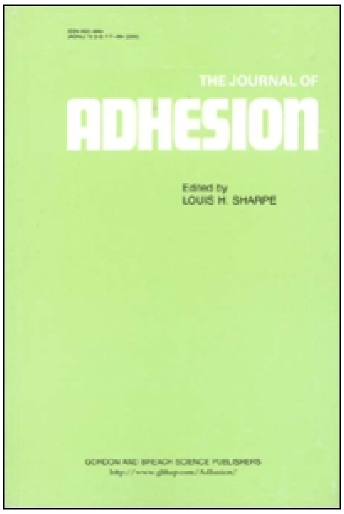

The Journal of Adhesion
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713453635

Optimal Design of the Adhesively-Bonded Tubular Single Lap Joint

Su Jeong Lee[a]; Dai Gil Lee[a]
[a] Department of Mechanical Engineering, Korea Advanced Institute of Science and Technology, Yusong-gu, Taejon-shi, Korea

To cite this Article Lee, Su Jeong and Lee, Dai Gil(1995) 'Optimal Design of the Adhesively-Bonded Tubular Single Lap Joint', The Journal of Adhesion, 50: 2, 165 — 180
To link to this Article: DOI: 10.1080/00218469508014364
URL: http://dx.doi.org/10.1080/00218469508014364

J. Adhesion, 1995, Vol. 50, pp. 165–180
Reprints available directly from the publisher
Photocopying permitted by license only

Optimal Design of the Adhesively-Bonded Tubular Single Lap Joint

SU JEONG LEE and DAI GIL LEE

Department of Mechanical Engineering, Korea Advanced Institute of Science and Technology, Kusong-dong, Yusong-gu, Taejon-shi, Korea 305–701

(Received December 13, 1993; in final form January 19, 1995)

In this paper, a method for the optimal design of the adhesively-bonded tubular single lap joint was proposed based on the failure model of the adhesively-bonded tubular single lap joint. The failure model incorporated the nonlinear mechanical behavior of the adhesive as well as the different failure modes in which the adhesive failure mode changed from bulk shear failure, *via* transient failure, to interfacial failure between the adhesive and the adherend, according to the magnitudes of the residual thermal stresses induced by fabrication.

The effects of the design parameters for the adhesively-bonded tubular single lap joint, such as the thicknesses of adhesive layer and adherends, the bonding length, and the scarfs of adherends, on the torque transmission capability and the efficiency of the adhesive joint were investigated.

KEY WORDS: adhesion; adhesively bonded tubular single lap joint; adhesive failure model; bulk failure mode; transient failure mode; interfacial failure mode; nonlinear mechanical behavior; residual thermal stress; optimal design; design variable; torsional strength; torque transmission capability.

INTRODUCTION

The mechanical joint is widely used in joining of conventional isotropic materials such as steel and aluminum because the stress concentration of the mechanical joint can be lessened due to the plastic deformation of the materials before fracture. However, the stress concentration in the mechanical joint for fiber-reinforced composite materials is usually much larger, due to the elastic behavior of the composite materials with little plastic deformation before fracture. Moreover, the anisotropic behavior of the material increases the stress concentration at the holes for the bolts and rivets of the mechanical joints. Therefore, the adhesively-bonded joint is more preferable to the mechanical joint in the joining of fiber-reinforced polymer composite materials because it enables the distribution of the applied load over a larger area than the mechanical joint, requires no hole, adds very little weight to the structure, and has superior fatigue resistance although it requires careful surface treatment of the adherends, is affected by service environments, and is difficult to disassemble for inspection and repair. The stress concentration of the adhesively-bonded joint can be further reduced if the adhesive is rubber-toughened because it has large plastic deformation before fracture.

There are several types of adhesively-bonded joints, such as the single lap joint, the double lap joint, the stepped lap joint, and the scarf joint. Among these, the single lap joint is most popular, due to its ease of manufacture and relatively low cost. However, linear elastic stress analysis of the single lap joint reveals that it produces relatively high stress concentration in the end region of the adhesive and, consequently, low load transmission capability.

There has been much research on adhesively-bonded joints. Alwar and Nagaraja[1] incorporated the time-dependent properties of the adhesive into the finite element analysis. Adams and Peppiatt[2] analyzed adhesively-bonded tubular lap joints which were subjected to axial and torsional loads using the finite element method when the adhesive had a fillet. Chon[3] analyzed the adhesively-bonded single lap joint whose adherends were made of composite materials. Hipol[4] analyzed a tubular lap joint comprised of a steel tube which was adhesively-bonded to a composite tube and subjected to torsion. Graves and Adams[5] used a finite element method to calculate the stresses in a tubular single lap joint whose adherends were orthotropic composite material subjected to torsion. Hart-Smith[6] analyzed several adhesively-bonded joints such as the double lap, the single lap, the scarf, and the stepped lap joint and developed computer software for the analysis. Lee *et al.*[7] experimentally investigated the effect of the adhesive thickness and the roughnesses of the adherends on the torsional fatigue strengths of adhesively-bonded tubular single lap joints. Lee and Lee[8] developed a failure model for the adhesively-bonded tubular single lap joint. The failure model incorporated the nonlinear behavior of the adhesive and the different failure modes in which the adhesive failure mode changed from the bulk shear failure, *via* transient failure, to interfacial failure between the adhesive and the adherends, according to the magnitudes of the residual thermal stresses due to fabrication.

Although there have been such many analyses on adhesively-bonded joints, they could not predict accurately the torque transmission capabilities of adhesively-bonded tubular single lap joints. The calculated elastic results usually under-predict the experimentally-measured torque transmission capabilities because of the assumed elastic behavior of the adhesive. In reality, some region of the adhesive is usually under plastic deformation if the adhesive is rubber-toughened. Therefore, it is not correct to conclude that the torque transmission capability of the single lap joint is inferior to that of the adhesively-bonded double lap joint. In other words, the single lap joint may have equally high torque transmission capability based on the bonding area in addition to the ease of manufacture and cost reduction if the joint is properly designed to exploit the nonlinear properties of the adhesive.

In this paper, the effects of joint parameters such as the thicknesses of the adhesive and the adherends, the bonding length and the scarf on the torque transmission capabilities of the adhesive joints, and the efficiency of the stress transmission per unit adhesive area, were investigated by using the developed failure model of the adhesively-bonded tubular single lap joint.[8] Using the failure model, a method for the optimal design of the torque transmission capabilities of the adhesively bonded tubular single lap joint was suggested.

FAILURE MODEL FOR THE ADHESIVELY-BONDED TUBULAR SINGLE LAP JOINT

A failure model[8] was developed to calculate the static torque transmission capability of the adhesively-bonded tubular single lap joint. In the failure model, two kinds of failure modes of the adhesively-bonded tubular single lap joints under torsion were assumed.

In one mode, there was good bonding between the surfaces of the adhesive and the adherends which made the joint very stable under torsion when the residual thermal stresses due to fabrication were small compared with the bulk strength of the adhesive. In this case, adhesive failure occurred after the shear strain increased far beyond the yield shear strain of the adhesive. Since the shear stress of the rubber-toughened adhesive usually does not increase after yielding, *i.e.*, the adhesive is perfectly plastic, the shear stress begins to saturate from the ends of the adhesive because the ends of the adhesive have maximum strains. Therefore, it was assumed that the failure of the adhesive occurred when an end region of the adhesive reached the failure strain of the adhesive. If all regions of the adhesive were in the plastic range and yet the ends of the adhesive did not reach the failure strain, the torque transmission capability of the joint could be calculated simply by multiplying the bulk shear strength of the adhesive, the adhesive area and the mean radius from the joint axis. If the end region of the adhesive reached the failure strain of the adhesive and yet the inside of the adhesive did not reach the yield strength of the adhesive, the torque was calculated by the finite element method which incorporated the nonlinear material properties of the adhesive. Therefore, if the adhesive thickness was small enough not to induce large residual thermal stress due to fabrication, the failure of the adhesive joint is predicted by the maximum strain criterion in which the adhesive was failed by the bulk failure mode. In the bulk failure mode, the optimal bonding length of the adhesively-bonded tubular lap joint was determined by the length at which the shear strain at the end region of the adhesive reaches the failure strain and all of the inner region of the adhesive reached the yield stress.

In the other mode, it was assumed that the bonding strength between the adhesive and the adherend was less than the adhesive bulk shear strength due to the residual thermal stress and the joint failed at the interface between the adhesive and the adherends.

Between these two types of the failure modes, it was assumed that there was a transient failure mode.

In order to predict the condition of the interfacial failure mode, the stress failure criterion was proposed by the following equation:

$$\left(\frac{\sigma_r^t}{S_t}\right)^2+\left(\frac{\sigma_\theta^t}{S_t}\right)^2+\left(\frac{\sigma_z^t}{S_t}\right)^2+\left(\frac{\tau_{r\theta}^m}{S_s}\right)^2+\left(\frac{\tau_{\theta z}^m}{S_s}\right)^2+\left(\frac{\tau_{rz}^t}{S_s}\right)^2=1 \tag{1}$$

where,

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

The superscripts t and m in Equation (1) represent the thermal and mechanical stresses, respectively. To predict the interfacial shear failure, the reduced bulk shear strength, S_a, was defined by the following equation:

$$\begin{aligned} S_a &= \sqrt{\tau_{r\theta}^{m2}+\tau_{\theta z}^{m2}} \\ &\equiv f(\textit{strength of adhesive, residual thermal stress}) \\ &= S_s\sqrt{1-\left\{\left(\frac{\sigma_r^t}{S_t}\right)^2+\left(\frac{\sigma_\theta^t}{S_t}\right)^2+\left(\frac{\sigma_z^t}{S_t}\right)^2+\left(\frac{\tau_{rz}^t}{S_s}\right)^2\right\}} \end{aligned} \tag{2}$$

Here, S_a represents the reduced bulk shear strength in which the effect of the residual thermal stresses due to fabrication in the adhesive layer was incorporated. Since the value of the reduced bulk shear strength varies from point to point, the minimum value calculated through the adhesive layer was chosen as the reduced bulk shear strength. Also, the nondimensionalized stress deviation factor, k_t, was defined by the following equation:

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

Here k_t represents the effect of the residual thermal stress on the adhesive failure shear strength. k_t is 0 when there is no residual thermal stress and increases as the residual thermal stress increases. In order to predict the torque transmission capability, T_R, of the adhesively-bonded tubular lap joint, the transient interpolation function, f_i, was defined by the following equation:

$$T_R = T_B \cdot f_i + T_I \cdot (1 - f_i) \tag{4}$$

where,

T_B = torque transmission capability in the bulk shear failure mode of the adhesive
T_I = torque transmission capability in the interfacial failure mode between the adhesive and the adherends

In order to determine the value of k_t, static torsion tests, for a specimen whose shape is shown in Figure 1, were performed. From the test results, the transient interpolation function, f_i, for the adhesively-bonded tubular single lap joint was fitted by the following equations:

$$\begin{aligned} k_t \le 0.085&: \ f_i = 1 \\ k_t > 0.085&: \ f_i = e^{-29.5(k_t - 0.085)} \end{aligned} \tag{5}$$

The physical meaning of f_i is the probability of the bulk shear failure mode of the adhesive in the adhesive joint.

Through the above mentioned procedures, the static torque transmission capabilities of the adhesively-bonded tubular single lap joint were calculated by using the finite element method. In calculating the stresses, a 9-node, axisymmetric, isoparametric element was used. Figure 2 shows the finite element mesh for the calculations of the residual thermal stresses and mechanical stresses under torsion. Calculating with different mesh sizes, it was found that, in the case of the tubular lap joint, the residual stress did not strongly depend on the mesh size. Figure 3 shows both the experimentally-measured torque transmission capabilities and those predicted by the developed failure model. In the experiment of Figure 3, the outer diameter and thickness of the female adherend were 19 mm and 2 mm, respectively.

In order to check whether the constants of Equation (5) were dependent on the size of the joint, larger adhesively-bonded single lap joints whose female adherend had a 30 mm diameter and 2 mm thickness were tested under torsion. Figure 4 shows both the torque transmission capabilities experimentally measured and predicted by the

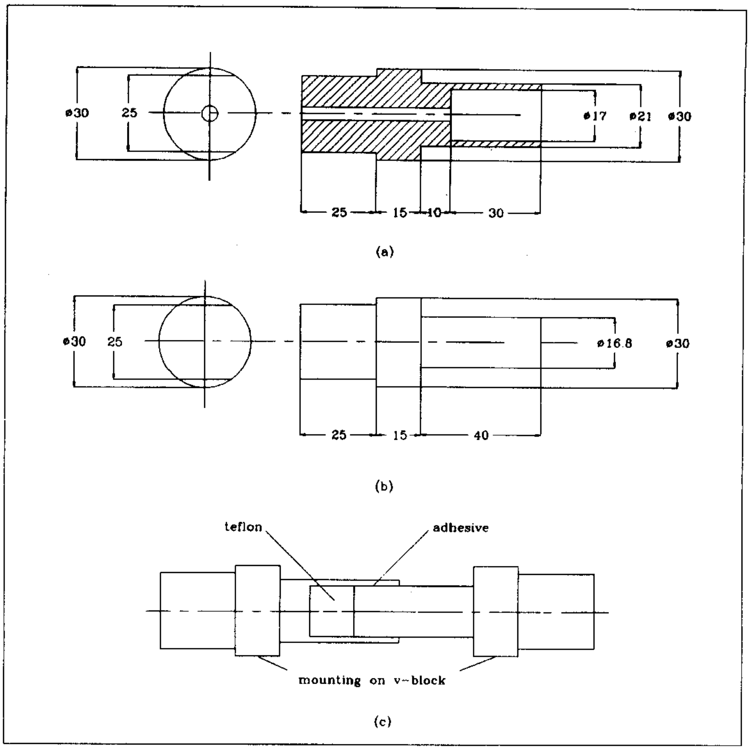

FIGURE 1 Shape of the specimen for torsion tests.

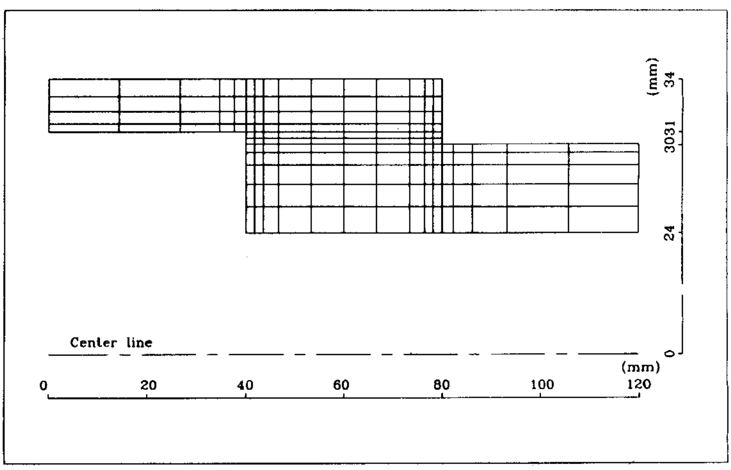

FIGURE 2 Finite element meshes for stress analysis.

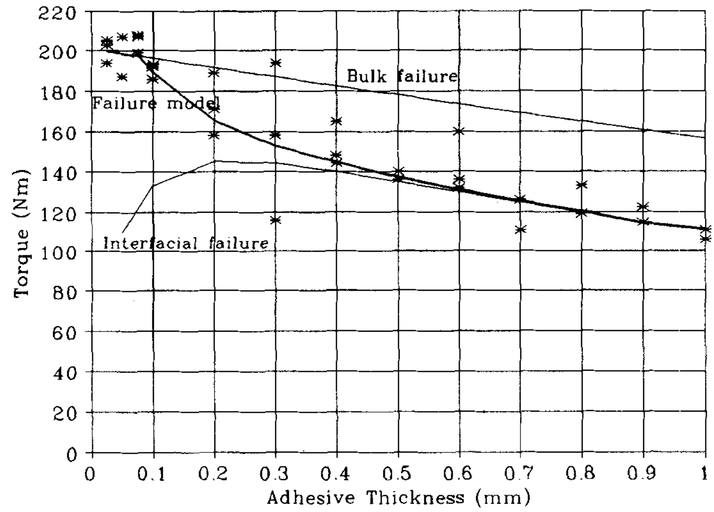

FIGURE 3 Torque transmission capabilities determined by experiments and calculations using the failure model (diameter of the outer adherend: 17 mm).

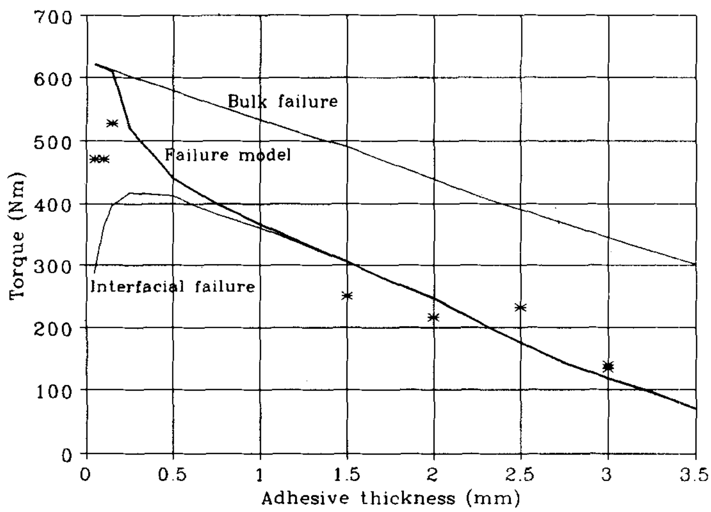

FIGURE 4 Torque transmission capabilities determined by experiments and calculations using the failure model (diameter of the outer adherend: 30 mm).

developed failure model with respect to the adhesive thickness of the larger adhesively-bonded tubular single lap joints.

Since the failure model also predicted the torque transmission capabilities of the larger adhesively-bonded joint fairly well, it was concluded that the constants of the failure model were independent of the size of the adhesive joint, but might be dependent on the adhesive.

OPTIMAL DESIGN OF THE ADHESIVELY-BONDED TUBULAR SINGLE LAP JOINT

In order to show the optimal design procedure, an adhesively-bonded tubular single lap joint whose outer adherend has 68 mm outside diameter and inner adherend has 60 mm outside diameter, as shown in Figure 5, was chosen. The selected size of the adhesive joint was typical for rear-driven passenger cars. In order to simplify the procedure, both the outer and inner adherends were assumed to be made of steel. However, when the adherend is made of composite material, this optimal design procedure can be equally applied if the modulus of the composite laminate is used. Figure 5 shows the joint dimensions used in the optimal design procedure. In order to compare the calculated results, the outside diameter of the inner adherend was fixed in the numerical simulation procedure.

(a) Adhesive Properties

The rubber-toughened epoxy IPCO 9923 (Imperial Polychemicals Corp., Azusa, CA, USA) was selected as an adhesive material. Its general material properties are shown in Table I. The adhesive had highly nonlinear material properties. Figure 6 shows the nonlinear shear stress-strain behavior of the adhesive. The finite element analysis in this paper incorporated the nonlinear properties of the adhesive and the developed failure model.

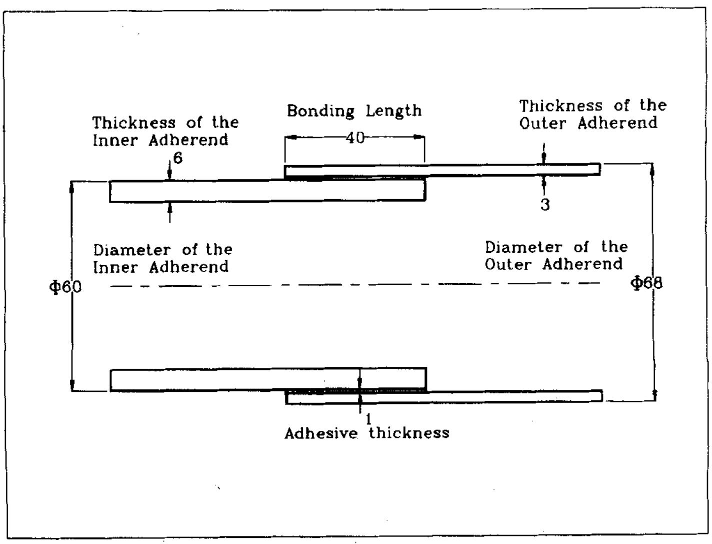

FIGURE 5 Dimensions of the adhesively-bonded tubular single lap joint used in the optimal design procedure.

TABLE I
Material data of the epoxy adhesive and the steel adherend

	Adhesive IPCO 9923	Steel
Tensile modulus (GPa)	1.30	200.0
Shear modulus (GPa)	0.461	76.9
Possion's ratio	0.41	0.30
Tensile strength (MPa)	45.0	not required
Shear Strength (MPa)	29.5	not required
Shear strain limit	0.60	not required
Thermal expansion coefficient (10^{-6} m/m°C)	72.0	11.7
Viscosity	paste type	not applicable
Cure temperature (°C)	80.0	not applicable
Cure time (hour)	3	not applicable

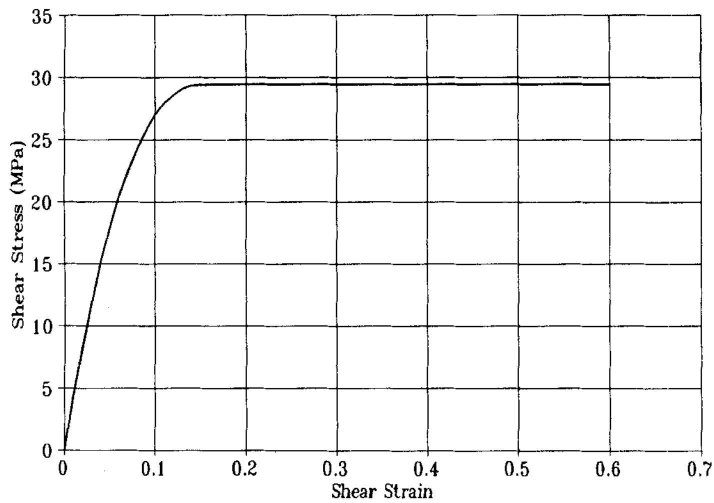

FIGURE 6 Shear stress-strain curve of the epoxy adhesive (IPCO 9923).

(b) Adhesive Thickness

In the optimal design of the adhesively-bonded joint, the adhesive thickness must be adjusted for the state of the adhesive to be in the bulk failure mode. This procedure requires the calculation of the residual thermal stresses in the adhesive layer by the finite element method. For the bulk failure mode, the value of k_t must be less than 0.085 as depicted in Equation (5). Table II shows the joint dimensions used in the analysis. Figure 7 shows the shear stress distributions in the adhesive layer with 0.1 mm adhesive thickness. From Figure 7, the stress relaxations due to nonlinear properties of the

TABLE II
Joint dimensions for the determination of the adhesive thickness

	Inner adherend	Outer adherend	Adhesive thickness (mm)	Bonding length (mm)
Diameter (mm)	60.0	66.0 + 2AT	0.05 ~ 3.0	40
Thickness (mm)	6.0	3.0		

AT = Adhesive thickness

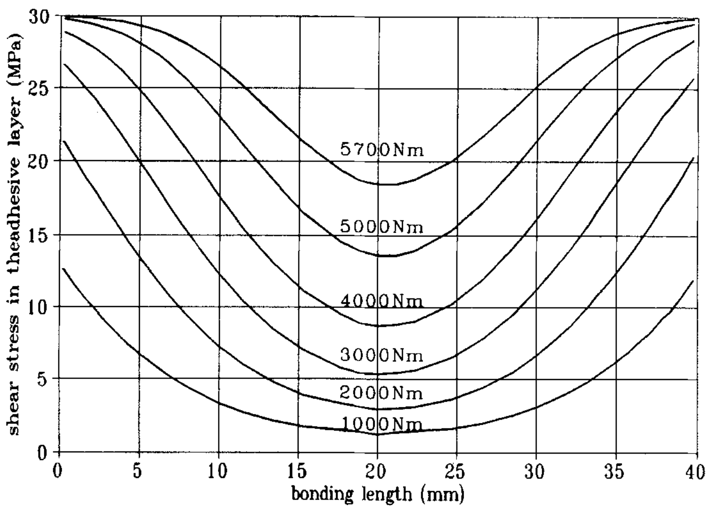

FIGURE 7 Shear stress distributions in the adhesive layer that were calculated by mechanical stress analysis (adhesive thickness = 0.1 mm).

adhesive were observed when the applied torque was increased. Figure 8 shows the torque transmission capabilities and residual thermal stresses calculated by the finite element method with respect to the adhesive thickness.

From the above mentioned facts and the numerical calculation results of Figure 8, 1.0 mm adhesive thickness was selected in this case.

When the bonding length was 40 mm, the torque transmission capabilities of the joints with 0.1 mm and 1.0 mm adhesive thicknesses were the same. However, when the bonding length became larger than 45 mm, the torque transmission capability of the adhesive joint with 0.1 mm adhesive thickness ceased to increase due both to the mechanical stress concentration and the strain limit of the adhesive at the ends of the joint, as shown in Figure 9. Therefore, the adhesive thickness should be increased until the adhesive failure mode changes from the bulk shear failure mode to the transient failure mode, which is the same result as for the linear-elastic, closed-form solution.[2]

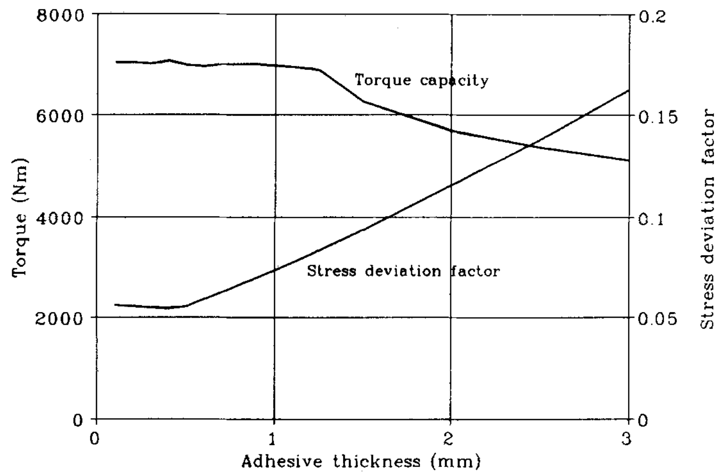

FIGURE 8 Thermal residual stress and torque transmission capability w.r.t. the adhesive thickness.

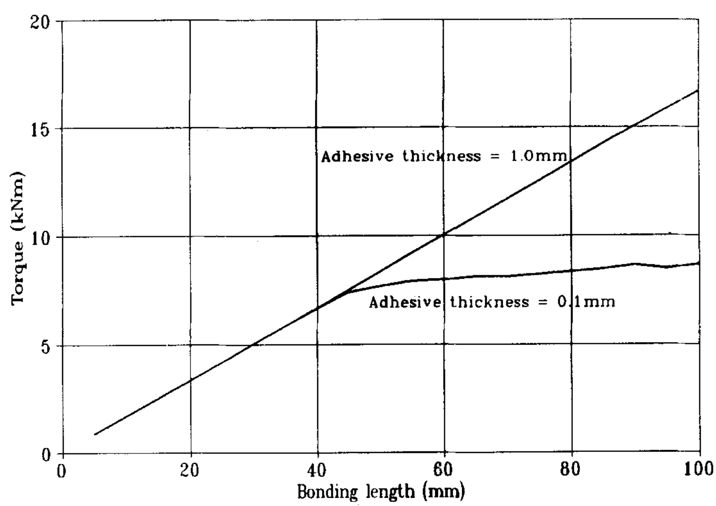

FIGURE 9 Torque transmission capability w.r.t. the bonding length.

Therefore, the optimal adhesive thickness for the maximum torque transmission capability is dependent on the residual thermal stress.

(c) Thickness of the Adherend

In order to determine the thicknesses of the adherends, the torque transmission capabilities of the adhesive joint were calculated when the thickness of the inner adherend was varied while the thickness of the outer adherend was fixed. Table III shows the joint dimensions which were used to determine the thickness of the adherend,

TABLE III
Joint dimensions for the determination of the thicknesses of the adherends

	Inner adherend	Outer adherend	Adhesive thickness (mm)	Bonding length (mm)
Diameter (mm)	60.0	68.0	1.0	40
Thickness (mm)	variable (0.5 ~ 10.0)	3.0		

O

and Figure 10 shows the torque transmission capabilities with respect to the thickness of the inner adherend.

Figure 11 shows the variation of the polar moments of inertia of the inner and outer adherends. In Figure 11, the inner adherend has the same polar moment of inertia as the outer adherend when the thickness of the inner adherend is 4.9 mm, which gives the maximum torque transmission capability in the linear solution of Figure 10. However, the failure model predicted constant torque transmission capability from 2 mm to 7 mm thickness of the inner adherend. The decrease of the torque transmission capability when the thickness of the inner adherend was larger than 7 mm might be explained by the change of the failure mode from the bulk to the transient mode. Without considering the stresses in the inner and outer adherends, a thickness of 4.9 mm for the inner adherend might be selected. However, a thickness of 6.0 mm for the inner adherend yields the same magnitude of the stress in both the inner and outer

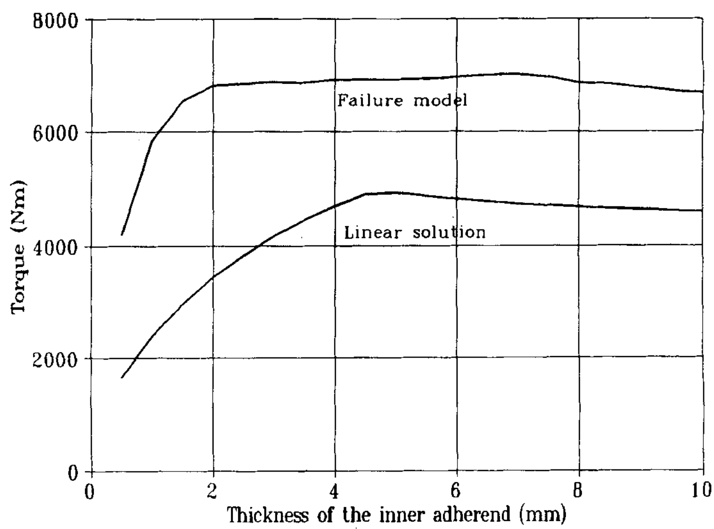

FIGURE 10 Torque transmission capability w.r.t. the thickness of the inner adherend (Adhesive shear strength: 29.5 MPa)

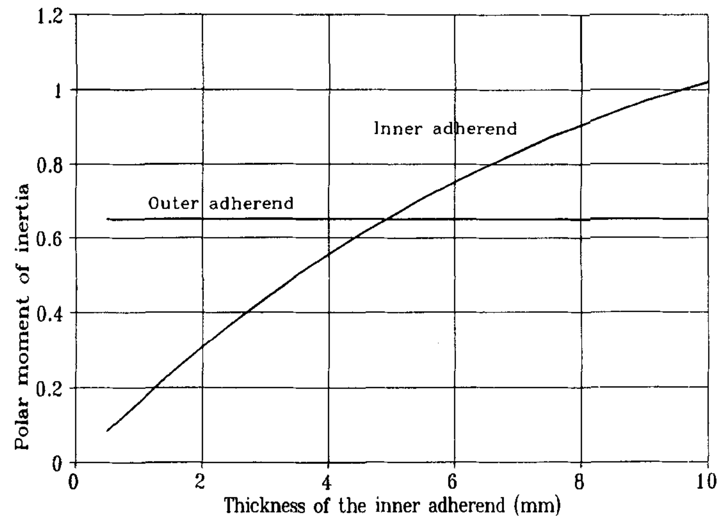

FIGURE 11 Polar moments of inertia of the inner and the outer adherends.

adherends, which might be considered as the optimal thickness of the adherend in this case.

(d) Bonding Length

In the theory using linear adhesive properties, the torque transmission capability increases and soon saturates as the adhesive bonding length increases. This phenomenon also appears when the nonlinear failure model was applied. However, the saturation of the torque transmission capability in the nonlinear failure model begins at much larger bonding length compared with the linear theory. Table IV shows the joint dimensions which were used for the determination of the adhesive bonding length.

Figure 9 show the torque transmission capabilities of the adhesively-bonded tubular single lap joint calculated by the failure model with respect to the adhesive bonding length when the thicknesses of the adhesive were 0.1 and 1.0 mm, respectively. Figure 12 shows the mean adhesive strength, which is the torque transmission capabil-

TABLE IV
Joint dimensions for the determination of the bonding length

	Inner adherend	Outer adherend	Adhesive thickness (mm)	Bonding length (mm)
Diameter (mm)	60.0	66.2/68.0	0.1/1.0	5 ~ 100
Thickness (mm)	6.0	3.0		

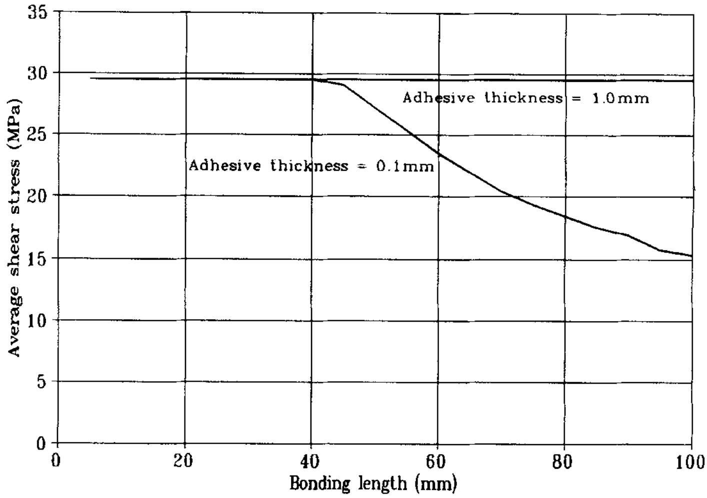

FIGURE 12 Average adhesive shear strength w.r.t. the bonding length.

ity divided by the adhesive area, as a function of the bonding length. From the results of Figure 12, it might be concluded that the mean adhesive strength decreased as the adhesive bonding length increased when the adhesive thickness was small. Since the weight of the joint increases as the adhesive bonding length increases, the adhesive bonding length must be determined such that the mean adhesive strength should be larger than a certain value at the given thickness of the adhesive.

(e) Effect of the Scarf

In the theory using linear adhesive properties, the torque transmission capability increases when the adherend has a scarf because the scarf reduces the stress concentrations at the ends of the joint. In order to verify whether this phenomenon occurs when the nonlinear failure model of the adhesive is used, the scarf whose shape is shown in Figure 13 was given to the joint. Table V shows the dimensions of the joint for the investigation of the effect of the scarf. In order to calculate the dependency of the torque transmission capability on the degree of the scarf, the value of R_r in Figure 13 was fixed as 0.7 for both the inner and outer adherends, and the value of R_z, which was assumed to be same for both the inner and outer adherends in Figure 13, was varied. Figure 14 shows the results of the calculation. From the results of Figure 14, it might be concluded that the existence of the scarf and the degree of the scarf did not contribute the torque transmission capability. This might be explained by suggesting that the nonlinear or plastic properties of the rubber-toughened epoxy adhesive could relax the stress concentration even when there was no scarf in the adherend of the adhesively-bonded tubular single lap joint.

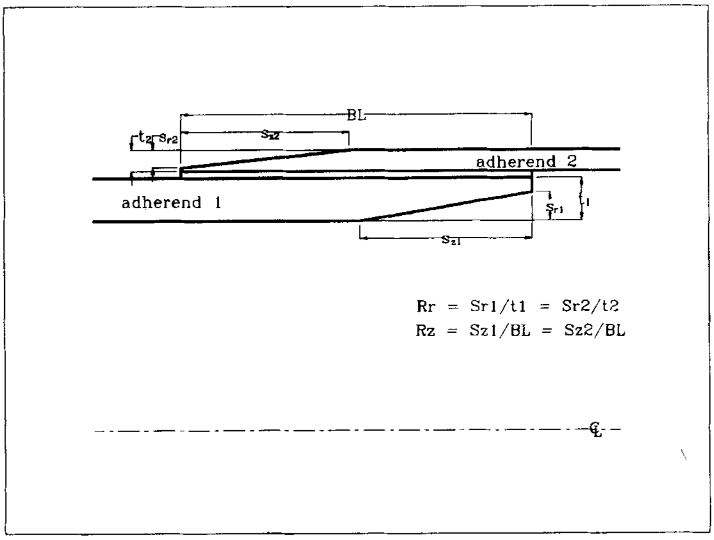

FIGURE 13 Configuration of the scarf joint.

TABLE V
Joint dimensions for the test of the effect of scarfed adherends

	Inner adherend	Outer adherend	Adjustable parameter
Diameter (mm)	60.0	68.0	$R_z = 0.1 \sim 0.9$ $R_r = 0.7$
Thickness (mm)	6.0	3.0	BL = 40 mm AT = 1.0 mm

AT = Adhesive thickness
BL = Bonding length
R_z; R_r = defined in Figure 13.

SUMMARY OF THE DESIGN PROCEDURE

In order to determine the joint parameters for the maximum torque transmission capability of the adhesively-bonded tubular single lap joint, a design procedure was suggested based on the developed failure model. However, all of the parameters cannot be determined independently. Therefore, the basic and important parameter must be determined first when two parameters conflict. For example, the diameter and length must be determined first if the size and weight of the joint are primary concerns.

However, the basic joint design procedure for the adhesively-bonded tubular single lap joint can be summarized as follows. Firstly, the size of the joint is approximately determined or assumed based on the required torque transmission capability. Secondly, the thicknesses of the adhesive and the adherend are determined, based on the assumed size of the joint, to yield the maximum torque transmission capabilities.

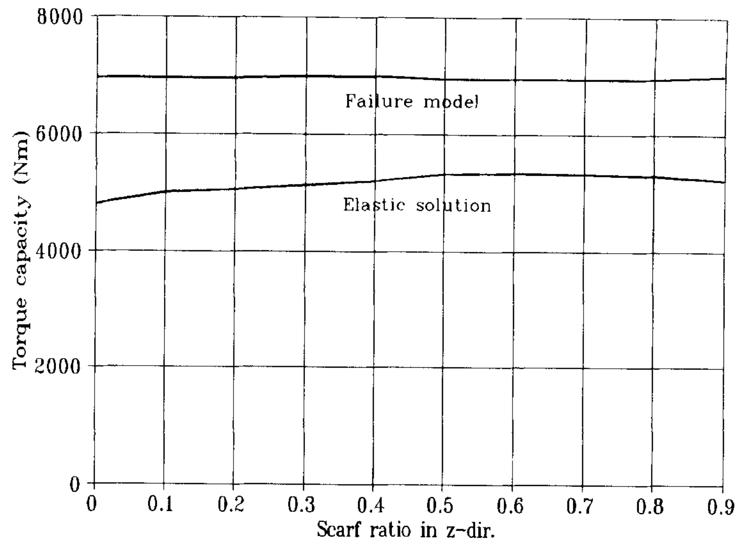

FIGURE 14 Torque transmission capability w.r.t. the degree of the scarf (Adhesive shear strength: 29.5 MPa).

Thirdly, the bonding length of the joint is determined considering the effectiveness of the joint. If the torque transmission capability is too small or too large, the design procedure should be returned to the first step to increase or decrease the size of the joint. After these procedures, the optimal, or most efficient, adhesively-bonded tubular single lap joint can be designed.

CONCLUSIONS

In this paper, a failure model is used to investigate the effects of design parameters such as the size of the adherend, thickness of the adhesive, bonding length and shape of the scarf, on the torque transmission capability of the adhesively-bonded tubular single lap joint.

Based on the investigation, procedures for the optimal design of the adhesively-bonded single lap joint were suggested.

References

1. R. S. Alwar and Y. R. Nagaraja, "Viscoelastic Analysis of an Adhesive Tubular Joint," *J. Adhesion*, **8**, 79–92 (1976).
2. R. D. Adams and N. A. Peppiatt, "Stress Analysis of Adhesive Bonded Tubular Lap Joints," *J. Adhesion*, **9**, 1–18 (1977).
3. C. T. Chon, "Analysis of Tubular Lap Joint in Torsion," *J. Composite Mater.* **16**, 268–284 (1982).
4. P. J. Hipol, "Analysis and Optimization of a Tubular Lap Joint Subjected to Torsion," *J. Composite Mater.* **18**, 298–311 (1984).
5. S. R. Graves and D. F. Adams, "Analysis of a Bonded Joint in a Composite Tube Subjected to Torsion," *J. Composite Mater.* **15**, 211–224 (1981).

6. L. J. Hart-Smith, "Further Developments in the Design and Analysis of Adhesive Bonded Structural Joints in Joining of Composite Materials," *ASTM STP 749*, pp. 3–31 (1981).
7. D. G. Lee, K. S. Kim and Y. T. Lim, "An Experimental Study of Fatigue Strength for Adhesively Bonded Tubular Single Lap Joints," *J. Adhesion*, **35**, 39–53 (1991).
8. S. J. Lee and D. G. Lee, "Development of a Failure Model for the Adhesively Bonded Tubular Single Lap Joint," *J. Adhesion*, **40**, 1–14 (1992).