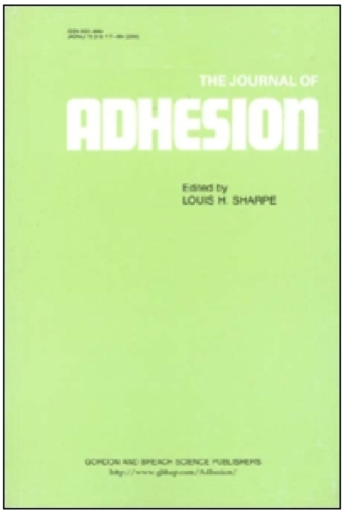

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An Experimental Study of the Static Torque Capacity of the Adhesively-Bonded Tubular Single Lap Joint

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An Experimental Study of the Static Torque Capacity of the Adhesively-Bonded Tubular Single Lap Joint

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With the wide application of fiber-reinforced composite materials in aircraft, space structures and robot arms, the design and manufacture of composite joints have become a very important research area because they are often the weakest areas in composite structures. In this study, the effects of the adhesive thickness and tensile thermal residual stress on the torque capacity of tubular single lap joints were studied. The torque capacities of the adhesive joints were experimentally determined and found to be inversely proportional to the adhesive thickness. In order to match the experimental results to the theoretical analyses, the elastic-perfectly plastic material properties of the adhesive were used in the closed form solution. Also, the tensile thermal residual stresses of the joints were calculated by the finite element method and it was found that the thermal residual stresses could play an important role in the torque capacity when the adhesive thickness was large.

KEY WORDS: Adhesion; adhesive thickness; residual thermal stress; adherend; finite element analysis; fiber reinforced composite; elastic adhesive; elastic-perfectly plastic adhesive; SEM.

1. INTRODUCTION

Continuous fiber reinforced composites have been widely used in aircraft, space structures and robot arms because of high specific modulus, high specific strength, and high damping characteristics. As composites have become popular in recent years, the design and manufacture of the composite joints have become a very important research area because the structural efficiency of the composite structure is determined by its joints, not by its basic structures.[1]

Generally, the joining methods for composites are classified into mechanical and adhesive types. The adhesive joint has several advantages over mechanical joints. Adhesive joints do not require holes and they distribute the load over larger areas than mechanical joints.[2] Also, they are excellent electrical and thermal insulators and add very little weight to the structure. However, adhesive joints are very sensitive to the adherend geometry, quality of surface treatment, service temperature, humidity and other environmental conditions.

Many researchers have studied the static and dynamic[3–5] load capacities of adhesive joints. Several important previous results in the static load capacity of adhesive joints are reviewed in this paper. Adams and Peppiatt refined the solution of Volkersen and arrived at a closed form solution for the shear stress in the adhesive tubular lap joint subjected to torsional loads. They analyzed the shear stress when the joint was subjected to both axial and torsional loads using the finite element method when the adhesive had a fillet.[6] Alwar and Nagaraja used the finite element method to obtain the stresses in a tubular joint subjected to torsion. The time-dependent properties of the adhesive were taken into account in the finite element solution.[7] Migery considered the viscoelastic properties of the composite adherend to analyze the stresses of the adhesive joint and verified experimentally the validity of the analysis.[8] Lee and his co-workers analyzed adhesive shear stresses of the tubular single lap joint considering the nonlinear behavior of the adhesive.[9] Chon analyzed the adhesive tubular lap joint whose adherends were composite material in closed form by a method simular to that of Adams.[10] Hipol analyzed the tubular lap joint comprised of a steel tube adhesively bonded to a composite tube and subjected to torsion.[11]

While static theoretical investigations for the adhesive tubular lap joint are extensive, experimental verifications of the static performance of the adhesive joint are rare.

In this paper, therefore, the effects of the adhesive thickness on the torque capacity of the tubular single lap joint were experimentally investigated and compared with the theoretical results. Also, the effects of tensile thermal residual stresses which were generated during cure were inverstigated by both finite element and experimental methods.

2. THEORETICAL ANALYSIS

The first theoretical analysis of the tubular single lap joint, as shown in Figure 1, was attempted by Volkersen and refined by Adams and Peppiatt.[6] They assumed that the adhesive and the adherend were linear elastic materials. The torque capacity with the linear elastic property of the adhesive was based on the failure criterion that the adhesive failed when the shear stress in the adhesive reached the ultimate shear strength of the adhesive. The adhesive shear stress, τ_a, in a tubular single lap joint under torque,

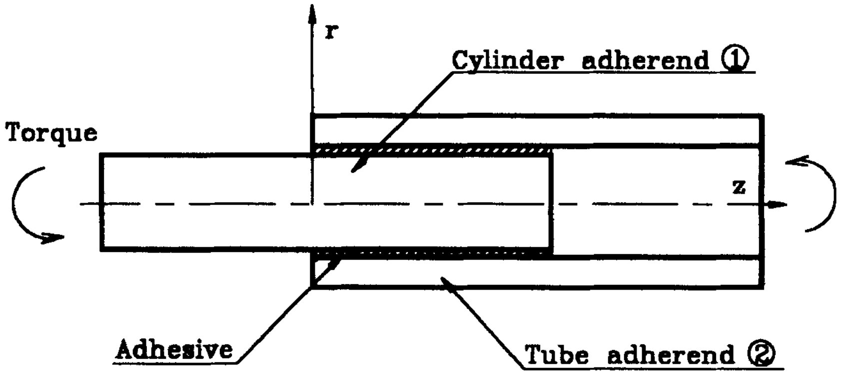


FIGURE 1 Shape of the adhesive bonded tubular single lap joint.

T, was represented as follows:

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

where,

$$\delta = \frac{2\pi\cdot a^2\cdot r_{1_o}\cdot G_a}{G_1\cdot J_1\cdot \eta} \tag{2}$$

$$\varphi = \frac{G_2\cdot J_2\cdot r_{1_o}}{G_1\cdot J_1\cdot r_{2_i} + G_2\cdot J_2\cdot r_{1_o}} \tag{3}$$

$$\alpha = \left(\frac{\delta}{\varphi}\right)^{0.5} \tag{4}$$

r_{1_o} : outer radius of the adherend ①.
r_{2_i} : inner radius of the adherned ②.
α : average radius $((r_{1_o} + r_{2_i})/2)$ of the adhesive.
J_1, J_2 : polar moment of inertia of the adherend ① and ②.
G_1, G_2 : shear modulus of the adherend ① and ②.
G_a : shear modulus of the adhesive.
η : adhesive thickness.

However, adhesive materials are usually rubber-toughened and show strong nonlinear behaviors. Therefore, the nonlinear behaviors of adhesive should be included in the analysis to obtain the accurate torque capacity. The adhesive material used in this study was the epoxy adhesive IPCO 9923 manufactured by IPCO-National Ltd.[12] Two different approaches have been adopted to measure the mechanical properties of the adhesive;[13] one is to measure the bulk properties of the adhesive by preparing bulk specimens of the adhesive. The other is to measure the film properties of the adhesive by using especially designed joint geometries. Some researchers studied whether the adhesive had the same material properties in both bulk and film forms. Knollman *et al.* found that the adhesive which was near to the adhesive/substrate interface possessed a lower shear modulus than that of the central regions in which the adhesive might have the same properties as those of the bulk adhesive material.[14] On the other hand, Post *et al.* suggested that the modulus of the adhesive was uniform across the thickness of the adhesive layer.[15] Therefore, in this paper, the bulk properties of the adhesive were adopted for the mechanical properties of the adhesive. Two kinds of tests were performed to measure the bulk shear modulus and strength of adhesive as shown in Figure 2.[16–18] Figure 3 gives the shear stress-strain curves of the adhesive which show its nonlinear behavior, and Table I lists the mechanical properties of the adhesive. Lee and his co-workers analyzed adhesive shear stresses of the tubular single lap joint considering the nonlinear behavior of the adhesive.[9] In this paper, the adhesive was assumed to be an elastic-perfectly plastic material as shown in Figure 4. The adhesive joining area was divided into three regions as shown in Figure 5, in which the regions I and III are perfectly plastic zones whose shear stresses are constant, τ_Y and region II is an elastic zone. The shear strains, γ_a, of regions I and III were represented as follows:

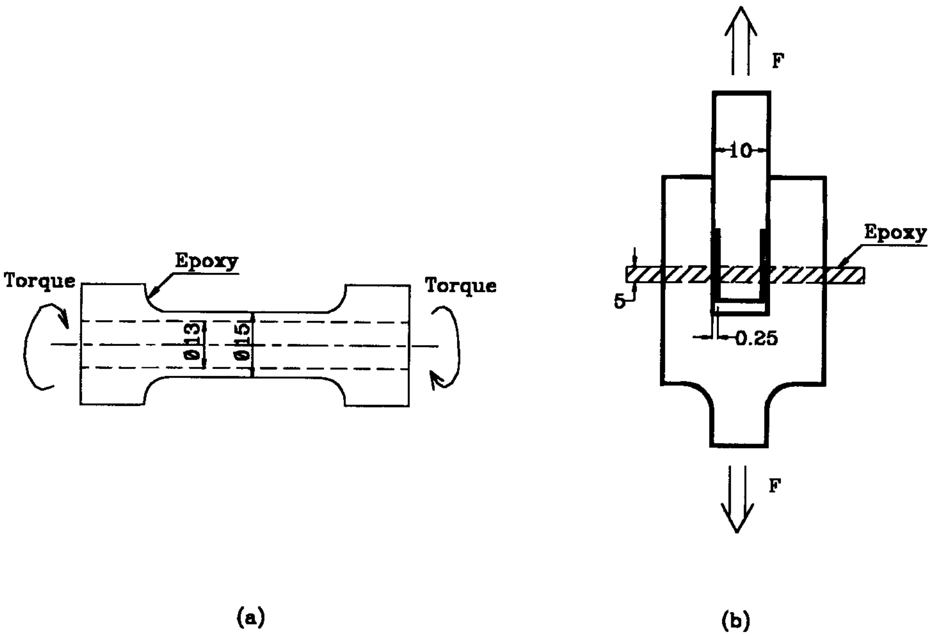


FIGURE 2 Bulk shear test methods for epoxy material.

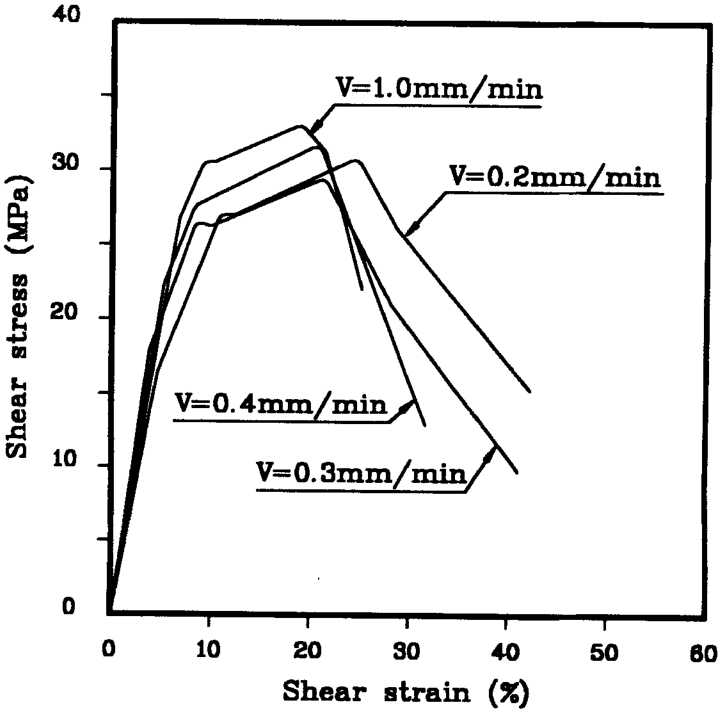


FIGURE 3 Shear stress-strain curves of the epoxy resin, (IPCO 9923).

TABLE I
Properties of the epoxy adhesive (IPCO 9923*)

Mix Ratio by Weight (Part A : Part B)	50:50
Curing Temp. (°C)	80
Lap Shear Strength (MPa)	13.7 (ASTM D-1002-72)
Tensile Strength (MPa)	45
Tensile Modulus (GPa)	1.3
Poisson's Ratio	0.41

*Imperial Polychemicals Corporation, Azusa, CA 91702, U.S.A.

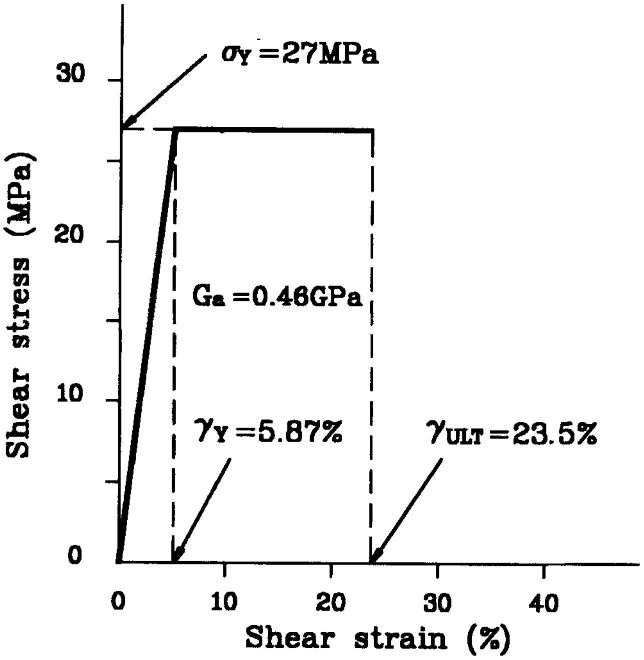


FIGURE 4 Elastic-perfectly plastic shear stress-strain curve of the epoxy resin, (IPCO 9923).

Region I $(0 < z < L_{Y1})$

$$\gamma_a = \frac{\tau_Y}{G_a} + \frac{1}{\eta}[A(z^2 - L_{Y1}^2) - B(z - L_{Y1})] \tag{5}$$

where,

$$A = \left(\frac{r_{1o}}{G_1 \cdot J_1} + \frac{r_{2i}}{G_2 \cdot J_2}\right)\pi a^2 \cdot \tau_Y \tag{6}$$

$$B = \frac{r_{1o}}{G_1 \cdot J_1} T. \tag{7}$$

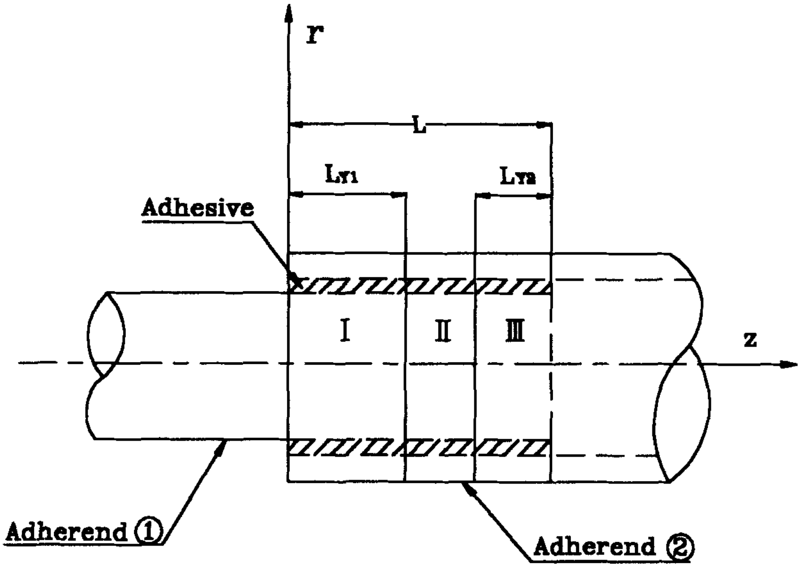


FIGURE 5 Linear elastic and perfectly plastic zones in the adhesive joints.

Region III ($L - L_{Y2} < z < L$)

$$\gamma_a = \frac{\tau_Y}{G_a} + \frac{1}{\eta}[A\cdot(z^2 - 2Lz + L^2 - L_{Y2}^2) + B'(z - L + L_{Y2})] \tag{8}$$

where,

$$B' \equiv \frac{r_{2i}}{G_2 \cdot J_2} T. \tag{9}$$

The fracture of the adhesive joint was assumed to occur when the maximum shear strain reaches the ultimate shear strain, γ_{ULT}, as shown in Figure 4.

Figure 6(a) shows the geometry of the joint specimens used in the analysis. The effect of adhesive thickness on the torque capacity of the joint was calculated both by the closed form solution and the numerical analysis with elastic-perfectly plastic material properties as shown in Figure 7. In Figure 7(a), the torque capacity with the elastic adhesive property increased as the adhesive thickness increased because the stress concentration at the ends of the adhesive was reduced as the adhesive thickness increased. However, the torque capacity with the elastic-perfectly plastic adhesive property decreased almost linearly when the adhesive bonding thickness increased, as shown in Figure 7(b), because, beyond a certain limit of shear strain of adhesive, the whole adhesive area became perfectly plastic without failure if the adhesive shear strain at either end did not reach the ultimate shear strain of the adhesive. In this case, the torque capacity might be constant if the mean diameter of the adhesive remained constant. However, the diameter of the cylinder adherend was changed to adjust the adhesive thickness, while the dimensions of the tube adherend of the joint were not

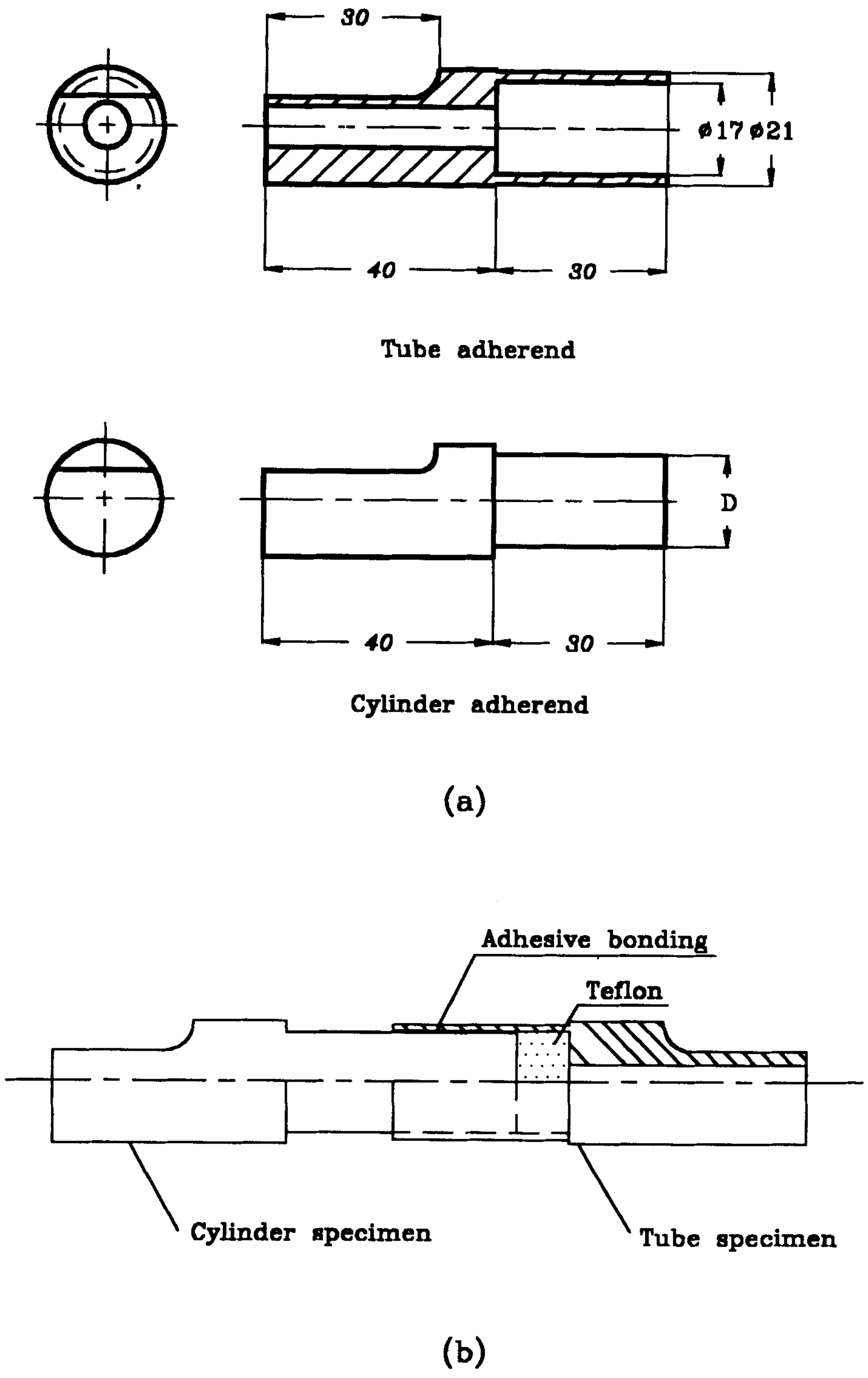


FIGURE 6 Shape of the adhesive tubular single lap joint specimens. (The diameter *D* of the cylinder adherend was adjusted to vary the adhesive thickness). (a) before bonding (b) after bonding.

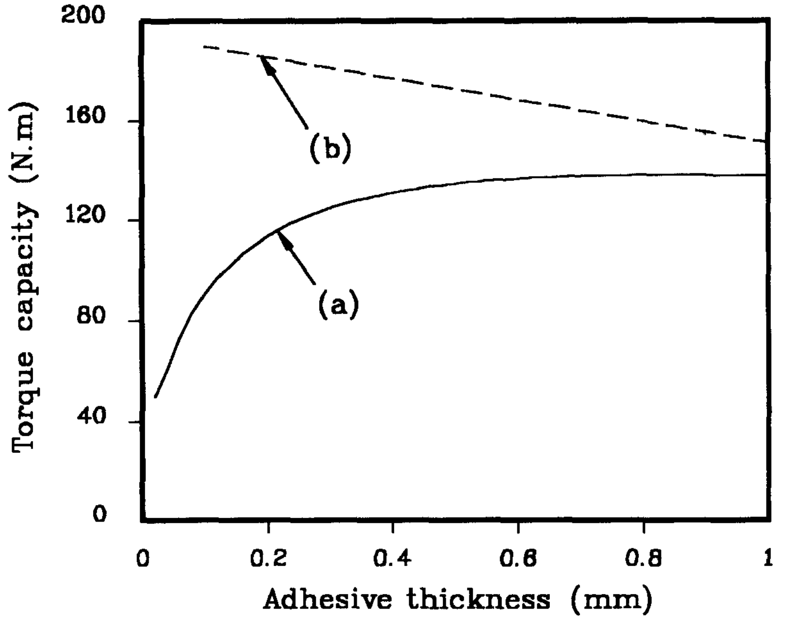


FIGURE 7 Effect of the adhesive thickness on the torque capacity. (a) Closed form solution with elastic material properties. (b) Numerical analysis with elastic-perfectly plastic material properties.

changed, as shown in Figure 6(a). Therfore, the torque capacity of the joint with the elastic-perfectly plastic adhesive property decreased linearly as the adhesive thickness increased when the diameter of the tube adherend was fixed, which is the opposite trend of the torque capacity of the joint with linear elastic adhesive property.

3. EXPERIMENTAL TORSION TESTS AND RESULTS

In this study, the static torque capacities of the adhesive tubular joints were experimentally measured and compared with the calculated values. The dimensions and types of specimens were selected based on the capacity of the torque tester, and the diameter of cylinder was changed to adjust the adhesive thickness as shown in Figure 6(a). Since the torque capacity with elastic adhesive property saturated beyond 15 mm adhesive overlap length, a 15 mm adhesive overalp length was selected in this study. In order to give a gap between the tube and cylinder adherends and to prevent the cylinder adherend from adhering to the tube adherend, a 15 mm length Teflon bar was tightly inserted into the tube specimen. Figure 6(b) shows the assembled configuration of the adhesively bonded tubular single lap joints tested.

The rubber-toughened epoxy (IPCO 9923) was used as an adhesive for the adhesively-bonded tubular single lap joint. The weight ratio of the resin and hardener was 1:1. Since the adhesion characteristics of adhesive are very sensitive to the surface roughness of the adherends, in this experiment the steel adherend was chosen because its surface roughness was easy to control. The material for the steel adherend was S45C and its arithmetic surface roughness was controlled at around 2 μm by abrading the adherends with 80 mesh sand paper in a lathe at 64 rpm rotating speed for 10 seconds.[5]

Since the adhesion is also sensitive to the temperature and humidity of the bonding environment, the bonding operation was performed in a room where the relative humidity was kept less than 40% by dehumidifying and the temperature was kept at $20 \pm 1°C$. The resin after mixing with hardener was stored for 10 minutes in a vacuum chamber to eliminate air bubbles which might have been introduced during the mixing operation. Then, the adhesive was carefully poured into an injector so as not to introduce additional air bubbles. The adhesive was then carefully injected from the bottom surface of the tube adherend. After this, the solid adherend was pushed slowly into the tube adherend.

Since the concentric bonding of the adhesive tubular lap joint was indispensible for reliable joint quality, the joint after wetting with the adhesive was clamped using a *V*-block as shown in Figure 8. Both the tubular adherend and the cylinder adherend have accurately ground surfaces to be mounted on the *V*-block.

The joint clamped on the *V*-block was put vertically in an autoclave, to suppress the size of the bubbles which might still exist, under air pressure of 0.7 MPa. Since the epoxy resin used in the adhesive joint had a minimum viscosity at around 80°C, the joint was cured for 18 hours at 80°C.

Figure 9 shows the experimental results for the torque capacity of the joint with respect to the adhesive thickness. The displacement rate of the torsion tester was fixed at 0.4 mm/min. The experimental results revealed that the numerical analysis with the elastic-perfectly plastic adhesive property predicted better the trends of the torque capacity than the closed form solution with elastic adhesive property when the adhesive thickness was smaller than 0.3 mm. To observe the fracture site, the outer adherend was machined leaving only 0.1 mm thickness and then the thin adherend was peeled from the adhesive.[14] From this experiment, it was found that bulk failure occurred in the adhesive joint when the adhesive thickness was around 0.1 mm, while interfacial failure occurred in the joint when the adhesive thickness was 1.0 mm.

However, the discrepancy of the torque capacity between experiments and calculations became larger when the adhesive thickness was large. This discrepancy of torque capacity when the adhesive thickness was large might come from the thermal residual

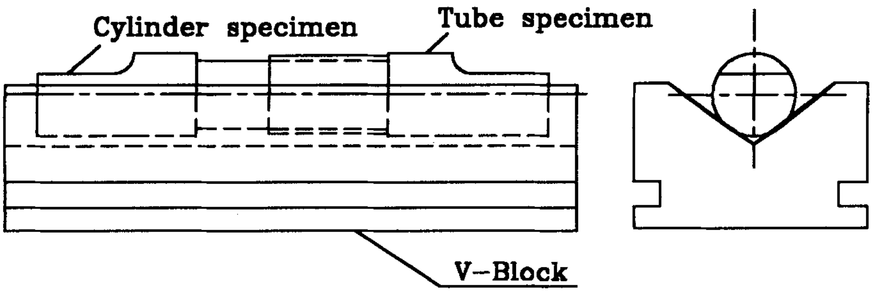


FIGURE 8 *V*-Block used for concentric bonding of the tubular adhesive joint.

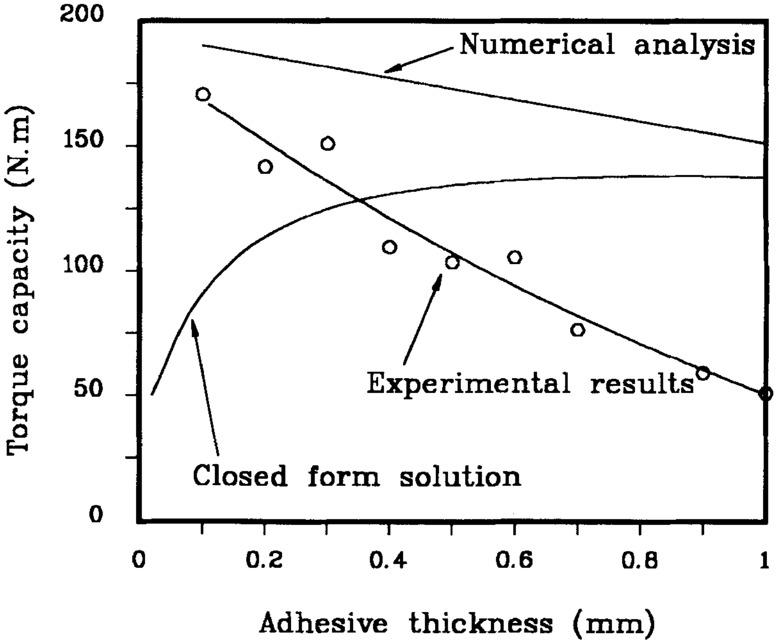


FIGURE 9 Experimental torque capacity variation w.r.t. the adhesive thickness.

stress produced during curing operation of the adhesive. Therefore, the effect of the thermal residual stress was experimentally investigated. Results are presented in the next section.

4. EFFECTS OF THE TENSILE THERMAL RESIDUAL STRESS OF THE ADHESIVE

In general, the curing operation is performed at elevated temperature to reduce the viscosity and to shorten the cure cycle of adhesives. However, the curing of adhesives at elevated temperature might induce tensile thermal residual stress. In this study, the bonding operation was performed at 20°C and the adhesive was cured at 80°C. To check whether the tensile thermal residual stress is larger enough to affect the joint strength, the thermal residual stress was analyzed by ANSYS,[19] a commercial finite element program. In this calculation, 8-node axisymmetric elements were used and the stress in θ-direction were assumed constant. With the assumption that the tensile thermal residual stress was small and in the elastic range, the elastic properties of the adhesive were used in finite element calculation. The total node numbers were 223 and the element numbers were 44. Figure 10 shows the axisymmetric finite element mesh for the calculation of the tensile thermal residual stress. Figure 11 shows the calculated tensile thermal residual stress with respect to the adhesive bonding thickness when the temperature difference is 60°C. The tensile thermal residual stress in Figure 11 increased as the adhesive bonding thickness increased. Taking into consideration that the

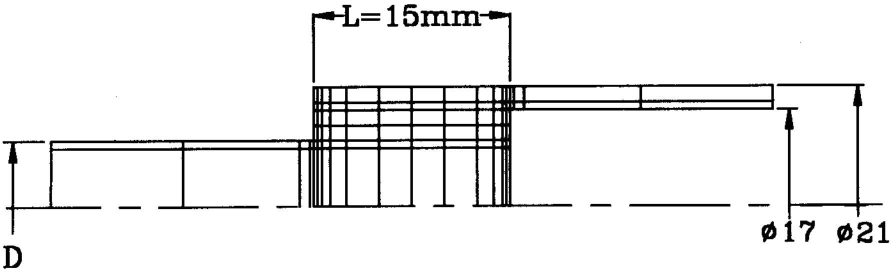


FIGURE 10 Axisymmetric finite element mesh for the calculation of the tensile residual stress in the joint.

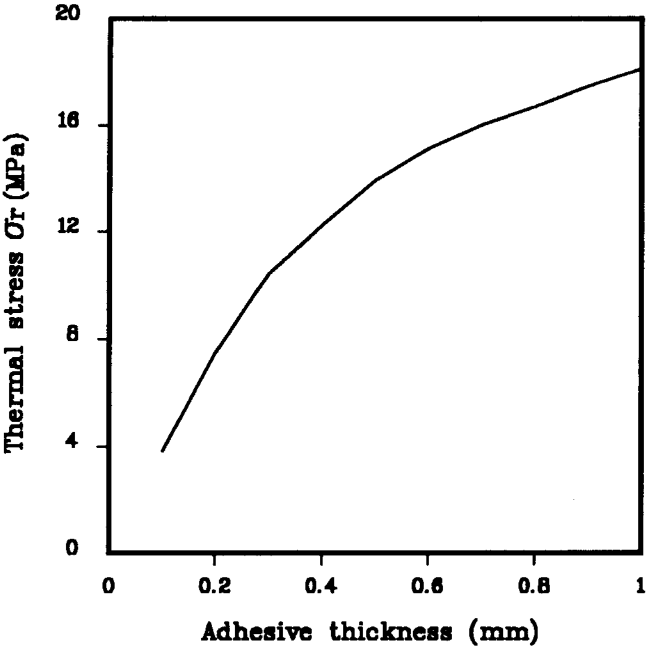


FIGURE 11 Tensile thermal residual stress generated in the adhesive by the cure temperature, ($\Delta T = 60°C$).

bulk tensile strength of the adhesive is 45 MPa from Table I, the tensile thermal residual stress was 1/3 of the bulk tensile strength when the adhesive thickness was 1.0 mm. Therefore, it was concluded that the tensile thermal residual stress could play an important role when the adhesive thickness was large.

In order to assess the reduction in the tensile thermal residual stress in the adhesive produced by reducing the temperature of the curing operation, adhesive joints which were cured at 20°C were also tested. The curing operation was performed for 3 days at 20°C and the specimen was postcured for 2 hours at 80°C to complete the chemical reaction. In this case, the torque capacity of the joint increased, as shown in Figure 12, when the adhesive thickness was larger than 0.3 mm. Furthermore, the torque capacity

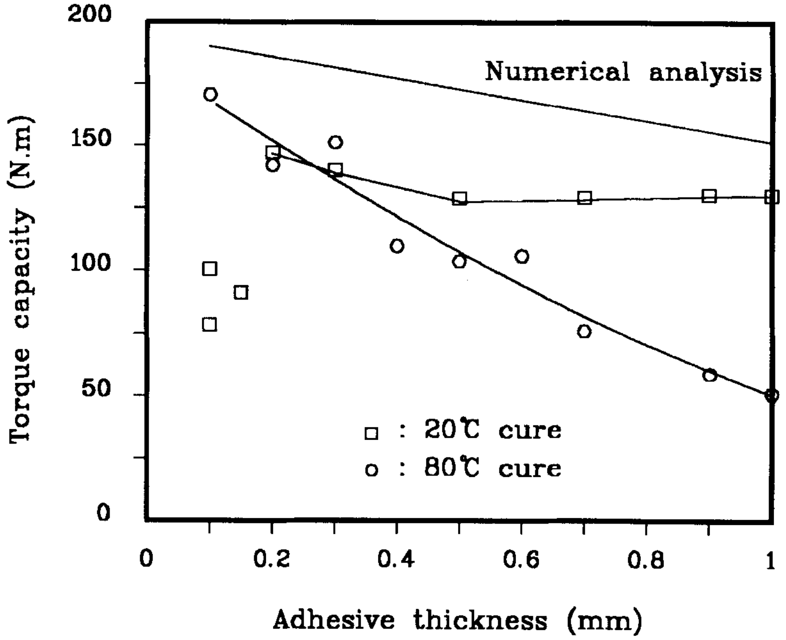


FIGURE 12 Effect of cure temperature on the torque capacity of the adhesive joints.

of the joint cured at 20°C was much larger than that of the joint cured at 80°C when the adhesive thickness was larger than 0.5 mm. Also, the torque capacity of the joint cured at 20°C appeared to follow closely the numerical solution. Therefore, it was found that the non-linear plastic behavior of the adhesive should be taken into consideration to predict the torque capacity of the adhesive joint accurately.

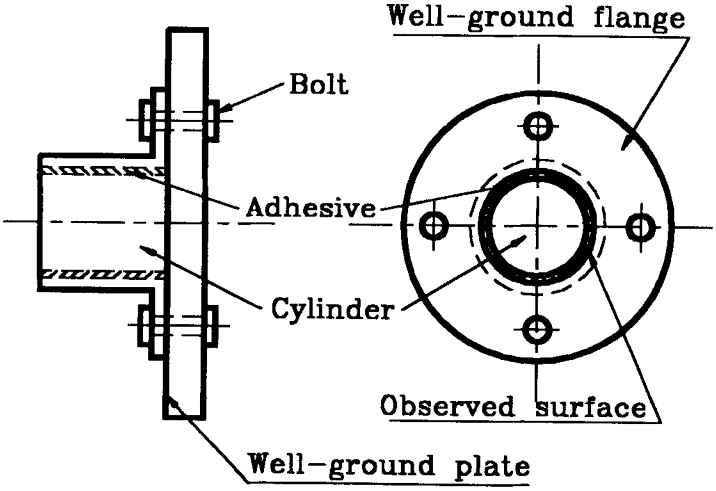


FIGURE 13 Shape of the specimens for the SEM photograph.

However, when the adhesive thickness was smaller than 0.2 mm the torque capacity of the adhesive joint cured at 20°C was much smaller than that of the adhesive joint at 80°C, and interfacial failure occurred. In order to examine this phenomenon, the interface between the adherend and adhesive was observed by SEM (Scanning Electron Microscopy). In order to observe the interface between the adhesive and the adherend, a tube adherend with a well-ground flange was attached to a well-ground plate as shown in Figure 13. After curing the adhesive, using the same procedure described earlier, the plate was separated from the joint and the face of the joint was observed. Figure 14(a) shows the interface between the adherend and the adhesive which was cured at 80°C and Figure 14(b) shows the interface between the adherend and the adhesive which were cured at 20°C. Both joints had the same 0.1 mm adhesive thickness. From Figure 14, it was observed that the adhesive cured at 20°C could not

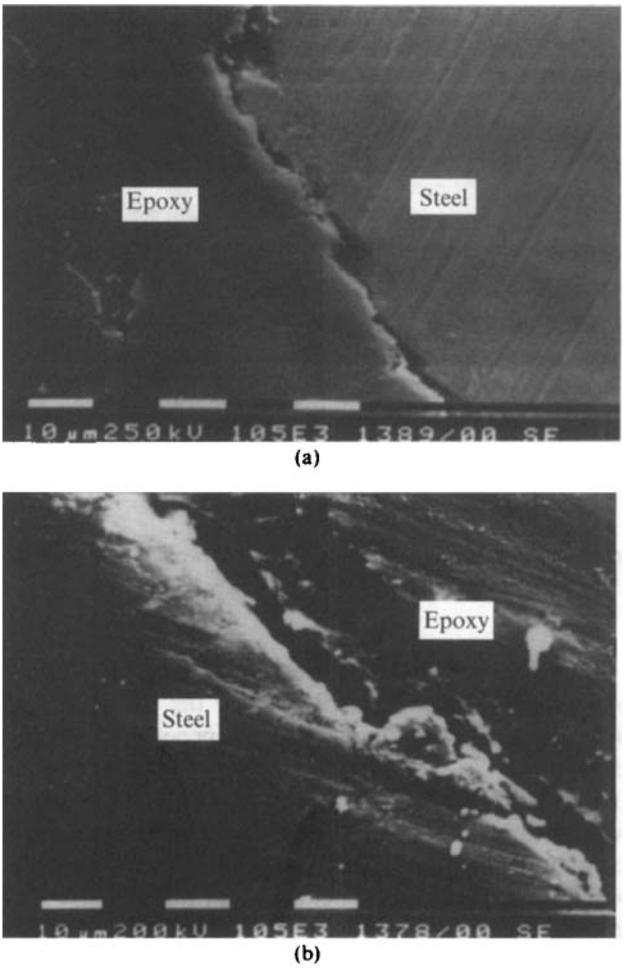


FIGURE 14 Scanning electron micrograph of the interface between the steel and the adhesive when the adhesive thickness is 0.1 mm. (a) cured at 80°C (b) cured at 20°C.

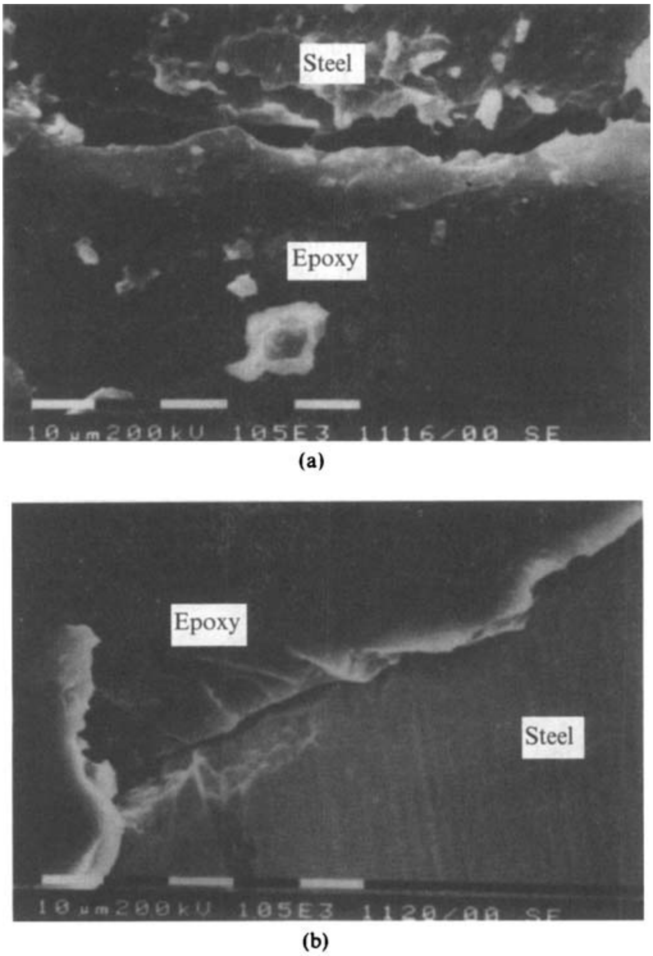
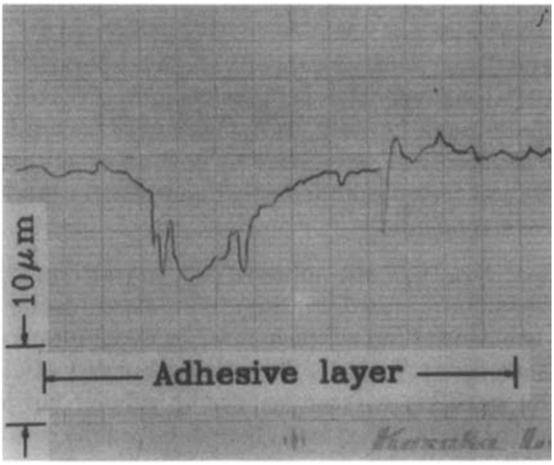


FIGURE 15 Scanning electron micrograph of the interface between the steel and the adhesive when the adhesive thickness is 1.0 mm. (a) cured at 80°C (b) cured at 20°C.

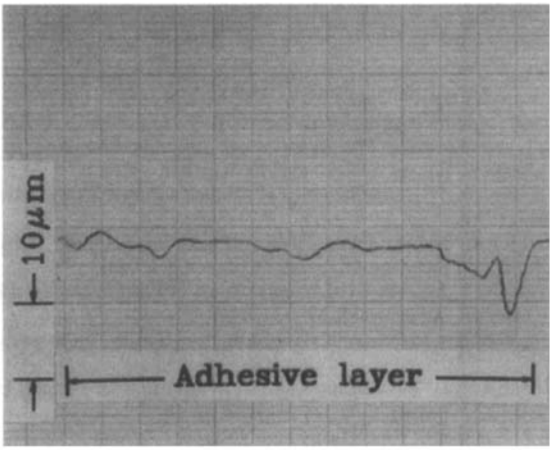
penetrate into the surface of the steel adherend when the adhesive thickness was 0.1 mm. This phenomenon could be explained by the fact that the viscosity of the adhesive was too high (at the lower temperature) to penetrate into the narrow cleavage of the adherends.

Figures 15(a) and (b) show the interfaces between the adherend and the adhesive when the adhesive thickness is 1.0 mm. From Figures 15(a) and (b), differences of the bonding characteristics of the interfaces between the adherend and the adhesive could not be easily found. Therfore, it was concluded that the adhesive cured at 80°C must have had better wetting characteristics than the adhesive cured at 20°C.

The surface profiles of a cross-section of the adhesive joint between two adherends were measured by a surface roughness tester (Kosaka FE3S manufactured by Kosaka Laboratory Ltd.[20]) Figures 16(a) and (b) show the surface roughness profiles of the



(a)



(b)

FIGURE 16 Surface profile of the interface between the steel and the adhesive when the adhesive thickness is 1.0 mm. (a) cured at 80°C (b) cured at 20°C.

adhesive surface when the adhesive thickness was 1.0 mm. From Figure 16(a), a 15 μm deep groove due to thermal shrinkage was found when the adhesive was cured at 80°C, while it was not found when the adhesive was cured at 20°C.

From the above results, it was concluded that the adhesive joint should be cured at elevated temperature when the adhesive thickness was small, but should be cured at room temperature when the adhesive thickness was large, in order to remove the tensile thermal residual stress. From the productivity point of view, the adhesive should be cured at elevated temperature to reduce the cure time. Therefore, the best way is that the adhesive should be cured at elevated temperature with small adhesive thickness.

5. CONCLUSIONS

In this research, the nonlinear adhesive property was incorporated through the elastic-perfectly plastic material characteristics in the calculation of the torque capacity of the adhesive bonded tubular single lap joint. Also, the effect of the tensile thermal residual stress on the torque capacity was determined by both an experimental method and a finite element calculation. From the theoretical and experimental observations, the following conclusions were made:

1. The torque capacity with elastic adhesive property increased asymptotically as the adhesive thickness increased, contrary to the experimental results. Therefore, the nonlinear behavior of the adhesive must be taken into consideration in the prediction of the torque capacity of the adhesive bonded tubular single lap joint.
2. A thin adhesive bondline is recommended in tubular lap joints because the residual thermal stress increased when the adhesive thickness was large.

Acknowledgements

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