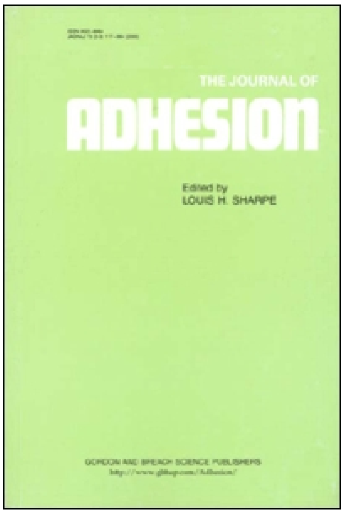

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The Torque Transmission Capabilities of the Adhesively-Bonded Tubular Single Lap Joint and the Double Lap Joint

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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 paper, the stress and torque transmission capabilities of the adhesively-bonded tubular single lap joint and the double lap joint were experimentally tested. In order to compare the experimental results with the calculated results, the stress and torque transmission capabilities were analyzed by the 3-dimensional finite element method taking into consideration the nonlinear properties of the adhesive.

From the experiments it was found that the torque transmission capabilities of the adhesively-bonded double lap joint was 2.7 times as large as that of the single lap joint. Also, it was found that the fatigue limit of the double lap joint was 16 times as large as that of the single lap joint.

KEY WORDS adhesion; steel adherneds; single lap joint; double lap joint; finite element method; fatigue; epoxy adhesive; mechanical properties; static and dynamic torsion; joint eccentricity.

INTRODUCTION

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

Generally, joining methods for composites are classified into mechanical and adhesively-bonded. Adhesively-bonded joints have several advantages over mechanical joints. They do not require holes and the load is distributed over a larger area than for mechanical joints.[2] Also, they are excellent electrical and thermal insulators. However, adhesively-bonded joints are very sensitive to the adherend geometry, quality of surface treatment, service temperature, humidity and other environmental conditions.[3]

There are several types of adhesively-bonded joints, such as the single lap joint, the double lap joint, the scarf joint and the butt joint. Stress analyses of adhesively-bonded joints have been conducted extensively by many reseachers using analytical and finite element methods. Adams and Peppiatt refined the solution of Volkersen and arrived at a closed form solution for the shear stress in the adhesively-bonded tubular lap joint subjected to torsional loads. They analyzed the shear stress when the joint was subjected to both axial and torsion loads using the finite element method when the adhesive had a fillet.[4] Chon analyzed, in closed form, by a method similar to Adams',[5] the adhesively bonded tubular lap joint the adherends of which were composite material. Hipol analyzed the tubular lap joint comprised of a steel tube adhesively bonded to a composite tube and subjected to torsion. He used the finite element method to characterize the stress concentration associated with the boundary layer effect in the end region of the adhesive layer.[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] Graves and Adams used the finite element method to calculate the stresses of the bonded joint, the adherends of which were made of orthotropic composite material, subjected to torsion. He obtained the stresses in the adherends using a ply-by-ply analysis. Also, he obtained the stresses in the adherends using smeared laminate properties.[8]

As mentioned before, many researchers have analyzed the stresses in adhesively-bonded single lap joints. The single lap joint is the most popular, due to its ease of manufacture and its relatively low cost. However, the single lap joint does not have high load transfer capability. Therefore, other joints such as the double lap and the stepped joint were frequently used in spite of the difficulty in manufacture.

In this paper, adhesively-bonded tubular single and double lap joints, as shown in Figure 1 (a) and (b), were manufactured and their torque transmission capabilities were experimentally compared. Also, the stress distribution and failure of the adhesively-bonded joints were investigated by finite element analysis and compared with the experimental results.

Since the dynamic fatigue characteristics are important in the design of mechanical structures, the fatigue life of the single lap joint was compared with that of the double lap joint.

Because perfect concentric bonding between the inner adherend and the outer adherend of an ahesively-bonded joint is seldom possible, the effect of eccentricity on the fatigue life of the adhesively-bonded tubular double lap joint was also investigated.

MECHANICAL PROPERTIES OF THE ADHESIVE

The adhesive material used in this study was an epoxy (IPCO 9923) manufactured by IPCO-National Ltd. The weight ratio of the resin and hardener was 1:1. A tensile test of the epoxy adhesive specimen shown in Figure 2 was performed in order to obtain its bulk properties. Figure 3 shows the stress-strain relationship obtained. In order to

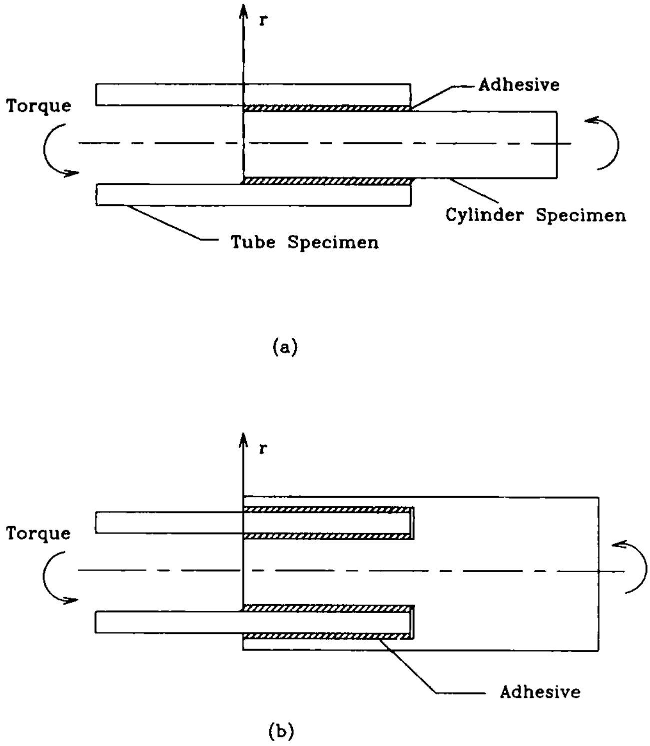


FIGURE 1 Shapes of the adhesively-bonded tubular lap joints. (a) Single lap joint; (b) Double lap joint.

obtain the shear properties of the epoxy adhesive, two kinds of tests were performed as shown in Figure 4. Torsion testing of the hollow epoxy adhesive shaft as shown in Figure 4 (a) was performed in order to obtain its shear modulus. However, the torsion test shown in Figure 4(a) proved unsuitable for measuring the shear strength and plastic characteristics because of buckling beyond the elastic limit. Therefore, the shear strength and plastic characteristics of the epoxy adhesive were obtained by the bulk shear test method shown in Figure 4(b). Figure 5 shows the shear stress-strain curves

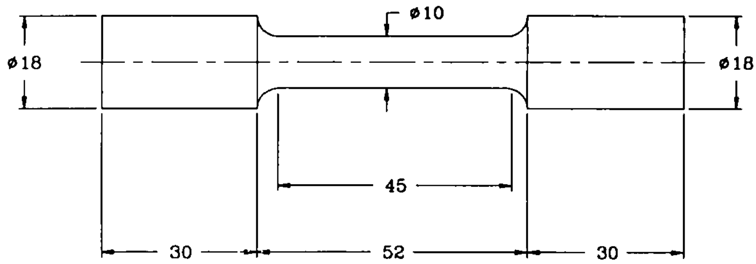


FIGURE 2 Geometry of the tensile test specimen of the epoxy adhesive. Dimensions in mm.

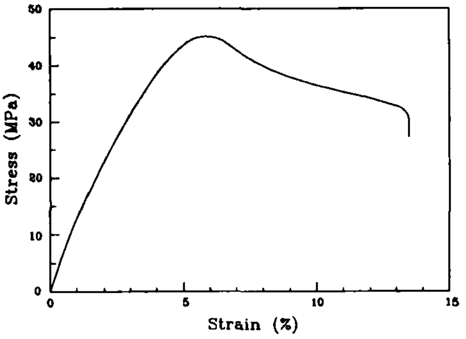
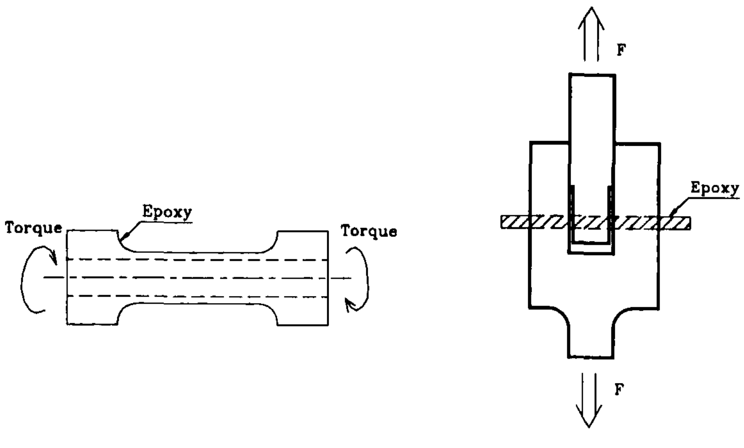


FIGURE 3 Tensile stress-strain curve of the epoxy adhesive (IPCO 9923).

obtained from experiments with the specimens of Figure 4 (a) and (b). Table I represents the mechanical properties and cure conditions of the epoxy adhesive.

TEST SPECIMENS AND TEST PROCEDURES

In this paper, the test result of the static and fatigue torsion transmission capabilities of the tubular single lap joint were compared with those of the tubular double lap joint. The dimensions of the tube and cylinder adherends for these joints are shown in Figures 6 and 7, respectively. In order to facilitate the manufacture and surface treatment of the adherends, S45C steel was selected for the adherend material. The outside and inside adherends of the cylinder specimen were manufactured separately



(a) (b)

FIGURE 4 Two methods to obtain the shear properties of the epoxy. (a) Torsion test of the hollow epoxy adhesive shaft; (b) Bulk shear test.

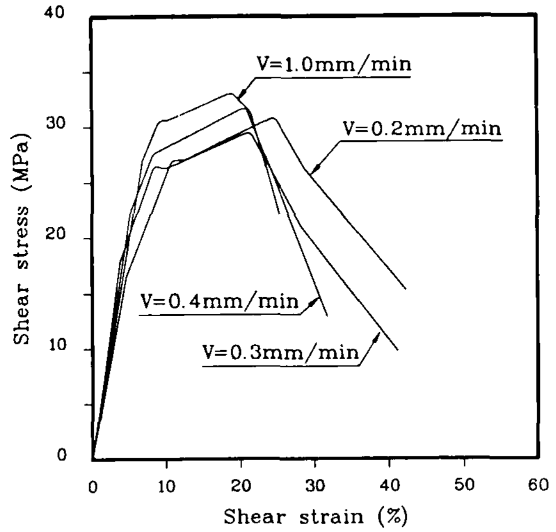


FIGURE 5 Shear stress-strain curves of the epoxy resin (IPCO 9923).

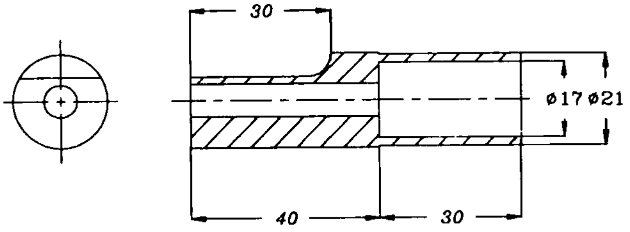
and joined by thermal fitting to eliminate the deep boring operation for the narrow gap shown in Figure 7. The arithmetic surface roughness of the adherends was fixed to 2 μm by abrading the adherends for 10 seconds with abrasive papers of 80 mesh in a lathe rotating at 64 rpm.[10] Figure 8 shows the bonded configuration of the adhesively-bonded tubular joint. In order to give an interval between the tube and cylinder adherends and to prevent the solid adherend from adhering to the tube adherend, a Teflon slice was tightly inserted into the tube adherend.

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 dehumidification and the temperature was kept at 20 ± 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. The adhesive was then carefully poured into an injector so as not to introduce additional air bubbles. The adhesive in the injector was carefully injected

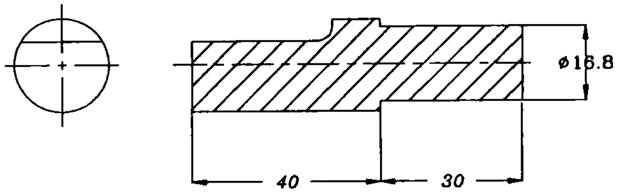
TABLE I
Properties of the epoxy adhesive (IPCO 9923*)

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
Shear Modulus (GPa)	0.46
Poisson's Ratio	0.41

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

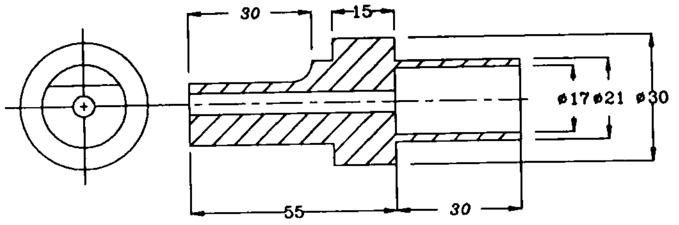


Tube Specimen

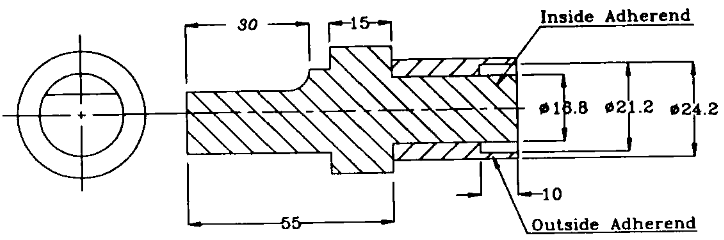


Cylinder Specimen

FIGURE 6 Shapes of the specimens for the single lap joint. Dimensions in mm.



Tube Specimen



Cylinder Specimen

FIGURE 7 Shapes of the specimens for the double lap joint. Dimensions in mm.

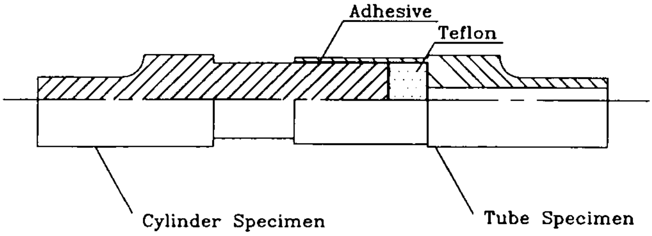


FIGURE 8 Configuration of the adhesively-bonded tubular lap joint.

from the bottom surface of the tube specimen of the adherend. After this injection, the solid adherend was pushed slowly into the tube adherend.

Since the concentric bonding of the adhesively-bonded 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 9. Both the tubular and the cylinder specimens had accurately ground surfaces for mounting in the V-block. The joint, clamped in the V-block, was put vertically in an autoclave to suppress the size of any bubbles which might still exist, under an air pressure of 0.7 MPa. Since the epoxy resin used in the adhesively-bonded joint had a minimum viscosity at around 80°C, the joint was cured for 18 hours at 80°C.

STATIC TORQUE TRANSMISSION CAPABILITIES

Experimental Results

In order to compare the torque transmission capabilities of the single lap joint with that of the double lap joint, static torsion tests were performed. The adhesive thickness and length were 0.1 mm and 10 mm, respectively. The thickness of the outside adherend of the tubular double lap joint was selected to be 1.5 mm. In the torsion tests, the rate of displacement of the torsion tester was fixed at 0.4 mm/min. Figure 10 shows the

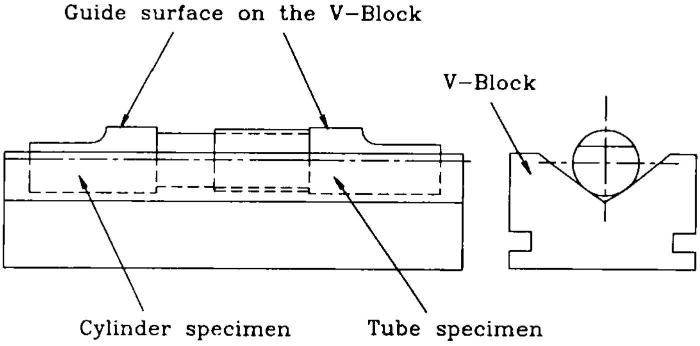


FIGURE 9 V-block used for concentric bonding of the adhesively-bonded lap joint.

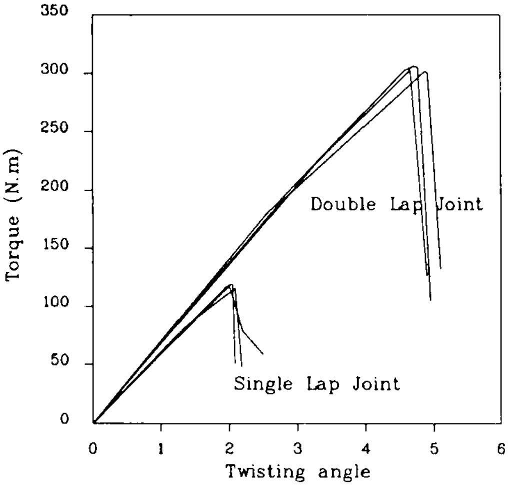


FIGURE 10 Torque-twisting angle curves of the adhesively-bonded tubular joint. Angle in degrees.

torque-twisting angle curves of the tubular single lap joint and the double lap joint. From this experiment, it was found that the torque transmission capability of the double lap joint was increased 2.7 times over that of the single lap joint. To observe the fracture site, the outer adherend was turned very carefully in a lathe, leaving only about 0.1 mm thickness of material. After this, the remaining 0.1 mm of the adherend was cut by a sharp razor. The outer adherend was then peeled carefully from the adhesive, so that the adhesive could be observed. Figure 11 shows the fractography of the adhesive, which indicates that bulk shear failure occured in the adhesive joint.

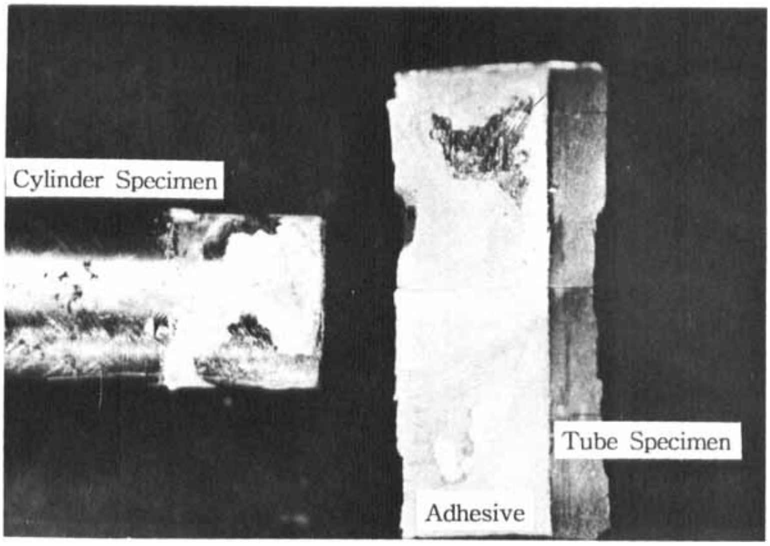


FIGURE 11 Photograph of the fracture surface of the adhesive joint.

Finite Element Analysis

The experimental torque transmission capabilities were compared with those obtained by the finite element analysis. The finite element program for the analysis of the adhesively-bonded tubular joint was ANSYS4.4A.[10] An 8-node, 3-D isoparametric element was used. Since the tubular joint has geometric symmetry, only one-quarter of the whole structure was analyzed. Figures 12 and 13 represent the element configurations of the tubular single and double lap joints. The total number of nodes and elements for the analysis of the single lap joint were 1647 and 1359, respectively, and for the analysis of the double lap joint were 2467 and 2052, respectively. The steel for the adherend material was assumed to be linear-elastic material and Table II gives the mechanical properties of the steel adherend (S45C). Since the epoxy for the adhesive is rubber toughened, it has strong nonlinear behavior as shown in Figure 5. Therefore, the nonlinear properties of the adhesive were included in the finite element analysis. In torsion, the shear properties of the adhesive must be used because shear stress is the most dominant stress component in the adhesively-bonded tubular joint. However, commercial software such as ANSYS generally accepts the tensile stress-strain curve for the material properties. Therefore, in this paper, the tensile stress-strain curve from

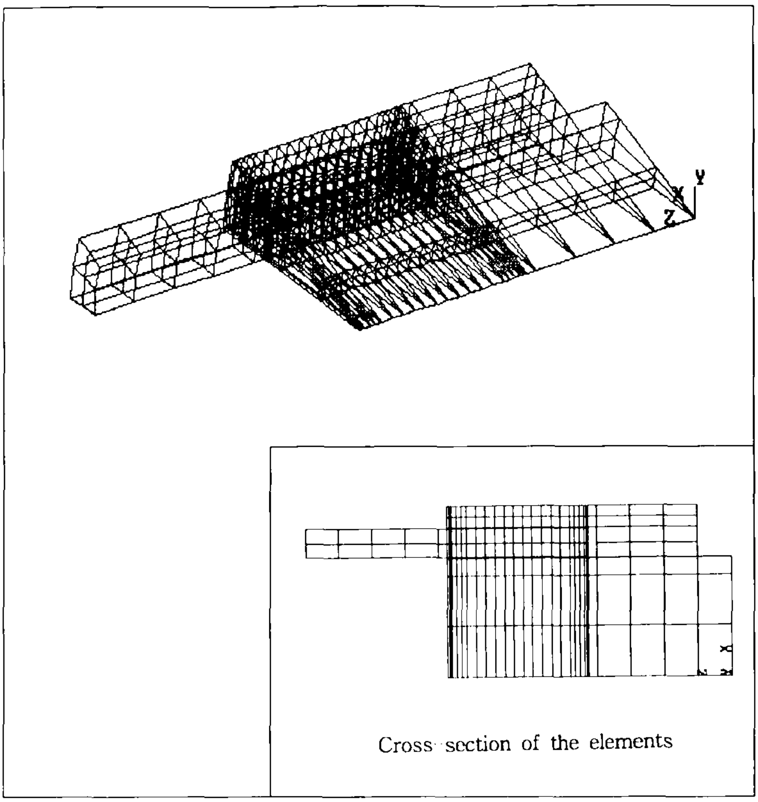


FIGURE 12 Finite element mesh for the calculation of the stresses in the single lap joint (For clarity, only a 20° section is displayed).

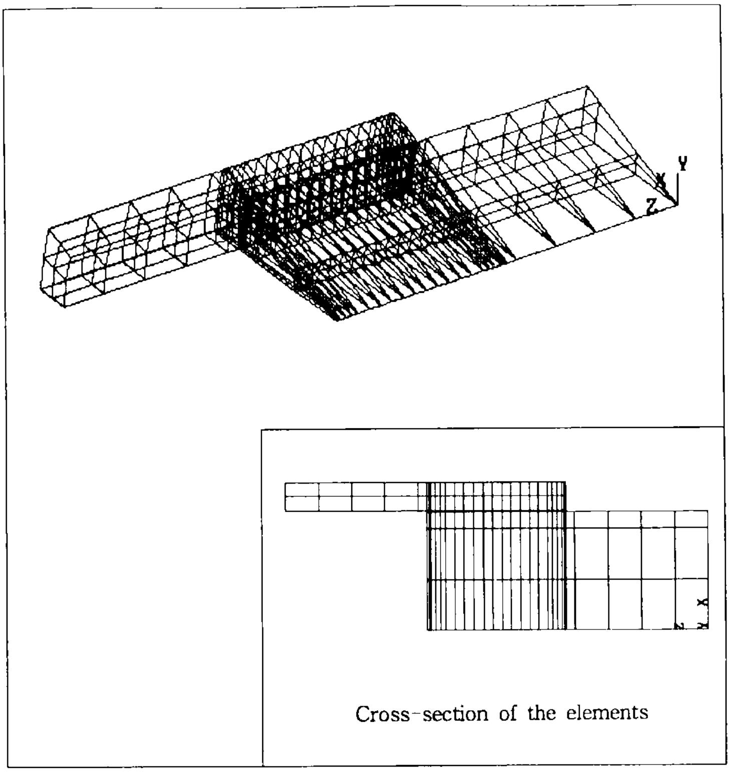


FIGURE 13 Finite element mesh for the calculation of the stresses in the double lap joint (For clarity, only a 20° section is displayed).

the shear stress-strain curve of the epoxy adhesive was obtained by using the VonMises failure criterion[11] as follows:

$$\sigma_Y = \sqrt{3} \cdot \tau_Y \tag{1}$$

$$\varepsilon_Y = \frac{\sqrt{3} \cdot \tau_Y}{2G(1+\nu)} \tag{2}$$

τ_Y: shear yielding stress
σ_Y: tensile yielding stress
ε_Y: tensile yielding strain
ν: Poisson's ratio
G: shear modulus

TABLE II
Mechanical properties of the steel (SM45C) adherend

Tensile Modulus (GPa)	200
Tensile Strength (MPa)	345
Poisson's ratio	0.33

Since the rate of displacement of the torsion tester was fixed at 0.4 mm/min in the torsion tests, the shear stress-strain curve for 0.4 mm/min as shown in Figure 5 was used for the epoxy adhesive. Figure 14 represents the calculated tensile stress-strain curve from the experimental shear stress-strain curve. In Figure 14, the fracture of the epoxy adhesive is assumed to occur when the maximum strain reaches the ultimate strain. Since interfacial failure does not occur in this specimen, as shown in Figure 11, interfacial shear failure of the adhesive joint was not considered. Also, the steel adherend is assumed to have failed when the equivalent stress proposed by the VonMises criterion reaches the yield stress.

The torque transmission capability, calculated using ANSYS, is compared with experimental torque transmission capability in Figure 15. The calculated torque transmission capabilities in the single lap joint and the double lap joint were within 14% and 1% of the experimental results, respectively. Figures 16 and 17 represent the adhesive shear stress distributions of the single and double lap joints at failure.

The dependency of the torque transmission capabilities of the double lap joint on the outside adherend thickness was also investigated by finite element analysis. It was found that the outside adherend failed prior to the fracture of the adhesive when the outside adherend thickness was less than 1.5 mm, as shown in Figure 18. If the outside adherend thickness is larger than 1.5 mm, the torque transmission capabilities of the double lap joint will be decreased because the adhesive shear strain concentration increased at one or other of the ends of the adhesive. Therefore, it is required for the maximum torque transmission capabilities that the shear strains at both ends of the adhesively-bonded joint should be equal and that the adherend thickness should be larger than the critical thickness at which the adherend fails. In this work, 1.5 mm outside adherend thickness was used.

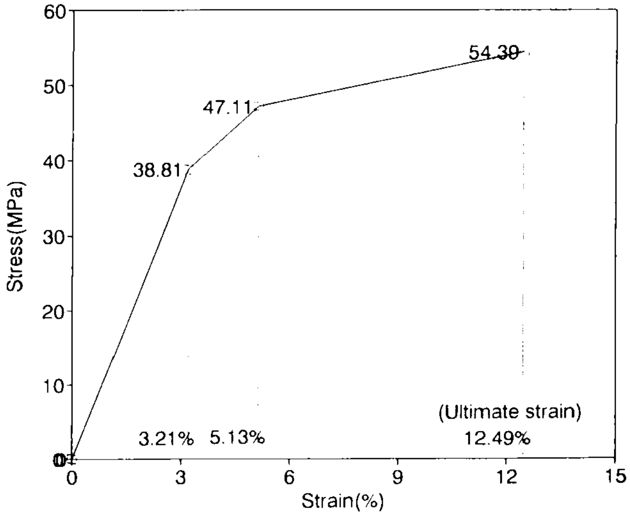


FIGURE 14 Calculated multi-linear tensile stress-strain curve from the experimental shear stress-strain curve of Figure 5 when the rate of displacement is V = 0.4 mm/min.

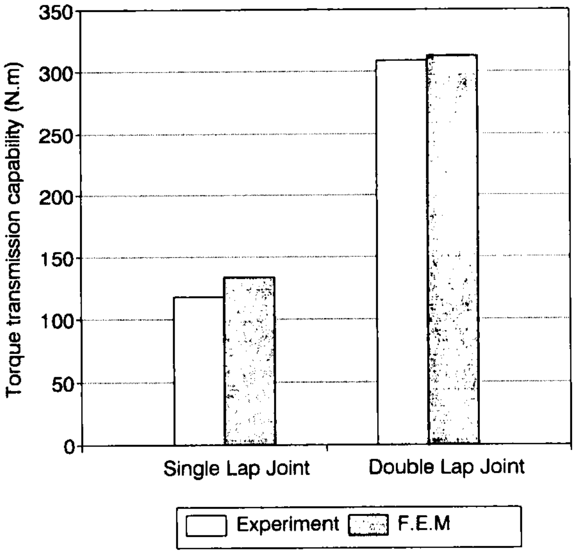


FIGURE 15 Comparison of the torque transmission capability calculated by the finite element analysis and measured by the static torsion test.

TORSIONAL FATIGUE TEST

In the torsional fatigue test, the fatigue limit of the single lap joint was compared with that of the double lap joint. The fatigue tester used in this work is a Shimadzu TB-10B manufactured by Shimadzu Corp.[13] It has a dynamic capability of ± 50 N.m for both

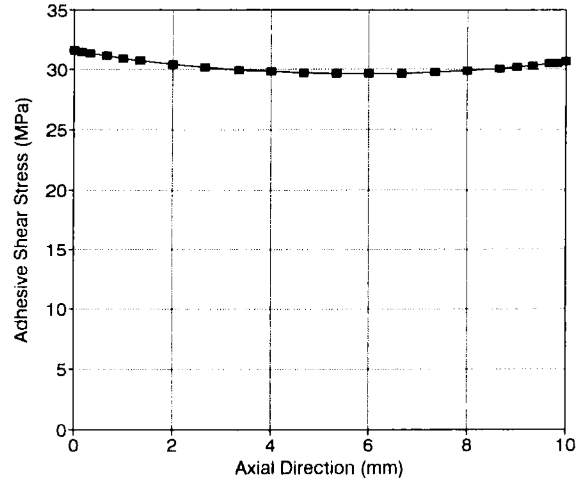


FIGURE 16 Shear stress distribution in the adhesive of the tubular single lap joint when the maximum shear strain reached the ultimate shear strain.

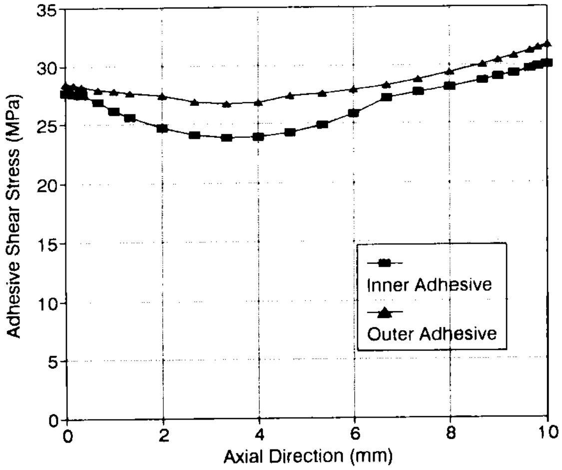


FIGURE 17 Shear stress distributions in the adhesive of the tubular double lap joint when the maximum shear strain reached the ultimate shear strain.

bending and torsion and the frequency of the cyclic stress was fixed at 33 Hz. Although the frequency of the cyclic stress is relatively high, the heat generated in the adhesive could be dissipated easily through the steel adherends because of their conductivity and large mass relative to the adhesive. Therefore, the problem of high frequency of the cyclic stress was not taken into consideration in this study. The fatigue test results were expressed by the average fatigue strength, S_a, which is defined by the following

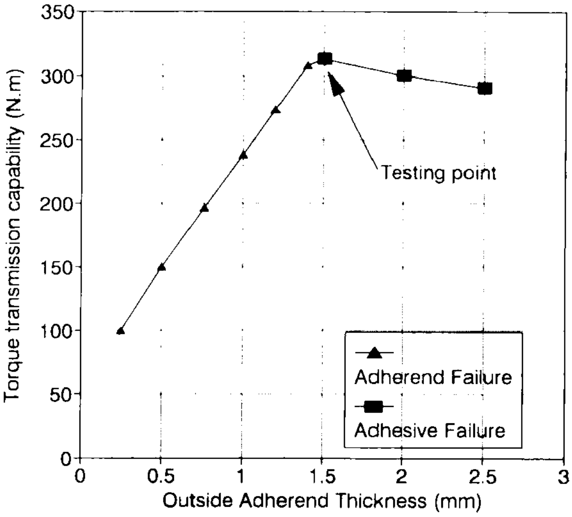


FIGURE 18 Effect of the outside adherend thickness on the torque transmission capability.

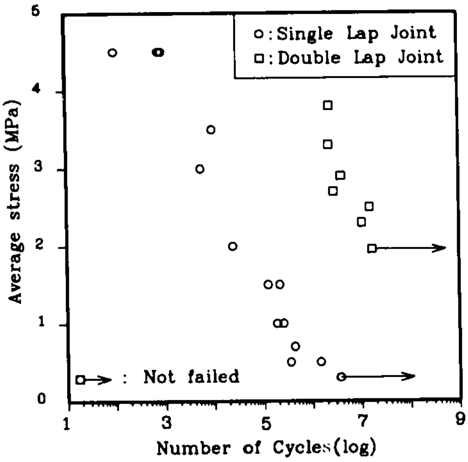


FIGURE 19 Fatigue strengths of the single lap joint and the double lap joint.

equation:

$$S_a = \frac{\text{Torque}}{2\pi r^2 l} \tag{3}$$

r: average radius of the adhesive
l: length of the adhesive joint

In the double lap joint, r was calculated as follows:

$$r = \sqrt{r_1^2 + r_2^2} \tag{4}$$

r_1: average radius of the inner surface of the adhesive
r_2: average radius of the outer surface of the adhesive

From the test, it was found that the average fatigue strength of the double lap joint was 6.5 times as large as that of the single lap joint, as shown in Figure 19. Also, it was found that the dynamic torque transmission capability of the double lap joint was 16 times as large as that of the single lap joint. Therefore, it may be concluded that as for as

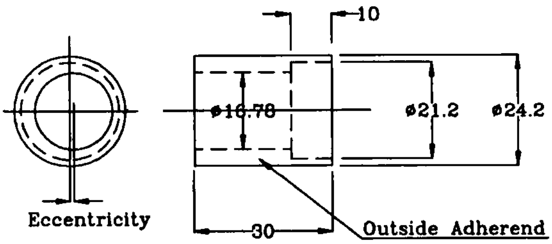


FIGURE 20 Outside adherend specimen of the double lap joint having an eccentricity. Dimensions in mm.

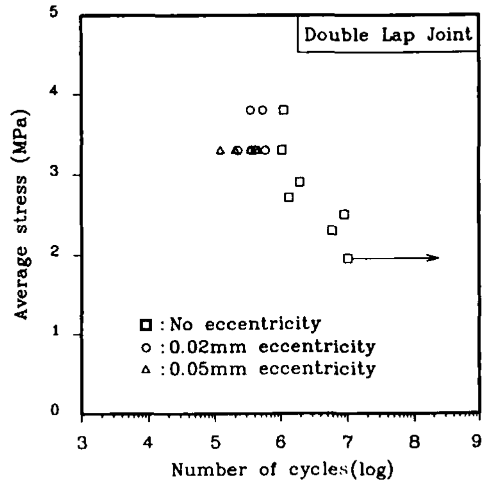


FIGURE 21 Effect of the eccentricity of the outer adherend of the double lap joint on the fatigue strength.

dynamic torque is concerned, double lap joints are much better structures as compared with single lap joints in dynamically-loaded tubular structures.

Since perfectly concentric adhesive bonding between the inner and outer adherends is seldom possible, the effect of the eccentricity of the outer adherend on the fatigue strength in the double lap joint was investigated. Figure 20 represents the shape of the outer adherend which has eccentricity. In this study, the amount of the eccentricity was fixed at 0.01 mm and 0.02 mm. The relative eccentricities were then 10% and 20%, respectively, because the adhesive thickness was fixed at 0.1 mm. As shown in Figure 21, the fatigue life of the double lap joint with eccentricity was significantly decreased.

CONCLUSIONS

In this work, the tubular adhesively bonded single lap joint and the double lap joint were manufactured and their torque transmission capabilities were investigated by an experimental method and by a finite element method. From the analytical and experimental observations, the following conclusions may be made:

1. Taking into consideration the nonlinearity of the adhesive, the torque transmission capabilities, calculated by a 3-dimensional finite element method, of the single lap joint and the double lap joint agreed within 14% and 1% with the experimental torque transmission capabilities, respectively.
2. In the static torsion test, it was found that the torque transmission capability of the double lap joint was 2.7 times as large as that of the single lap joint.
3. The average fatigue strength of the double lap joint was increased 6.5 times over that of the single lap joint and the dynamic torque transmission capabilities of the double

lap joint was increased 16 times over that of the single lap joint. Therefore, double lap joints are recommended for dynamically-loaded structures.

4. The fatigue life of the double lap joint was significantly decreased if there was an eccentricity between the inner and outer adherends.

References

1. T. J. Reinhart, *Composites* (ASM International, Metals Park, Ohio 44073, U.SA., 1987), pp. 479–495.
2. J. R. Vinson and R. L. Sierakowski, *The Behavior of Structures Composed of Composite Materials* (Martinus Nijhoff Publishers, Boston, U.S.A., 1987), Chap. 8.
3. D. Kutscha and K. E. Hofer, Jr., "Feasibility of Joining Advanced Composite Flight Vehicles," AFML-TR-68-391 (1969).
4. R. D. Adams and N. A. Peppiatt, "Stress Analysis of Adhesive Bonded Tubular Lap Joints", *J. Adhesion* **9**, 1–18 (1977).
5. C. T. Chon, "Analysis of Tubular Lap Joint in Torsion", *J. Composite Materials* **16**, 268–284 (1982).
6. P. J. Hipol, "Analysis and Optimization of a Tubular Lap Joint Subjected to Torsion", *J. Composite Materials* **18**, 298–311 (1984).
7. R. S. Alwar and Y. R. Nagaraga, "Viscoelastic Analysis of an Adhesive Tubular Lap Joint", *J. Adhesion* **8**, 79–82 (1976).
8. S. R. Graves and D. F. Adams, "Analysis of a Bonded Joint in a Composite Tube Subjected to Torsion", *J. Composite Materials* **15**, 211–224 (1981).
9. D. G. Lee, K. S. Kim and Y. T. Im, "An Experimental Study of Fatigue Strength for Adhesively Bonded Tubular Single Lap Joints", *J. Adhseion* **35**, 39–53 (1991).
10. ANSYS *User's Manual* (Swanson Analysis Systems, Inc., Houston, TX, U.S.A., 1989).
11. S. H. Crandall, N. C. Dahl and T. J. Lardner, *An Introduction to the Mechanics of Solids* (McGraw-Hill, New York, U.S.A., 1978), Chap. 5.
12. 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).
13. Shimadzu Corp., 3, Kanda-Nishikicho 1-chome, Chiyoda-ku, Tokyo 101, Japan.