese), Vol. 19, No.87 (1953-1), p.14.
- (8) Weibull, W., Ing. Vetenskaps Akad. Handl., No.151 (1939); No.153(1939).
- (9) Yokobori, T., Zairyo Kyōdogaku (in Japanese), (1966), p.86, Gihōdō.
- (10) Suzuki, Y., et al., J. Adhesion Soc. Jpn. (in Japanese), Vol. 18, NO.1 (1982-1), p.7.
- (11) Sato, Y. and Sakurai, Y., Trans. Jpn. Soc. Mech. Eng. (in Japanese), Vol.43, No.374 (1977-10), p.3702.
- (12) Sasaki, Y., et al., Trans. Jpn. Soc. Mech. Eng. (in Japanese), Vol.44, No.388 (1978-12), p.4024.
- (13) Noguchi, T., J. Soc. Mater. Sci., Jpn. (in Japanese), Vol.28, No.307 (1979-4), p.306.
- (14) Bascom, W. D., et al., J. Mater. Sci., Vol.10 (1975), p.1037.
- (15) Wollock, I. and Newman, S.B. (ed. Rosen, B.), Fracture Processes in Polymeric Solids, (1964), p.237, John-Wiley & Sons.
- (16) Ueda, Y., et al., Trans. Jpn. Soc. Mech. Eng. (in Japanese), Vol.44, NO.378 (1978-2), p.433.
- (17) Narisawa, I. and Ogawa, H., Prepr. of Jpn. Soc. Mech. Eng. (in Japanese), No.801-1(1980-6), p.62.
- (18) Narisawa, I., et al., Kobunshi Ronbunshu (in Japanese), Vol.36, No.8 (1979-8), P.543.