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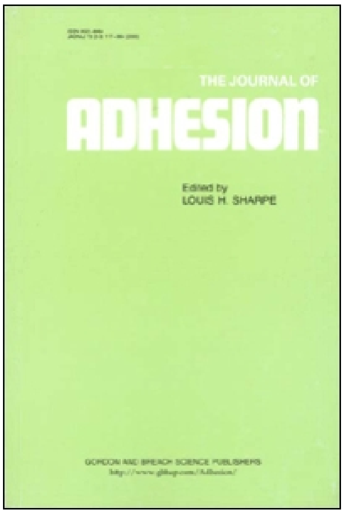

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Development of a Fatigue Failure Model for the Adhesively Bonded Tubular Single Lap Joint under Dynamic Torsional Loading

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The adhesively bonded tubular single lap joint shows nonlinear torque transmission capability and deformation characteristics under static torsional loading because of nonlinear properties of the adhesive. However, the dynamic or fatigue torque transmission capability can be calculated with linear. analysis because the stress-strain relation under torsional fatigue loading is linear, due to the small dynamic transmission capability compared with the static torque transmission capability.

In this paper, a failure model for the adhesively bonded tubular single lap joint under torsional fatigue loading was developed with respect to the adhesive thickness, which is the critical factor for the static torque transmission capability. Also, a design method for the adhesively bonded tubular single lap joint under torsional fatigue loading was proposed.

KEY WORDS: Adhesively bonded tubular lap joint; analytical solution; dynamic torsional loading; fatigue failure model; thermally-induced residual stresses; applied peak stresses; shear stress distribution; effect of adhesive thickness on fatigue.

INTRODUCTION

Epoxy adhesives used in joining of mechanical elements are usually rubber-modified to increase toughness and they are nonlinear in characteristics. Therefore, structures assembled by bonding with these adhesives also have nonlinear properties and the exact solutions for load transmission capability of the structures can not be easily obtained. The exact solutions of the adhesively bonded joints were only possible if the assumption of linear elastic behavior of the adhesive and the adherend was made.

Much research on adhesive joints was performed after Adams[1] obtained the elastic solution of the adhesively bonded tubular single lap joint. The time-dependent viscoelastic behavior of the adhesive was included in the investigation of the adhesively bonded joint by Alwar and Nagaraja.[2] The torque transmission capabilities of the partially-tapered tubular scarf joints were investigated by Adams and Peppiatt.[1] The behaviors of the adhesively bonded joints with adherends made of composite materials were investigated by several researchers.[3,4,5] Different types of adhesively bonded

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joints such as the single lap, the double lap, the scarf, and the stepped lap joint were analyzed by Hart-Smith.[6] The effects of the adhesive thickness and adherend roughness on the torsional fatigue strength of the adhesively bonded tubular single lap joint were investigated by Lee *et al.*[7] The failure model for the adhesively bonded tubular single lap joint was developed by Lee and Lee.[8] The closed-form solution for the torque transmission capability of the adhesively bonded tubular double lap joint with linear elastic properties of the adhesive and the adherend was derived by Lee and Lee.[9] The static and fatigue strengths of adhesively-bonded tubular polygonal lap joints were experimentally investigated by Choi and Lee.[10] The effect of the design parameters for the adhesively-bonded tubular single lap joint, such as the thickness of adhesive layer and adherends and the bonding length, on the torque transmission capability was investigated.[11]

In spite of such numerous investigations on adhesively bonded joints, the simple linear elastic solution developed by Adams[1] that underestimates the torque transmission capability is usually used in the first stage of design of such joints because it is simple and reveals the design parameters.

Although adhesively bonded joints under static torque can be designed using finite element methods which can incorporate the material nonlinearity of adhesive, the fatigue characteristics of adhesively bonded joints are indispensable because adhesively bonded joints are usually used under dynamic loading conditions.

In this paper, the torsional fatigue life of adhesively bonded tubular single lap joints under several torque levels was measured. With the measured fatigue life, a failure model for adhesively bonded tubular single lap joints under torsional fatigue loadings was developed, using a nondimensional parameter that incorporates both the geometry and material properties of the joint.

Using the developed failure model, a design method for the adhesively bonded tubular single lap joint under torsional fatigue loadings was proposed.

EXPERIMENTS

In order to investigate the effect of the adhesive thickness on the fatigue torque transmission capability of the adhesively bonded tubular single lap joint, fatigue torsional specimens consisting of steel-steel adherends and a rubber-toughened epoxy adhesive were prepared. The adhesive used was a rubber-toughened epoxy (IPCO 9923 manufactured by Imperial Polychemicals Corporation, Azusa, California, U.S.A.). The fatigue life of the specimens was measured under several torque levels. Then the torque levels were changed into peak shear stresses in the adhesive layer.

Figure 1 shows the configuration of the adhesively bonded tubular single lap joint under torsional fatigue loading. The dimensions of the female adherend were fixed but the outer diameter of the male adherend was varied to adjust the adhesive thickness. The bonding length of the adhesive was fixed at 15 mm.

Both the mounting surfaces of the female and male adherends were machined accurately with a lathe to be used as the reference surfaces during the bonding operation. The mounting surfaces were clamped on an accurate V-block during the curing operation of the joint. The arithmetic surface roughness of the bonded area was

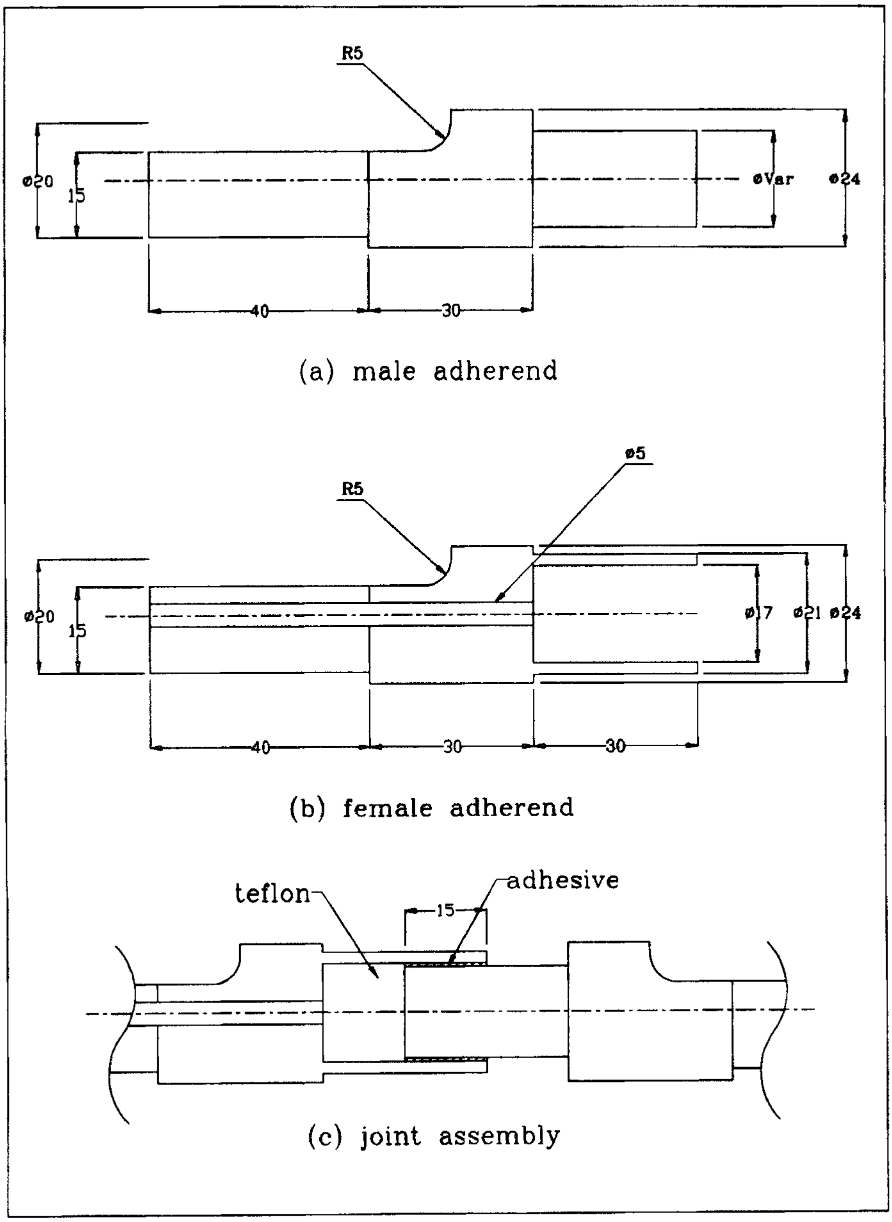

FIGURE 1 Configuration of the adhesively bonded tubular single lap joint used for the measurement of fatigue life.

controlled around 2 μm by abrading with 80 mesh abrasive paper, because it was revealed in earlier studies that the maximum torque transmission capability of the tubular single lap joint under cyclic load was obtained around 2 μm arithmetic surface roughness.[7] The bonding operation was performed at a temperature of 80°C for

3 hours in an autoclave and 0.4 MPa pressure was applied to the air in the autoclave during the bonding operation.

The effect of adhesive thickness on the S-N curve of the adhesively bonded tubular single lap joint was measured under controlled loading conditions. The fatigue tester used was a TB-10B manufactured by Shimadzu (Japan). The frequency of cyclic loading of the tester was 33 Hz and the amplitude of torque was 50 N·m. The environmental temperature of the adhesively bonded joint during the experiment was maintained at 30°C to eliminate external temperature effects on the fatigue characteristics.

Table I shows mechanical properties of the adherend and the adhesive.

Figure 2 shows the shear stress *vs.* shear strain curve of IPCO 9923, a rubber-toughened epoxy adhesive. The adhesive shows highly nonlinear behavior beyond 20 MPa shear stress; however, the shear stress-strain relation may be approximated linearly under 20 MPa shear stress.

Therefore, if the joint fails at a shear stress larger than 20 MPa, the adhesive joint should be analyzed using the entire shear stress-shear strain curve to obtain accurate torque transmission capabilities. However, if the shear stress of the joint does not exceed 20 MPa, which is the case of the adhesive joint under fatigue loading, because the torque transmission capability under fatigue loading is usually very small compared with that under static loading, linear analysis of the adhesively bonded joint under fatigue loading is possible.

RESULTS

It has been shown that the thermally-induced residual stresses in the adhesive must be considered in calculating the static torque transmission capability of the adhesively bonded tubular single lap joint, because the static failure mode of the joint changes from adhesive bulk failure to interfacial failure according to the magnitude of the residual stress.[8]

Through a procedure similar to that for the static analysis, in this work a fatigue failure model of the adhesively bonded tubular single lap joint was proposed taking into account the effect of the residual stresses in the adhesive on the S-N curve of the joint.

TABLE I
Material properties of the adherend and the adhesive

	Adherend (Steel)	Adhesive (IPCO 9923)
Tensile modulus (GPa)	210	1.3
Poisson's ratio	0.3	0.41
Tensile strength (MPa)	–	45
Shear strength (MPa)	–	29.5
Coefficient of thermal expansion	11.7×10^{-6}/°C	72×10^{-6}/°C
Cure temperature		80°C
Cure time		3 hours

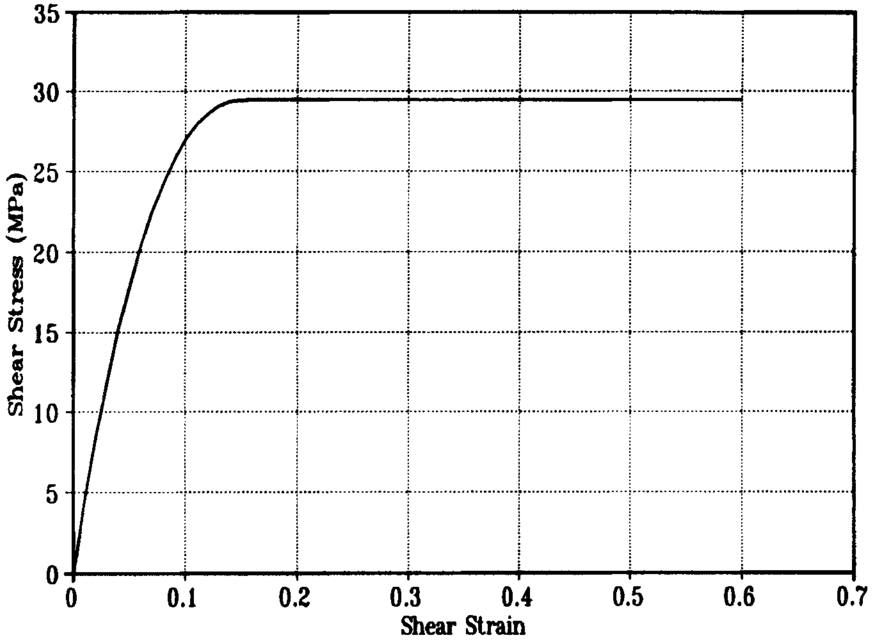

FIGURE 2 Shear stress and strain curve of the rubber-toughened epoxy adhesive, IPCO 9923.

Several assumptions were made in deriving the fatigue failure model: a linear relation between the shear stress-shear strain in the adhesive, and a linear semi-logarithmic relation of the S-N curve with two constants that were dependent on the thermally-induced residual stresses in the adhesive.

Figure 3 shows the number of fatigue failure cycles of the adhesively bonded tubular single lap joint with respect to the adhesive thickness under 4 MPa average shear stress. The average shear stress was calculated by dividing the applied torque by the adhesive area.

Although Figure 3 shows a linear semi-logarithmic relation between the number of cycles to failure and the adhesive thickness, a failure model should be derived based on the local shear stress and strain because the average shear stress in the adhesive is not the actual shear stress distribution in the adhesive.

Figure 4 shows the specification of the adhesively bonded tubular single lap joint for the derivation of the failure model.

To obtain the shear stress distribution in the adhesive area of the bonded joint under torque, the Adams' analytic solution[1] was modified and used. Since the shear stress in the adhesive varies along the adhesive thickness and the highest shear stress in the adhesive occurs at the outer radius of the male adherend, the outer radius of the male adherend was selected as the adhesive radius in the shear stress calculation. Then, the shear stress in the adhesive layer under torque is expressed by the following equations:

$$\tau_a = \frac{T\alpha}{2\pi a^2}\left[\left\{\frac{1-\psi(1-\cosh(\alpha L))}{\sinh(\alpha L)}\right\}\cosh(\alpha z) - \psi \sinh(\alpha z)\right] \tag{1}$$

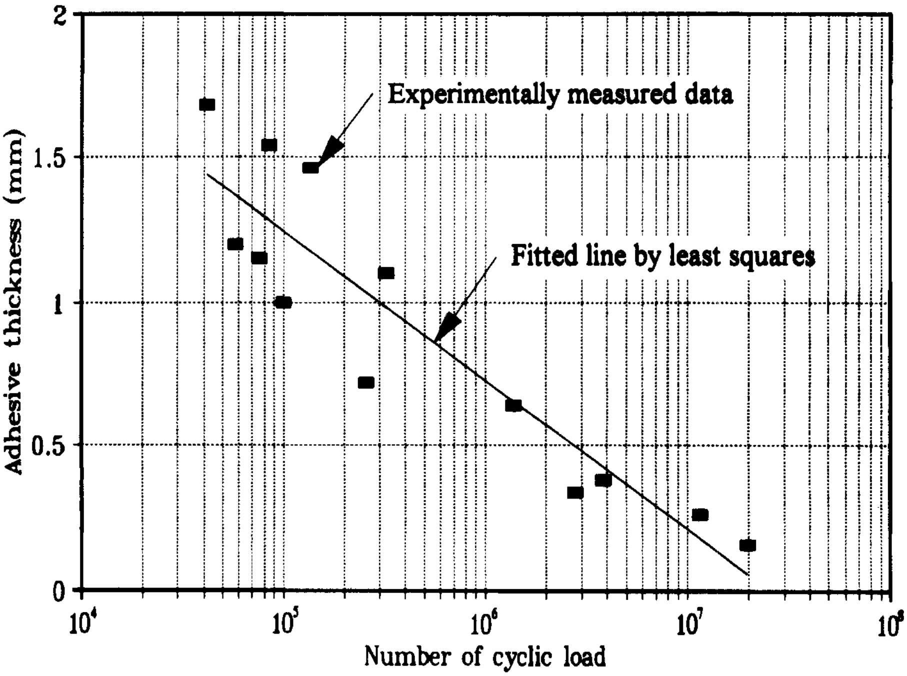

FIGURE 3 Fatigue failure cycles *vs.* adhesive thickness when the average shear stress was 4.0 MPa.

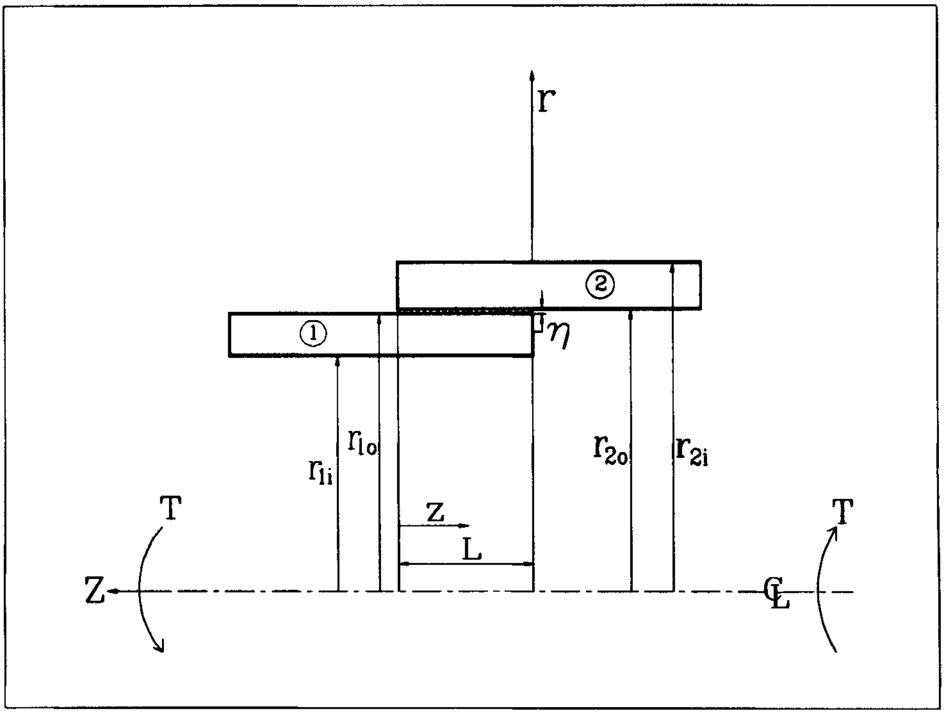

FIGURE 4 Schematic diagram of the adhesively bonded tubular single lap joint.

where,

$$a = r_{1o}$$

$$\delta = \frac{2\pi a^2 r_{2o} G_a}{G_2 J_2 \eta}$$

$$\psi = \frac{G_1 J_1 r_{2o}}{G_1 J_1 r_{2o} + G_2 J_2 r_{1i}}$$

$$\alpha = \sqrt{\frac{\delta}{\psi}}$$

G_a, G_1, G_2 = shear moduli of the adhesive, adherend 1 and adherend 2, respectively
J_1, J_2 = polar moments of inertia of adherend 1 and adherend 2, respectively.

Figure 5 shows the shear stress distribution in the adhesive layer when the applied average shear stress was 4.0 MPa. In Figure 5, the shear stresses at the ends of adhesive increased rapidly when the adhesive thickness was less than 0.1 mm. Therefore, it is clear that the fatigue failure analysis should be based on the local shear stress rather than on the average shear stress.

The stress deviation factor introduced by Lee and Lee[8] is the nondimensional parameter for predicting the failure mode of the adhesively bonded tubular single lap

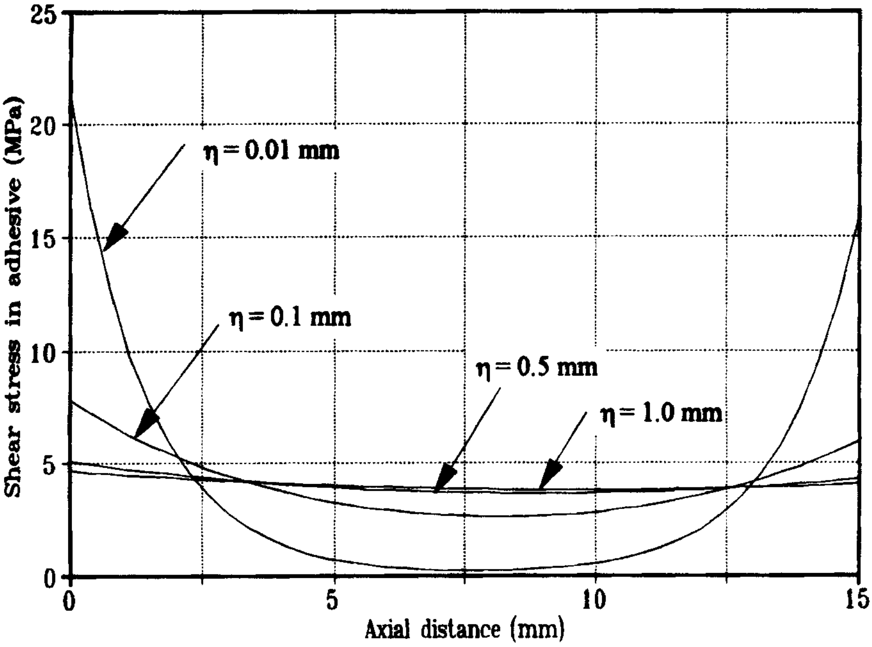

FIGURE 5 Shear stress distributions in the adhesive layer of the adhesive joint under the same average shear stress, 4.0 MPa, when the adhesive thickness, η, is 0.01, 0.1, 0.5, and 1.0 mm.

joint under static torsional loading. In order to calculate the stress deviation factor, k_t, that represents the effect of the residual thermal stress due to fabrication on the adhesive failure shear strength, the reduced shear strength, S_a, was calculated using finite element analysis, incorporating the thermally-induced residual stresses in the adhesive as follows:

$$S_a = S_s\sqrt{1-\left(\frac{\sigma_r}{S_t}\right)^2-\left(\frac{\sigma_\theta}{S_t}\right)^2-\left(\frac{\sigma_z}{S_t}\right)^2-\left(\frac{\tau_{rz}}{S_s}\right)^2} \tag{2}$$

where,

S_t = bulk tensile strength of the adhesive
S_s = bulk shear strength of the adhesive

The reduced shear strength of the adhesive, S_a, was used to take into account the thermally-induced residual stress originating from the temperature difference between the elevated curing temperature and room temperature. Then, the stress deviation factor, k_t, was calculated using the reduced shear strength and the shear strength of the adhesive as follows:

$$k_t = \frac{S_s - S_a}{S_s} \tag{3}$$

The stress deviation factor, k_t, is 0 when there is no residual thermal stress due to fabrication and increases as the fabrication-induced residual thermal stress increases. Figure 6 shows the peak shear stress in the adhesive and the stress deviation factor with respect to the adhesive thickness when the average shear stress was 4.0 MPa.

Figure 7 shows the number of cyclic loadings to failure of the adhesively bonded tubular single lap joints with respect to the applied peak shear stress in the adhesive when the adhesive thickness was 0.1, 0.2, 0.5 and 1.0 mm.

From the results of Figure 7, the number of the cycles to failure, N_f, of the adhesively bonded joint was represented in terms of the applied peak shear stress, τ_p, in the adhesive as follows:

$$A\cdot\tau_p + B = \log_{10}(N_f) \tag{4}$$

The constants A and B can be calculated from the results of Figure 7. Since the values of A and B vary as the adhesive thickness changes, the constants A and B were obtained in terms of the stress deviation factor.

Figure 8 shows the coefficient A in Equation (4) which was fitted to a linear equation with respect to the stress deviation factor of the joint as follows:

$$A = -1.29\cdot k_t - 0.157 \tag{5}$$

Figure 9 shows the coefficient B in Equation (4) which was fitted to a linear equation with respect to the stress deviation factor of the joint as follows:

$$B = -6.38\cdot k_t + 8.19 \tag{6}$$

Since the coefficients A and B can be obtained from Equations (5) and (6) when the stress deviation factor is calculated, Equation (4) represents a failure model to predict

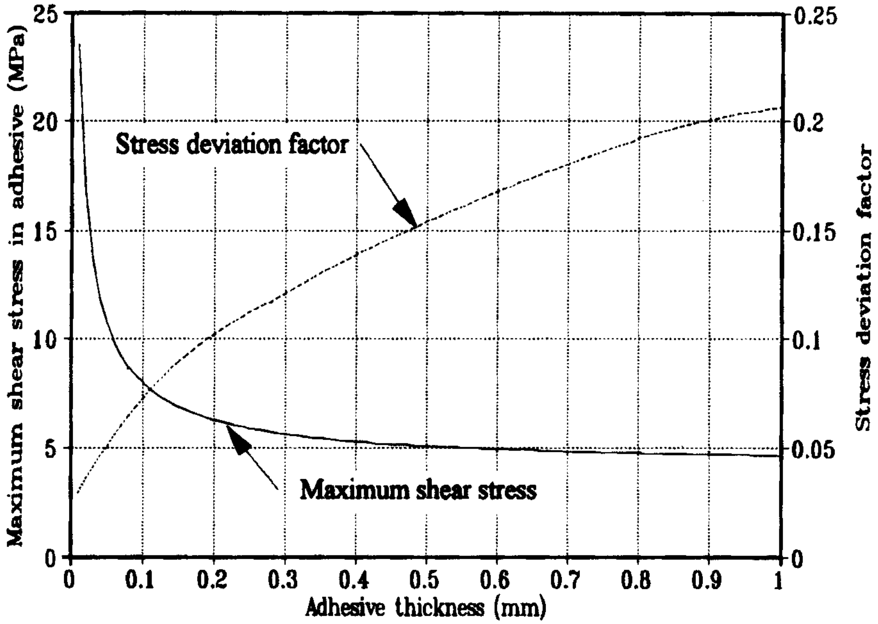

FIGURE 6 Peak shear stress in the adhesive and the stress deviation factor *vs.* the adhesive thickness when the average shear stress was 4.0 MPa.

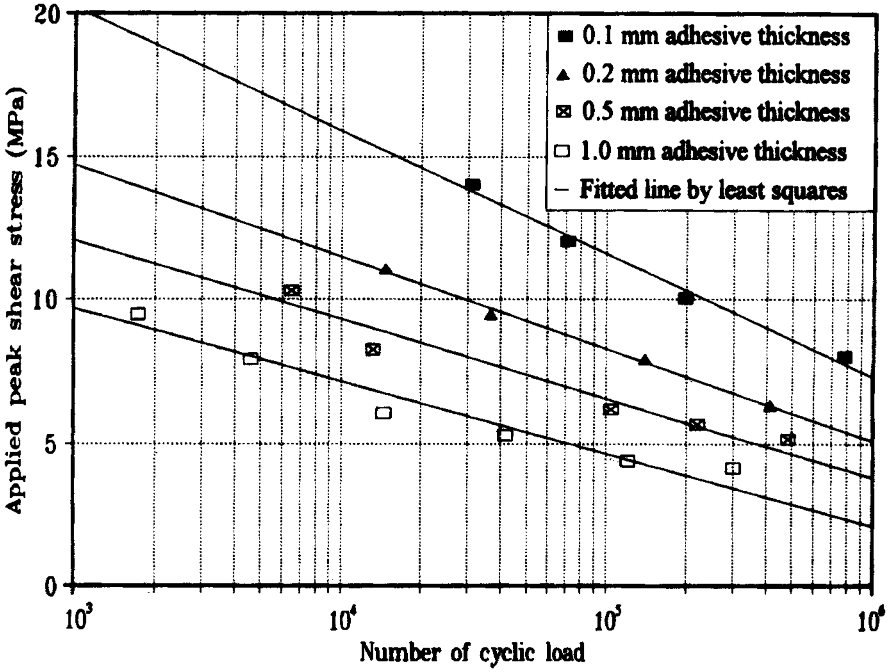

FIGURE 7 Number of cyclic loadings to failure *vs.* the applied peak stress. (k_t is the stress deviation factor).

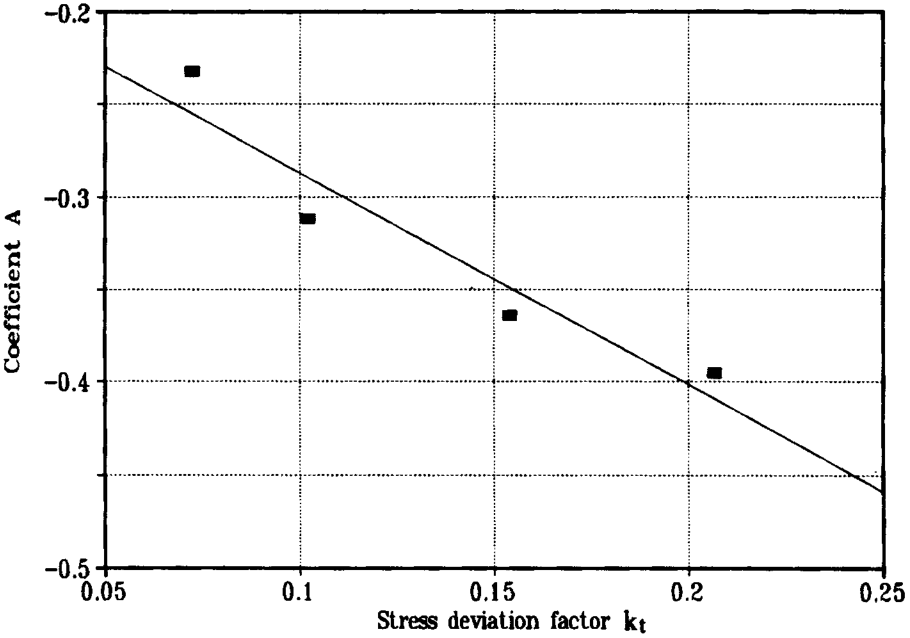

FIGURE 8 Value of A vs. the stress deviation factor, k_t.

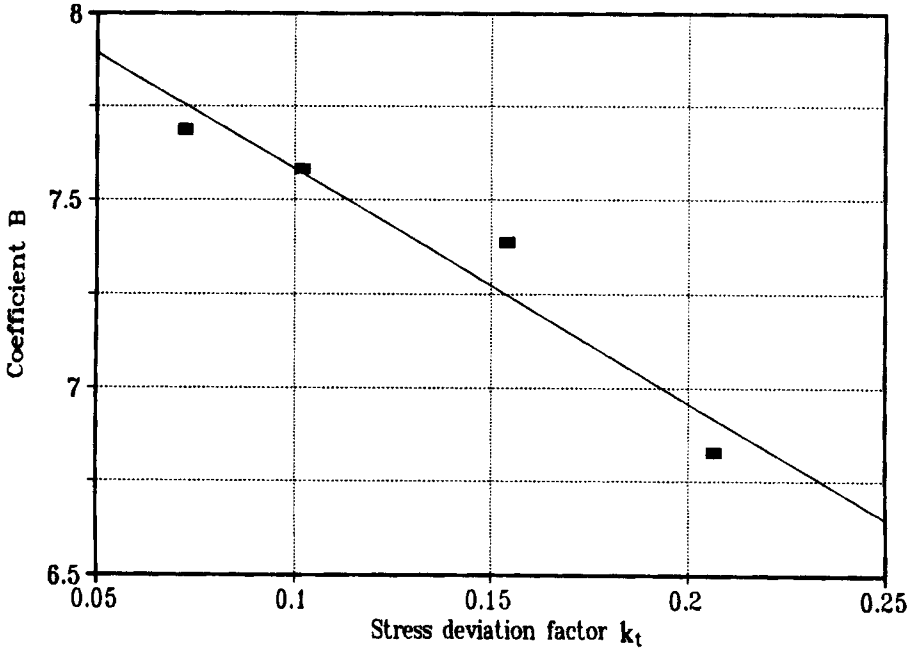

FIGURE 9 Value of B vs. the stress deviation factor, k_t.

the number of the cycles to failure of the adhesively bonded joint. Equation (4) takes into consideration the residual thermal stress in the adhesive which is an important factor of the adhesively bonded joint.

In order to apply the fatigue failure model for the design of the adhesively bonded tubular single lap joint under cyclic fatigue loading, several parameters such as the joint size, the material properties of the adherends and the adhesive, and the temperature difference between the curing temperature and room temperature are necessary. In general, several parameters must be defined from the specifications of the joint, and the others can be adjusted to maximize the performance of the adhesively bonded joint using the fatigue failure model.

Figure 10 shows an example of the application of the fatigue failure model for the determination of the optimum adhesive thickness. In Figure 10, the number of cycles to failure of the adhesively bonded joint was calculated using the fatigue failure model with respect to the adhesive thickness when the applied fatigue loads were 10, 20, 30, 40, and 50 N·m.

Although the thermally-induced residual stresses in the adhesive were very low when the adhesive thickness was very small, the failure of the adhesively bonded joint occurred early because the shear stress concentration at the ends of the adhesive was very high. When the adhesive thickness was very large, the failure of the joint also occurred early, in spite of the low stress concentration, because the thermally-induced residual stresses in the adhesive were very large. Therefore, the adhesive thickness must

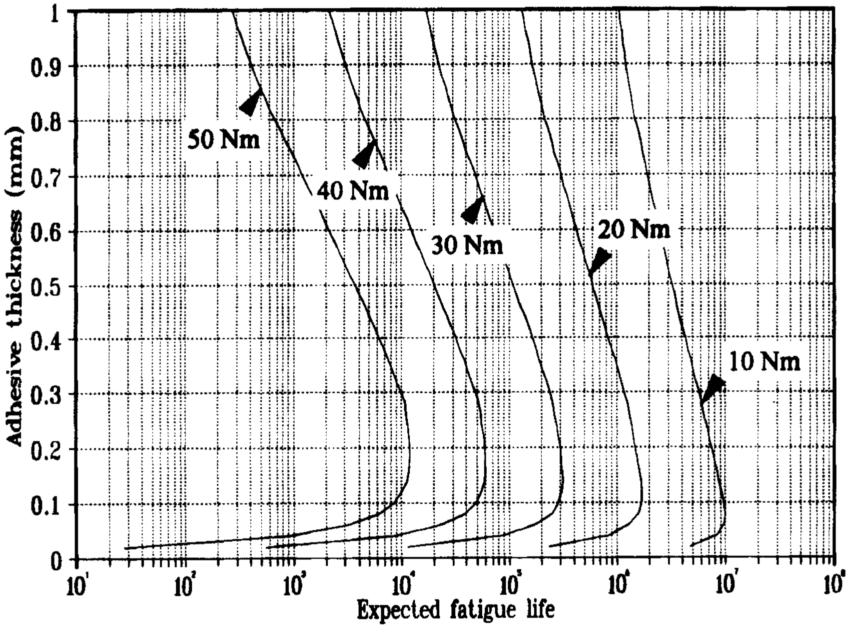

FIGURE 10 Calculated fatigue life *vs.* the adhesive thickness for applied torques of 10, 20, 30, 40, and 50 N·m.

be optimized to minimize both the thermally-induced residual stresses and peak shear stresses in the adhesive for the improvement of the fatigue life of the bonded joint.

From the calculation, it was found that when the applied fatigue load was relatively low, such as 10 or 20 N·m, the optimum adhesive thickness to maximize the fatigue life was 0.1 mm. As the applied fatigue load increased to 40 and 50 N·m, the optimum adhesive thickness changed to 0.2 mm. Using data such as those in Figure 10, the optimum adhesive thickness can be selected if the amplitude of the applied torque is known.

Figure 11 shows another example of the application of the fatigue failure model for the determination of the optimum bonding length. In Figure 11, the number of cycles to failure of the bonded joint was calculated using the fatigue failure model with respect to the bonding length when the adhesive thickness was 0.2 mm and the applied fatigue loads were 10, 20, 30, 40, and 50 N·m.

From the calculation, it was found that the fatigue life increased and saturated to a limit as the bonding length increased. When the applied fatigue load was relatively low, such as 10 or 20 N·m, the optimum bonding length for the fatigue life and efficiency of the adhesively bonded joint was 20 mm. As the applied fatigue load was increased to 40 and 50 N·m, the optimum bonding length was changed to 30 mm. Using data such as those in Figure 11, the optimum bonding length can be selected if the amplitude of the applied fatigue load is known, which is a kind of fatigue design method for the adhesively bonded tubular single lap joint. This method also makes it possible to determine the optimum dimensions of the adhesively bonded joint.

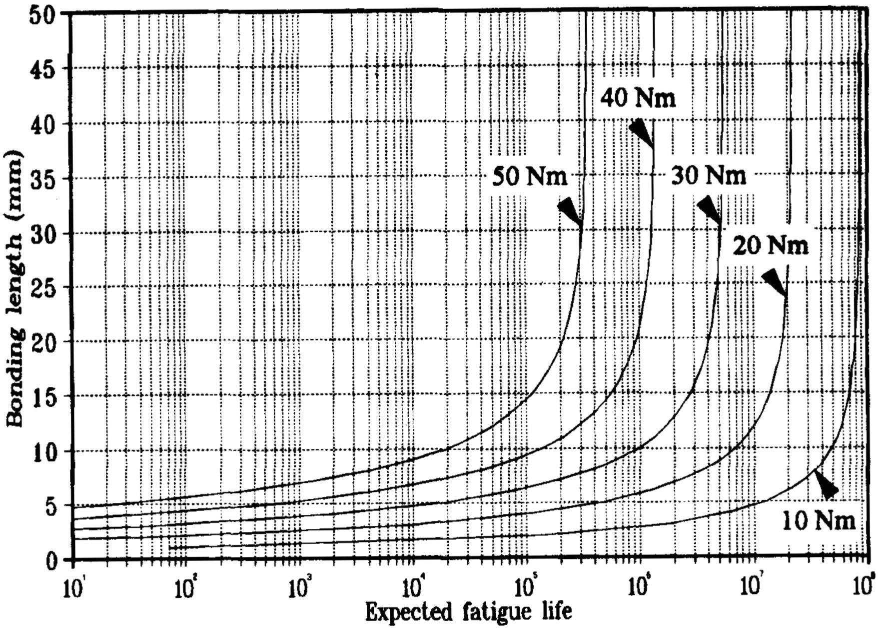

FIGURE 11 Calculated fatigue life *vs.* bonding length for an adhesive thickness of 0.2 mm and applied torques 10, 20, 30, 40, and 50 N·m.

CONCLUSIONS

Since the thermally-induced residual stresses and the peak shear stresses in the adhesive are dependent on the adhesive thickness and the applied torque, the number of cycles to failure of the adhesively bonded tubular single lap joint under cyclic torque was measured with respect to the adhesive thickness and the applied torque.

Using the measured S-N curve, a fatigue failure model for the adhesively bonded tubular single lap joint was developed in terms of the applied peak shear stresses and the thermally-induced residual stresses in the adhesive of the joint.

Also, a design method for the adhesively bonded tubular single lap joint was proposed.

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