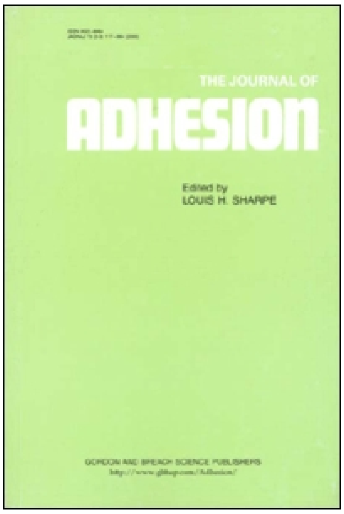

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Torque Transmission Capabilities of Bonded Polygonal Lap Joints for Carbon Fiber Epoxy Composites

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Although carbon fiber epoxy composite materials have excellent properties for structures, the joint in composite materials often reduces the efficiency of the composite structure because the joint is often the weakest area in the composite structure.

In this paper, the effects of the adhesive thickness and the adherend surface roughness on the static and fatigue strengths of adhesively-bonded tubular polygonal lap joints have been investigated by experimental methods. The dependencies of the static and fatigue strengths on the stacking sequences of the composite adherends were observed.

From the experimental investigations, it was found that the fatigue strength of the circular adhesively-bounded joints was quite dependent on the surface roughness of the adherends and that polygonal adhesively-bonded joints had better fatigue strength characteristics than circular adhesively-bonded joints.

KEY WORDS adhesive polygonal single lap; adhesive circular single lap; adhesive; adherend; fatigue test; static torque test; bonded joints.

1. INTRODUCTION

Although carbon fiber epoxy composite materials have been widely used in aircraft and spacecraft structures because of their high specific strength, modulus and high damping capacity,[1–3] the structural efficiency of the composite structure is established, with very few exceptions, by its joints, not by its basic structure.

There are two kinds of joints: mechanical and adhesively-bonded. Mechanical joints are created by fastening the substrates with bolts or rivets. The holes for bolts and rivets have an adverse effect on the stress transmission due to fiber breakage. Furthermore, the stress concentration of the composite materials around holes can be larger than that of conventional isotropic materials due to the anisotropy of the composite materials.[4] Moreover, the requirements of fatigue strength, aerodynamically-smooth surface and aesthetic appearance limit the employment of the mechanical joints.

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Adhesively-bonded joints can distribute the load over a larger area than mechanical joints, require no holes, add very little weight to the structure and have superior fatigue resistance. Therefore, such joints can have more than 3 times as large a joint strength under shear as that of the riveted joint.[5] The adhesively-bonded joint reduces the noise and vibration of the structure.

However, the adhesively-bonded joint requires careful surface preparation of the adherends and its quality is dependent on the skill of the manufacturing personnel. The employment of the adhesive joint is limited by service environment burdens such as humidity and temperature. Also, it is difficult to disassemble for inspection and repair. Although there are many such difficulties in the realization of reliable adhesively-bonded joints, recent developments of good quality adhesives have made the adhesive joint early applicable in composite structures.

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 the most popular, due to its ease of manufacture and its relatively low cost. However, the single lap joint produces high stresses and rapidly-changing stress gradients in the end region of the adhesive layer.

Static studies, utilizing analytical and finite element methods, for the tubular single lap joint have been performed more frequently than for other configurations.

Adams and Peppiatt[6] refined the solution of Volkersen and gave a closed-form solution for the shear stresses in the tubular single lap joints. They analyzed adhesively-bonded tubular single lap joints which were subjected to axial torsional loads using the finite element method when the adhesive had a fillet.[6]

Chon[7] analyzed the adhesive tubular single lap joint whose adherends were composite materials in a closed-form using a method similar to that of Adams and Peppiatt.

Graves and Adams[8] used the finite element method to calculate the stresses of the tubular single lap joint whose adherends were orthotropic composite materials subjected to torsion. They obtained the stresses of the adherends by the ply-by-ply analysis. They also obtained the stresses of the adherends with smeared laminate properties.

Alwar and Nagaraja[9] used a finite element method to obtain the stresses in the tubular single lap joint subjected to torsion. The time-dependent properties of the adhesive were included in the finite element analysis.

Hart-Smith[10] 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.

Imanaka *et al.*[11] investigated the effect of filler addition on the fatigue strength of an adhesively-bonded butt joint under cyclic load. They also investigated the effect of the adhesive thickness on the fatigue strength.

While the stress analyses of the adhesive tubular lap joints were extensive, the experimental verifications of the static and dynamic strengths of the adhesive joint were not. Since adhesively-bonded joints are usually under dynamic load, the dynamic behavior of the joint must be investigated.

The adhesively-bonded single lap joints whose cross sections are polygonal shapes can sustain some load after the adhesive failure; hence, they might be a safer design.

In this work, adhesively-bonded circular single lap joints were tested to investigate the dependency of the static and dynamic torque transmission capabilities on the adhesive thickness and on the arithmetic surface roughness of the adherend. Also, adhesively-bonded polygonal single lap joints such as the circular, triangular, tetragonal, pentagonal and hexagonal joints whose outer adherends were made of S45C steel, were manufactured in order to give partial mechanical characteristics to the adhesively-bonded tubular joints. These joints were tested in fatigue modes to investigate the effects of the cross-sectional shape, the adhesive thickness, the arithmetic surface roughness, and the cyclic stress level on the static and fatigue torque transmission capabilities. Also, adhesively-bonded polygonal and elliptical single lap joints whose adherends were composed of steel and carbon fiber epoxy composite materials were statically tested to investigate the dependency of the torque transmission capabilities on the stacking sequences of the composite adherends.

2. JOINT SPECIMENS AND THE ADHESIVE

The epoxy adhesive used was IPCO 9923 manufactured by the Imperial Polychemicals Corporation (Azusa, California, USA). The epoxy was a rubber-toughened, two-part adhesive which had high shear and peel strength. The mixing ratio of the resin and hardener was 1:1 by weight and the curing time was 75 minutes at 120°C. Table I shows the typical properties of the adhesive.

The fatigue tester used in the experiment was a Shimadzu TB-10 made by Shimadzu Corporation in Japan and had a dynamic capacity of $\pm$ 50 Nm for both bending and torsion applications. The bending and torsional moments of the tester were produced by rotating the eccentric mass and the frequency of the cyclic stress was fixed at 2,000 rpm. When the frequency of the cyclic stress is high, there is a chance of a temperature rise in the adhesive. In these experiments, however, since the inner adherends were made of steel and had larger mass compared with the adhesive mass, the heat generated in the adhesive was dissipated easily through the steel adherends. Therefore, the high frequency of the cyclic stress was not taken into consideration in this test. The static torque transmission tests were performed by a tension-torsion tester, manufactured by MTS (Minneapolis, Minnesota, USA), whose torque capacity was 1,000 Nm.

The size and shape of the test specimens were determined according to the recommendation of the tester manufacturers. Figure 1 shows the dimensions of the steel-steel circular single lap joints and Figure 2 shows the dimensions of the steel-steel polygonal single lap joints. For the steel-steel joints both the outer and inner adherends were composed of S45C steel. In the manufacturing of the joint specimens, a Teflon bar was

TABLE I
Properties of the epoxy adhesive (IPCO 9923)

Lap Shear Strength (MPa)	13.7 (ASTM D-1002–72)
Tensile Modulus (GPa)	1.3
Tensile Strength (MPa)	45
Shear Modulus (GPa)	0.46
Poisson's ratio	0.41

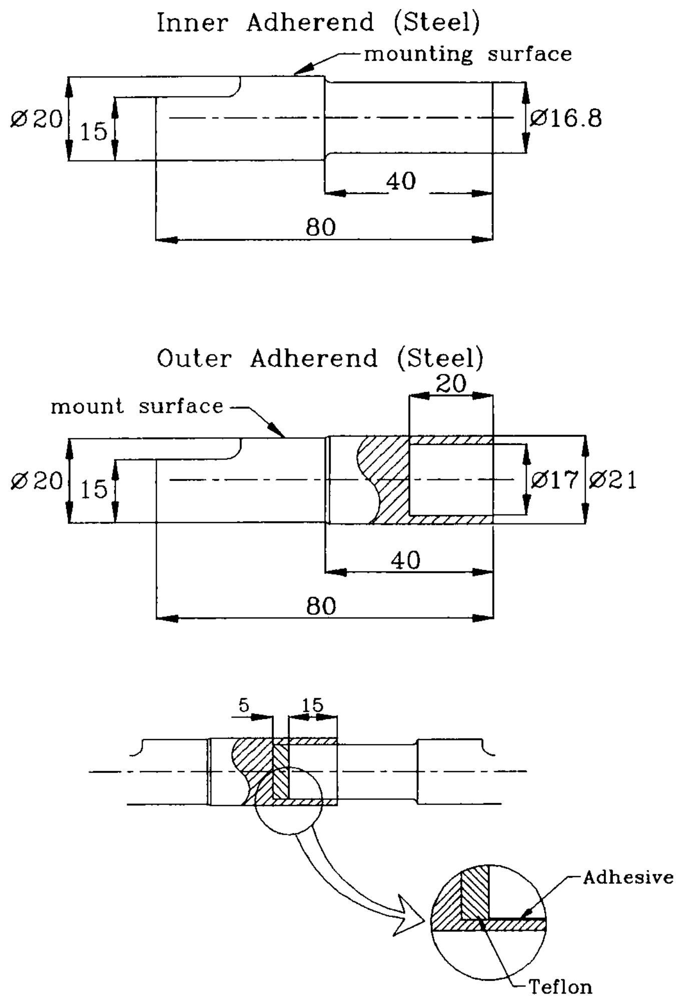


FIGURE 1 Dimensions of the adherends of the steel-steel circular single lap joint.

tightly inserted inside the outer adherend to remove the fillet of the adhesive which might affect the torque transmission capabilities of the joint.

Figure 3 shows the dimensions of the steel-composite circular single lap joint and Figure 4 shows the dimensions of the steel-composite polygonal single lap joints. The composite-steel adhesively-bonded joint was composed of the outer composite adherend and two inner steel adherends. The composite adherend was made of carbon fiber epoxy composite materials whose unidirectional properties are shown in Table II. Since there are two adhesively-bonded areas in the composite-steel joints, the angle of twist measured in experiments was divided by two to obtain the angle of twist of one joint.

The bonding operation was performed in a room where relative humidity was maintained at less than 60% by dehumidifying. The mixed adhesive (resin and

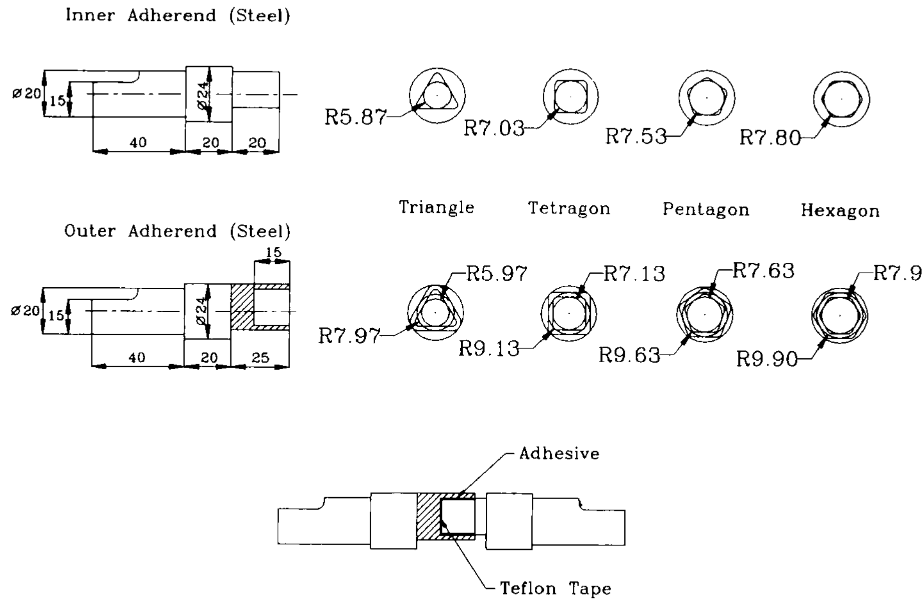


FIGURE 2 Dimensions of the adherends of the steel-steel polygonal single lap joints.

hardener) was stored for 10 minutes in a vacuum chamber to eliminate air bubbles. The material was then poured in an injector with care so as not to introduce additional air bubbles. The adhesive in the injector was slowly injected to the bottom surface of the outer adherend. After this, the inner adherend was pushed down slowly to the bottom surface of the outer adherend. Since concentric bonding of the adhesively-bonded tubular lap joint was indispensable for reliable joint quality, the joint clamped, after wetting with the adhesive, was using a V-block whose surface was ground accurately (Figure 5). In the bonding operation for the joint with steel-steel adherends using the V-block, the mounting surfaces of the inner adherend and the outer adherend as shown in Figure 1 were clamped on the inside surface of the V-block. However, in the bonding operation for the joint with steel-composite adherends using the V-block, the steel adherend and the composite adherend were clamped after a tight circular steel tube was fitted onto the outer surface of the composite adherend. Figure 6 shows the photograph of the adhesively-bonded polygonal single lap joints with the steel-composite adherends.

3. FATIGUE AND STATIC TESTS OF THE ADHESIVELY-BONDED JOINTS

3-1. Fatigue Test of the Circular Single Lap Joint with Steel-Steel Adherends

When the adhesively-bonded circular single lap joint was under static torque, the theoretical calculation by Adams[6] predicted that the torque transmission capabilities would increase as the adhesive thickness increased. However, there is a paper which

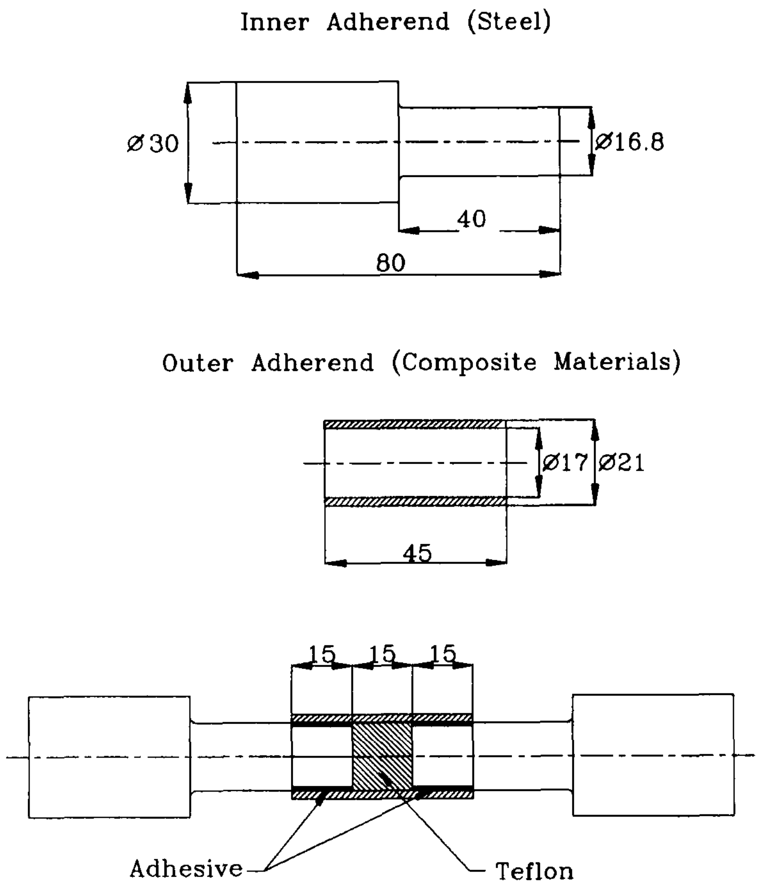


FIGURE 3 Dimensions of the adherends of the steel-composite circular single lap joints.

reports that the fatigue limit increases as the adhesive thickness decreases, which is contrary to the static case.[12] In the present work, adhesive joints with adhesive thickneses of 0.1 and 0.2 mm were again tested to verify the dependency of the fatigue limit on the arithmetic surface roughness under a dynamic torque load whose average amplitude of alternating shear stress was expressed as follows:

$$\tau_a = \frac{T_{amp}}{2\pi a^2 l}$$

where T_{amp} is the amplitude of the alternating torque, a is the mean radius of the adhesive and l is the bonding length. All the fatigue experiments were performed at a stress ratio $R(\sigma_{min}/\sigma_{max}) = -1$.

Figure 7 shows the fatigue test results of the circular steel-steel single lap joints in which the best fatigue limit was obtained when the adhesive thickness and arithmetic

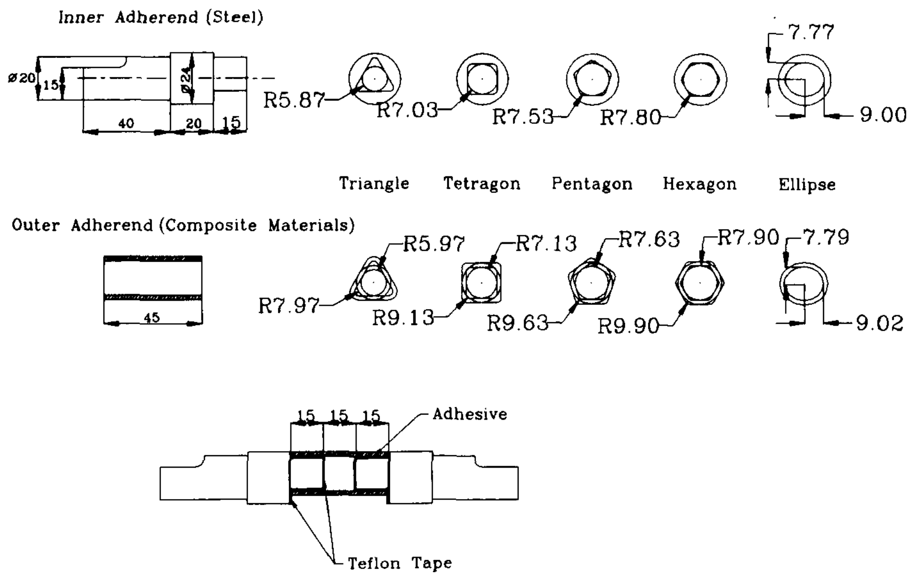


FIGURE 4 Dimensions of the adherends of the steel-composite polygonal single lap joints.

TABLE II
Properties of the unidirectional carbon fiber epoxy composite

Tensile Modulus (GPa)	153.0
Transverse Modulus (GPa)	10.9
Shear Modulus (GPa)	5.6
Poisson's Ratio	0.3
Tensile Strength (GPa)	2.0
Transverse Strength (MPa)	56
Shear Strength (MPa)	72
Fiber Content (Volume Fraction, %)	60
Density (10^3 kg/m^3)	1.6

surface roughness were 0.1 mm and 2 μm, respectively. In order to observe the effect of the arithmetic surface roughness of the adherend on the fatigue strength of the adhesively-bonded joint, the outer adherends of the specimens failed under fatigue loading were machined to remove 0.1 mm thickness with a lathe. Then, the outer adherends were cut with a sharp razor in the axial direction. Figures 8(a)–(d) show the fractographies of the steel-steel joint adherends when the arithmetic surface roughnesses were 1 μm, 2 μm, 3 μm and 4 μm, respectively, and the adhesive thickness was 0.2 mm. When the arithmetic surface roughnesses were 1 μm and 4 μm, a longer portion of the adhesive was adhered to the surface of the inner adherend. This phenomenon might be attributed to the interfacial failure of the adhesive by the shear stress between the surface of the adhesive and the adherend. When the arithmetic surface roughnesses were 2 μm and 3 μm, the adhesive was adhered to the surfaces of both the inner and

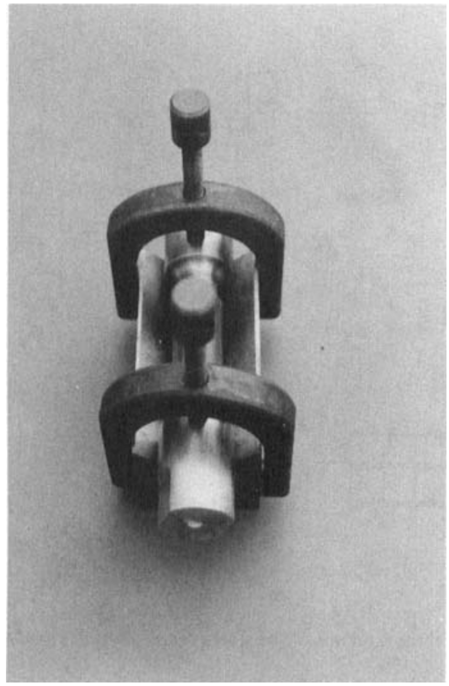


FIGURE 5 V-block for the concentric bonding.

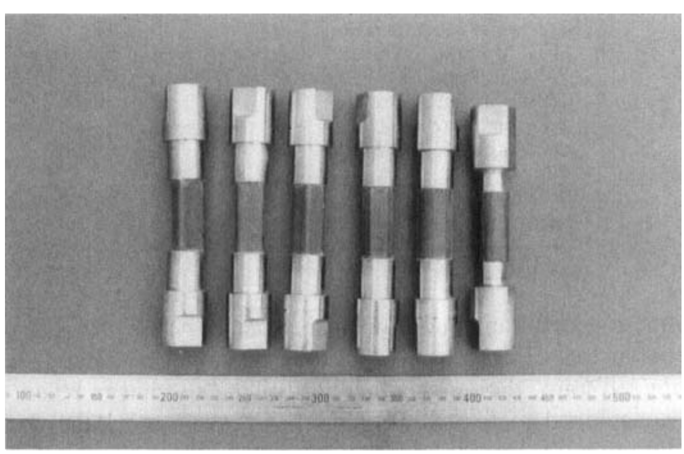
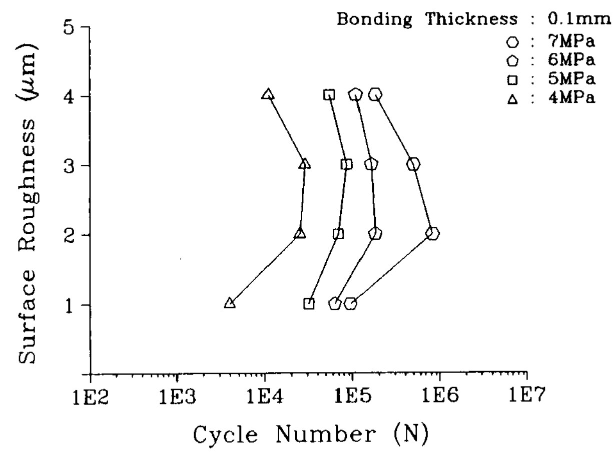


FIGURE 6 Photograph of the adhesively-bonded polygonal single lap joints with the composite-steel adherends. (from the left: triangular, tetragonal, pentagonal, hexagonal, elliptical and circular)

outer adherends. The adhesive was most uniformly distributed on both surfaces when the arithmetic surface roughness of the adherend was 2 μm. This phenomenon might may be attributed to the bulk failure of the adhesive. From these experiments, it might be concluded that the optimum arithmetic surface roughness was 2 μm.



(a) adhesive thickness : 0.1mm

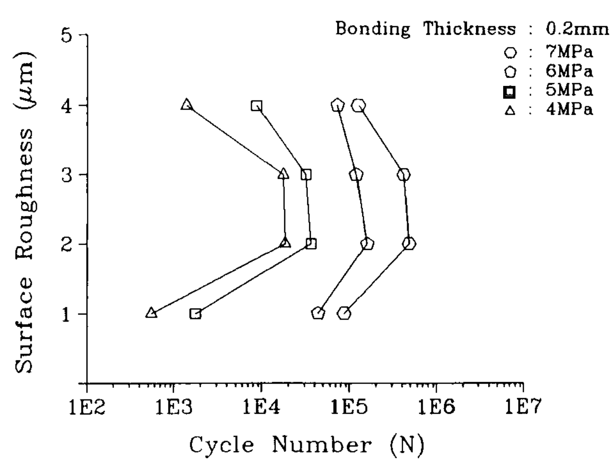


FIGURE 7 Relationship of the fatigue limit *vs.* arithmetic surface roughness of the steel-steel adherends for the circular single lap joints, when $R(\sigma_{min}/\sigma_{max}) = -1$. (a) adhesive thickness: 0.1 mm (b) adhesive thickness: 0.2 mm.

3-2. Static Torque Test of the Circular Single Lap Joint with Steel-Steel Adherends

Since 2 μm arithmetic surface roughness of the adherend gave the best fatigue strength, the dependency of the adhesive thickness on the static strength of the adhesively-bonded circular steel-steel single lap joint was tested at 2 μm arithmetic surface

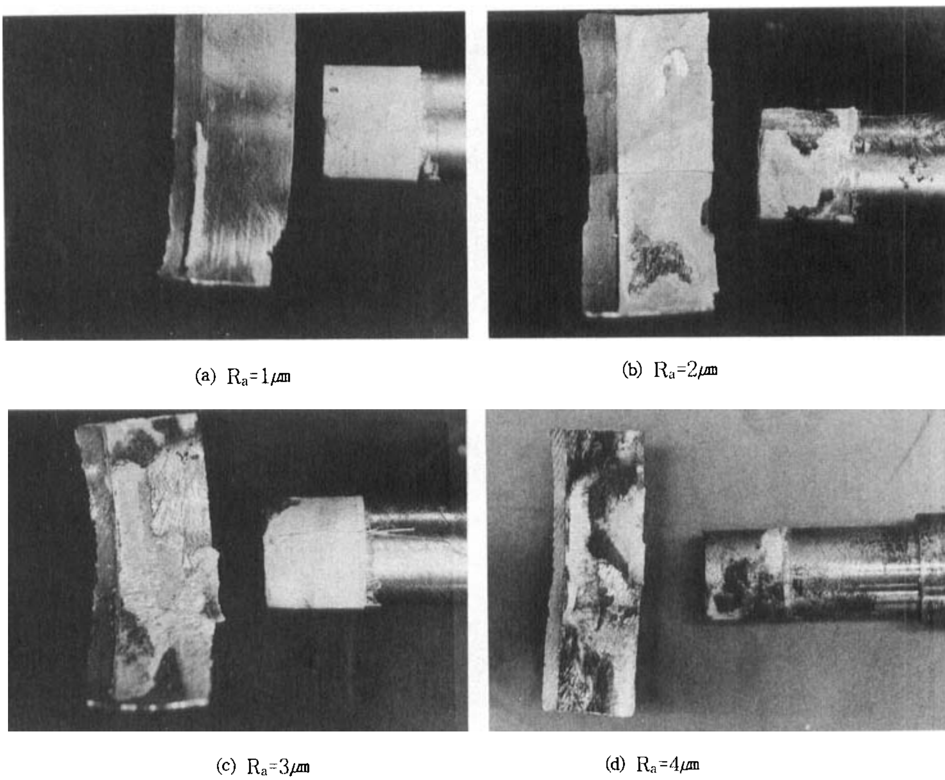


FIGURE 8 Fractography of the failed adherends of the steel-steel joints in the fatigue test the arithmetic average surface roughnesses, R_a. (a) $R_a = 1$ μm (b) $R_a = 2$ μm (c) $R_a = 3$ μm (*d*) $R_a = 4$ μm.

roughness. Figure 9 shows the dependency of the static torque transmission capabilities of the circular steel-steel single lap joint on the adhesive thickness. In Figure 9, the torque transmission capabilities decreased as the adhesive thickness increased, contradictory to the result of the previous theory.[6] However, it was found that the adhesive bonding operation was difficult when the adhesive thickness was less than 0.1 mm. Therefore, it was concluded that 0.1 mm adhesive thickness was optimum for a practical bonding operation.

3-3. Fatigue Test of the Polygonal Steel-Steel Single Lap Joint

The adhesively-bonded circular single lap joint cannot sustain torque after adhesive failure, but the adhesively-bonded polygonal single lap joint can sustain some torque after adhesive failure due to the mechanical joining mechanism of polygons under torque. The adhesive in the polygonal joints is subjected to shear and normal stresses under torque.

In order to compare the torque transmission capabilities of the polygonal joints, all the areas of the cross sections of the polygons were designed to be the same and the sides

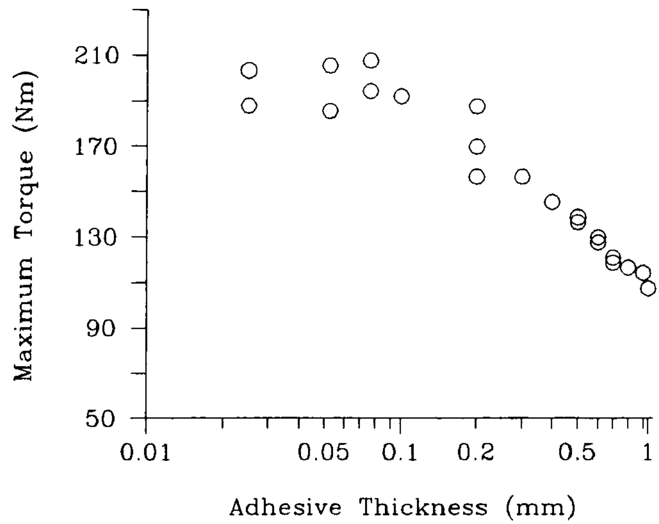


FIGURE 9 Static torque transmission capabilities of the adhesive circular steel-steel single lap joints with respect to the adhesive thickness when the arithmetic surface roughness was 2 μm.

were equilateral. The arithmetic surface roughness and adhesive thickness were selected as 2 μm and 0.1 mm, respectively, since these two values gave the best fatigue limits for circular single lap joints. Since the polygonal joints sustained some torque even after adhesive failure, it was not easy to detect the exact cycle of the initial failure of the adhesive. Therefore, in this work, an accelerometer was attached to the fatigue tester as shown in Figure 10 to detect the increase of the amplitude of the angle of twist of the joint after adhesive failure. The amplitude signal from the accelerometer was processed by a personal computer to count the fatigue cycles. As shown in Table III, the triangular joint had the longest number of cycles before fatigue failure. Figure 11 shows that the hexagonal joint could sustain some torque after adhesive failure.

3-4. Static Torque Test of the Circular Single Lap Joint With Steel-Composite Adherends

The mechanical properties of carbon fiber epoxy composite materials which were used as the outer adherend material of the composite-steel adhesively bonded joint are dependent on the stacking sequence. Consequently, the dependenc of the torque transmission capabilities of the joints on the stacking angle $[\pm\alpha]_{nT}$ was tested by varying the stacking angle, α, from the axis of the composite adherends. The inner adherend was made of steel. In order to compare the torque transmission capabilities, the size of the composite adherend was designed to be the same as that of the outer steel adherend. The adhesive thickness and the arithmetic surface roughness of the adherend were 0.1 mm and 2 μm, respectively. Even though the control of the surface roughness of the composite adherend was not easy, it was possible to obtain an arithmetic surface

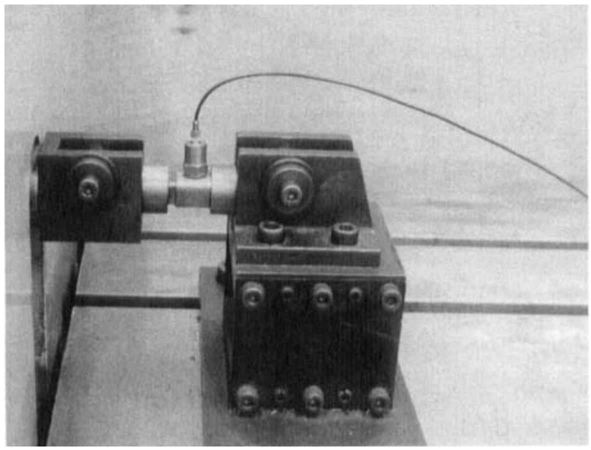


FIGURE 10 Photograph of the adhesive joint in the fatigue tester with the accelerometer attached to detect the fracture status of the adhesive.

TABLE III
Fatigue failure cycles of polygonal single lap joints (Amplitude of the alternating stress: 5MPa, Bonding thickness: 0.1 mm)

Cross section of the specimen	Number of stress cycles before fracture
Triangular	1.8×10^6
Tetragonal	3.5×10^5
Pentagonal	8.0×10^4
Hexagonal	6.0×10^4
Circular	2.0×10^5

roughness of 2 μm by abrading with sand papers. The stacking angles of the composite adherend were increased from $[\pm 5]_{nT}$ to $[\pm 45]_{nT}$ in $\pm 5°$ intervals.

Figure 12 shows the static torque transmission capabilities of the adhesively-bonded single lap joint whose outer adherend was made of carbon fiber epoxy composite materials and inner adherend was made of steel. In Figure 12, the torque transmission capabilities increased until $[\pm 25]_{nT}$ and then decreased as the stacking angle increased. Figure 13 shows the angle of twist of the joint in which the angle of twist decreased as the stacking angle increased.

3-5. Static Torque Test of the Polygonal Composite-Steel Single Lap Joint

Since the polygonal joint can sustain some torque after adhesive failure, in this experiment the polygonal single lap joints whose adherends were made of the carbon fiber epoxy composite material and the steel, were tested to investigate the effects of the cross sectional shapes and the stacking sequence on the torque transmission capabili-

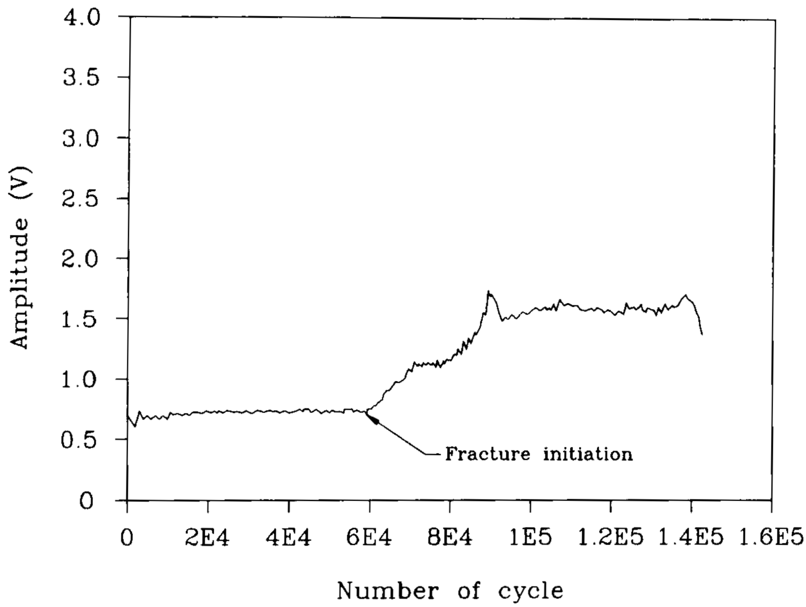


FIGURE 11 Amplitude of the accelerator *vs.* number of cycles in the fatigue torsion tests. (Cross section: hexagon, amplitude of the alternating stress: ± 5MPa)

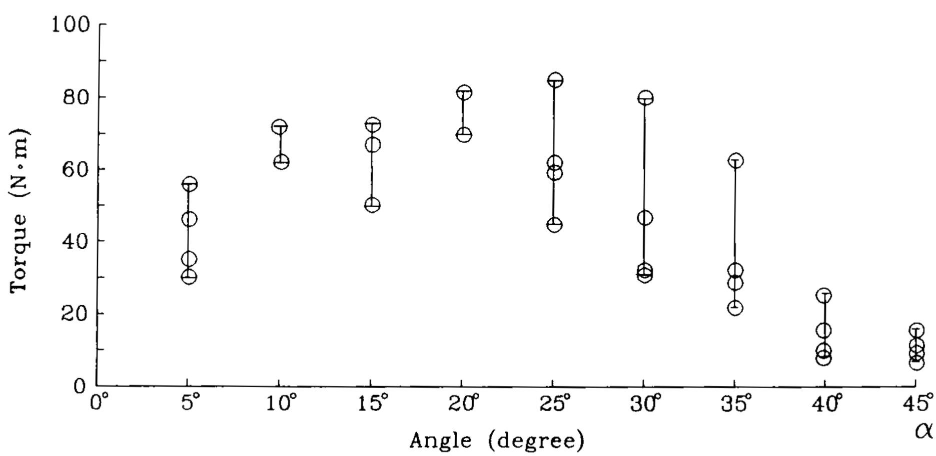


FIGURE 12 Static torque transmission capabilities of the circular single lap joint with respect to the stacking sequence $[\pm \alpha]_{nT}$ of the composite adherends.

ties. The adhesive joining areas of the polygonal joints were designed to be the same as the circular joint to compare the torque transmission capabilities. To reduce the number of experiments, only the stacking sequences $[\pm 15]_{nT}$, $[\pm 30]_{nT}$ and $[\pm 45]_{nT}$ of the outer composite adherends were tested.

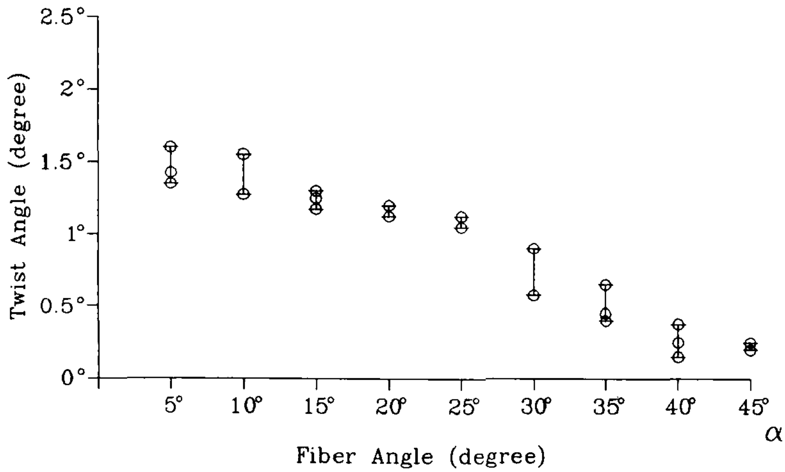


FIGURE 13 Maximum static twist angle of the circular single lap joint with respect to the stacking sequence $[\pm\alpha]_{nT}$ of the composite adherends.

Table IV shows that the torque transmission capabilities of the triangular and the tetragonal joints increased as the stacking angle of the composite adherends decreased, while those of the pentagonal and the hexagonal joints were independent of the stacking sequences. For the elliptical joint, the maximum torque transmission capability was obtained when the stacking sequence was $[\pm 30]_{nT}$.

Figure 14 shows the torque *versus* twist angle of the triangular joint after the first adhesive failure when the composite adherend had a $[\pm 30]_{nT}$ stacking sequence. Table V shows the secondary torque transmission capabilities of the joints after the first adhesive failure. The secondary torque transmission capabilities of the joint after the first adhesive failure were found not to be very dependent on the cross sectional shapes but dependent on the stacking sequences of the outer composite adherends.

TABLE IV

Static Torque transmission capabilities of adhesively-bonded polygonal single lap joints (Arithmetic surface roughness : 2 μm, Bonding thickness: 0.1 mm)

[unit: N_m]

Stacking sequence / Cross section	$[\pm 15]_{nT}$	$[\pm 30]_{nT}$	$[\pm 45]_{nT}$
Triangular	108 ~ 123	64 ~ 82	42 ~ 61
Tetragonal	104 ~ 117	63 ~ 72	52 ~ 60
Pentagonal	69 ~ 76	72 ~ 77	75 ~ 83
Hexagonal	70 ~ 87	87 ~ 98	76 ~ 87
Elliptical	86 ~ 97	152 ~ 157	22 ~ 26
Circular	62 ~ 71	79 ~ 83	16 ~ 20

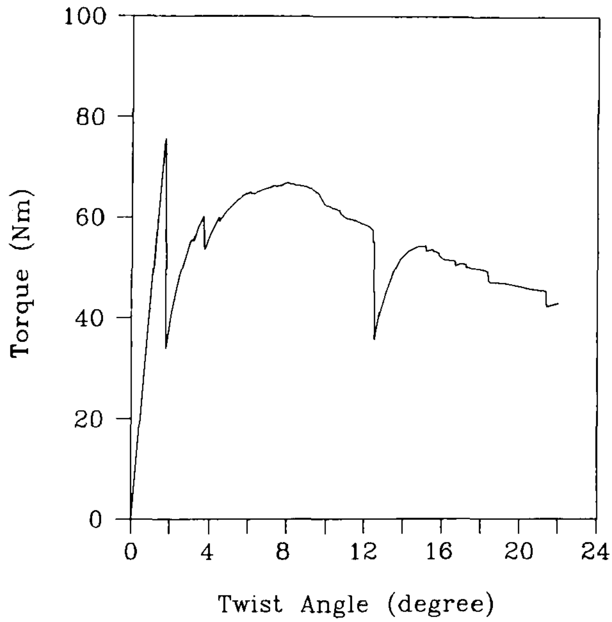


FIGURE 14 Variations of the torque with respect to the twist angle of the triangular cross sectional adhesive joint (Stacking sequence: $[\pm 30]_{nT}$).

TABLE V
Secondary torque transmission capabilities of the polygonal single lap joints when the composite adherends were failed after the adhesive fracture

[unit: N_m]

Stacking sequence	$[\pm 15]_{nT}$	$[\pm 30]_{nT}$	$[\pm 45]_{nT}$
Torque	23 ~ 41	62 ~ 82	75 ~ 120

4. CONCLUSIONS

From static and fatigue experiments of adhesively-bonded single lap joints such as the circular, triangular, tetragonal, pentagonal, hexagonal and elliptical joints, the following conclusions were made:

(1) The optimum adhesive thickness and the optimum arithmetic surface roughness of the adherend for the circular adhesively-bonded steel-steel single lap joint under fatigue loads were 0.1 mm and 2 μm, respectively.
(2) The adhesively-bonded steel-steel single lap joint whose cross sectional shape was triangular had the longest fatigue life.
(3) The static torque transmission capability of the adhesively-bonded circular single lap joint increased as the adhesive thickness decreased.

(4) The adhesively-bonded circular single lap joint whose outer adherend was carbon fiber epoxy composite material and inner adherend was steel had the largest static torque transmission capability when the stacking sequence of the composite material was $[\pm 25]_{nT}$. The angle of twist before fracture decreased as the stacking angle increased to $[\pm 45]_{nT}$.

(5) For the triangular and tetragonal cross sections, the adhesively-bonded single lap joints whose outer adherend was carbon fiber epoxy composite material and whose inner adherend was steel, the largest torque transmission capabilities were obtained when the stacking sequence of the composite materials was $[\pm 15]_{nT}$. For the circular cross sections, the largest torque transmission capability was obtained when the stacking sequence was $[\pm 30]_{nT}$. For the pentagonal and hexagonal cross sections, the torque transmission capabilities were independent of the stacking sequences.

Acknowledgements

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