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Fatigue Strength of Adhesive/Rivet Combined Lap Joints*

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Adhesive/rivet combined bonding has attracted special interest recently as a joining technique of high-strength steel because of its high joint efficiency.

In the present study, the strength characteristics of adhesive/rivet combined lap joints were investigated. To clarify bonding conditions capable of improving the fatigue strength of combined joints, fatigue tests were conducted on the rivet, adhesive and adhesive/rivet combined joints with different lap widths, adhesive and rivet strengths. Furthermore, to compare fatigue crack initiation and propagation behavior of the adhesive joint with that of the combined joint, the strain changes were measured by strain gauges bonded onto the adherend plate near the lap end.

The results indicate that the fatigue strength of adhesive joints can be improved through combination with rivets of nearly equal or slightly higher fatigue strength than the adhesive joint. Furthermore, we also confirmed that fatigue cracks propagate more gradually in combined joints than in adhesive joints after crack initiation.

KEY WORDS: adhesive joints; rivet joints; combined joints; high strength steel; fatigue; S—N relations.

1 INTRODUCTION

In many branches of industry, thinner high-strength steel has been substituted for low carbon mild steel in a move towards lightweight construction. However, it is difficult to join these thin plates by welding or rivet bonding. The use of high-strength thin plates makes special demands on the bonding process.

Hence, adhesive bonding of high-strength steel has attracted interest recently because of its high joint efficiency. However, from the viewpoint of reliability or the manufacturing process, there have been few cases where steel plates have been joined solely by adhesives. Usually, adhesive/rivet or spot-weld combined joining methods are

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used. Since weld-bonding methods have begun to be used in automobile construction, studies of its strength characteristics have been increasing. On the other hand, most current interest lies with adhesive/rivet combination joining methods as this minimizes damage to both the adherend and adhesive by obviating the need for exposure of the joint to strong heat, as with spot-welding. However, few studies have investigated the strength of the adhesive/rivet combined joint.[1–5]

In the present study, to clarify the bonding conditions which increase the fatigue strength of combined joints, the fatigue strengths of several kinds of rivet, adhesive and adhesive/rivet combined joints were investigated. In addition, the stress distributions of these joints were analyzed by finite element methods. Furthermore, to compare fatigue crack initiation and propagation behaviors of the adhesive joint with those of the combined joint, strain changes were measured by strain gauges bonded to the adherend plate near the lap end.

2. TEST SPECIMENS AND EXPERIMENTAL PROCEDURES

Figure 1 shows shapes and sizes of the adhesive/rivet combined joints. Adherend material was high-strength steel whose tensile strength is 110 kg/mm^2 (Sumitomo Steel Co. Ltd.). The adhesives used for bonding were the epoxy adhesive DP-gray (Sumitomo 3M Co. Ltd.) and the acylic adhesive Hard Rock C-355 (Denkikaga Ku Ind. Co. Ltd.). Hereafter, we refer to these adhesives as epoxy adhesive and acrylic adhesive, respectively. Mechanical properties of the adherend and adhesives are summarized in Table I. The aluminum alloy rivet Rv-6606-84 (Pop Rivet Fastener Co. Ltd.) and nickel-copper alloy rivet Rv-6696-84 (Pop Rivet Fastener Co. Ltd.) were used for bonding. Hereafter, we refer to these as 6606 and 6696 rivets, respectively. The bonding process of the combined joint was as follows: Bonding surfaces of the adherend were polished with grade 180 mesh emery paper under dry conditions then degreased with acetone. After pasting with adhesive, the adherend plates were fastened with rivets using an air riveter. The fastening process of the rivet is shown in Figure 2. The joint was allowed to stand for 1 day at room temperature and was then cured at 343° K for 6 hr. The adhesive and rivet joints were prepared with omission of the rivet fastening and adhesive bonding processes, respectively.

Cyclic tensile fatigue tests were conducted with an electro-hydraulic, closed-loop, fatigue testing machine with a loading capacity of 30 kN under a stress ratio of $R = 0.1$ and a loading frequency of $f = 30$ Hz.

To investigate fatigue crack initiation and propagation behaviors, strain changes were measured by strain gauges cemented onto the adherend plates near the lap end. The location of the strain gauges and schematic illustration of output waves are shown in Figure 3.

TABLE I
Mechanical properties of the adherend and adhesives

	Young's Modulus (GPa)	Poission's ratio
Epoxy adhesive	1.10	0.33
Acrylic adhesive	0.765	0.40
High strength steel	183.0	0.33

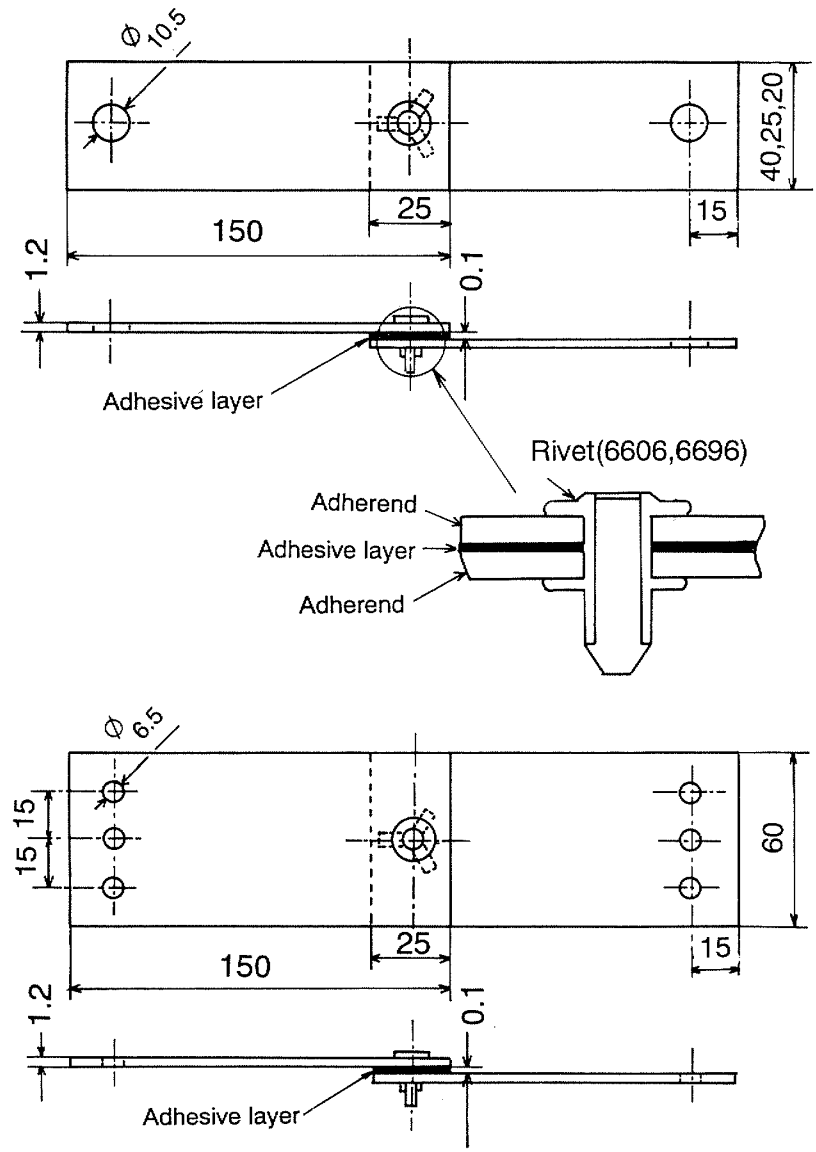


FIGURE 1 Shape and sizes of the adhesive/rivet combined joints.

3. EXPERIMENTAL RESULTS

3.1 S—N Relationships

The fatigue strength of adhesive joints increases with lap width; however, that of rivet joints is independent of lap width. To investigate the effects of adhesive strength in combined joints on the fatigue strength, in Figure 4(a), (b) and (c) are shown the S—N relationships of the rivet, adhesive and combined joints at different lap widths, where

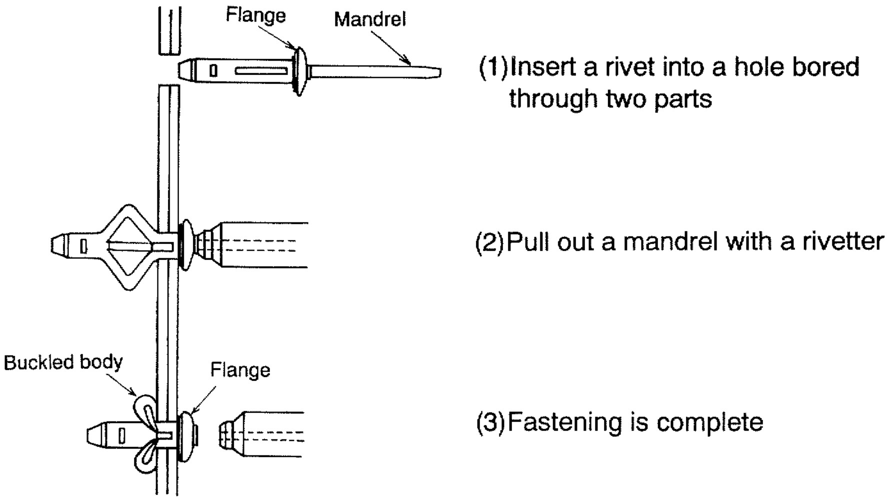


FIGURE 2 Rivet fastening process.

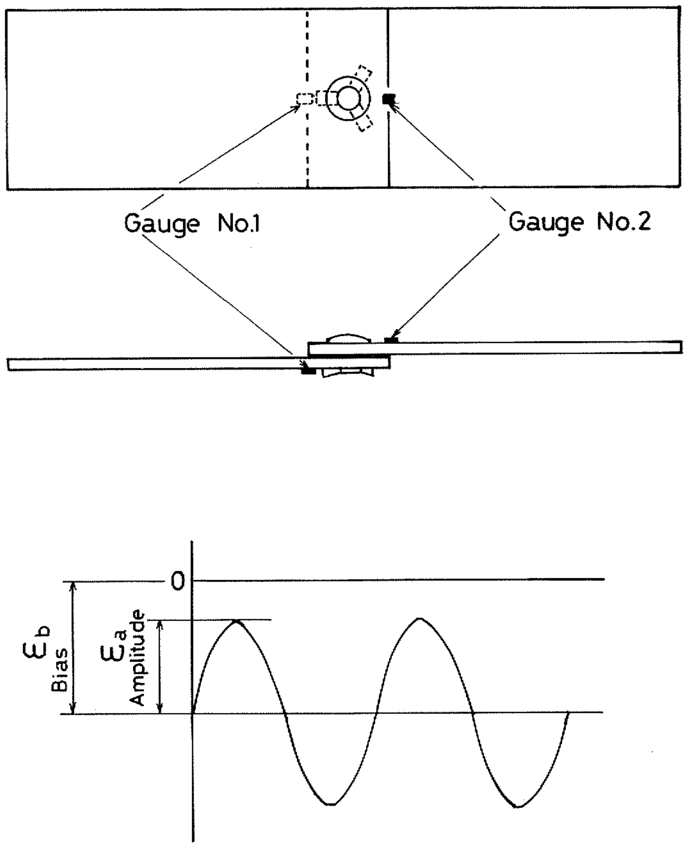


FIGURE 3 Bonding positions of strain gauges and schematic illustration of output wave.

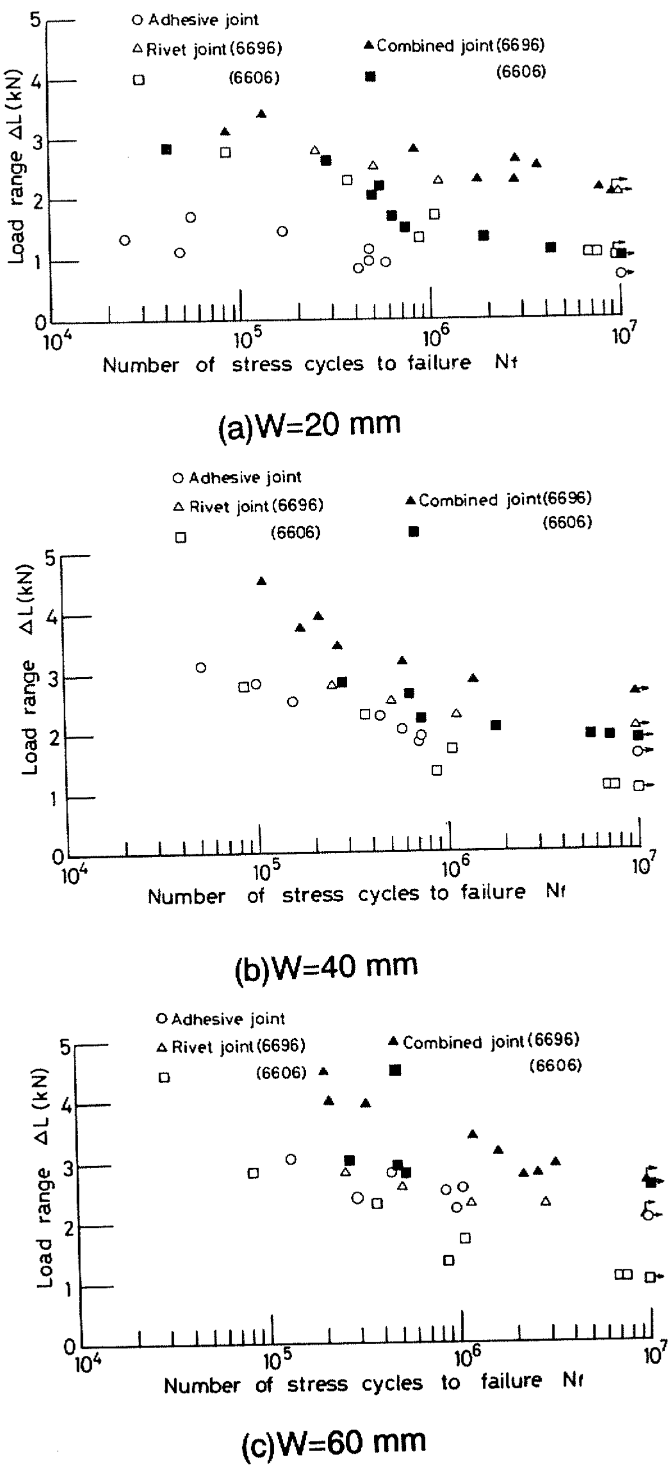


FIGURE 4 S—N relationships (Epoxy adhesive).

6696 and 6606 rivet and epoxy adhesive were used, and lap length was constant at 25 mm. The 6696 rivet showed higher fatigue strength than the 6606 rivet.

When lap width, W, is 20 mm, Figure 4(a) shows that 6696 and 6606 rivet joints have greater fatigue strengths than the adhesive joint. In addition, the fatigue strengths of combined joints using 6696 and 6606 rivets are almost equivalent to those of 6696 and 6606 rivet joints, respectively. This indicates that the fatigue strength at this lap width is not improved by combination with adhesive. However, with $W = 40$ mm or 60 mm, as shown in Figure 4(b) and (c), the combined joints using 6696 and 6606 rivets have greater fatigue strengths than 6696 and 6606 rivet joints, respectively. Furthermore, fatigue strengths of both combined joints are greater than that of the adhesive joint. This shows that fatigue strength is improved through adhesive/rivet combination at these lap widths.

The results shown in Figure 4 indicate that the improvement of fatigue strength through adhesive/rivet combination is affected by the lap width, which relates to the adhesive strength. That is, we expect the degree of improvement in fatigue strength through combination to increase with the strength of the adhesive bonding.

Using acrylic adhesive, whose fatigue strength is around 2.5 times that of the 6696 rivet joint, we investigated the effects of adhesive combination on fatigue strength. Figure 5 shows the S—N relationships of the rivet, adhesive and combined joints, where the acrylic adhesive and 6696 rivet were used and lap length and width were 25 mm. This figure indicates the fatigue strength of the combined joint to be approximately equivalent to that of the adhesive joint, *i.e.* the fatigue strength is not improved through adhesive/rivet combination. Therefore, we assume that the fatigue strength of the adhesive or rivet joint is increased through combination within a restricted range of the ratio of fatigue strength for the adhesive bonding to that for the rivet bonding. Figure 6 shows the effect of the ratio of the fatigue strength at 10^7 cycles of the adhesive

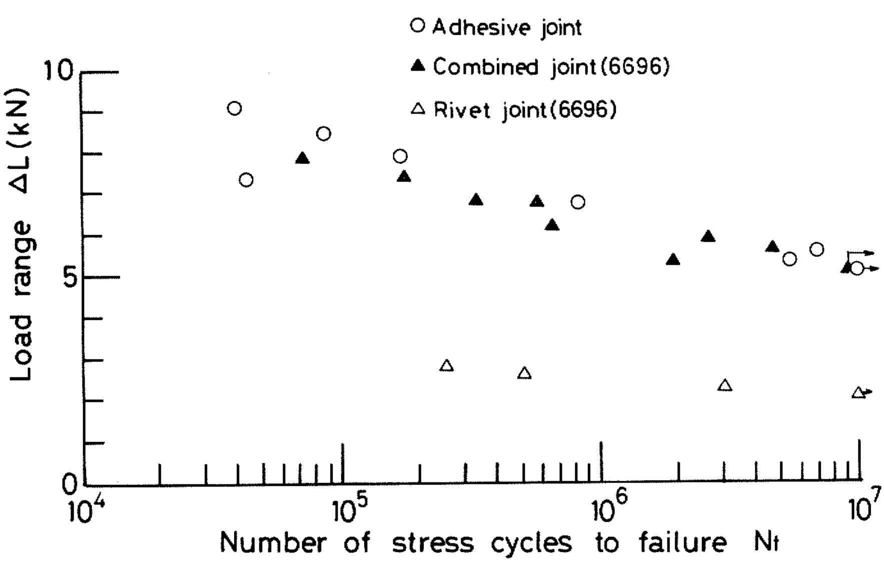


FIGURE 5 S—N relationships (Acrylic adhesive).

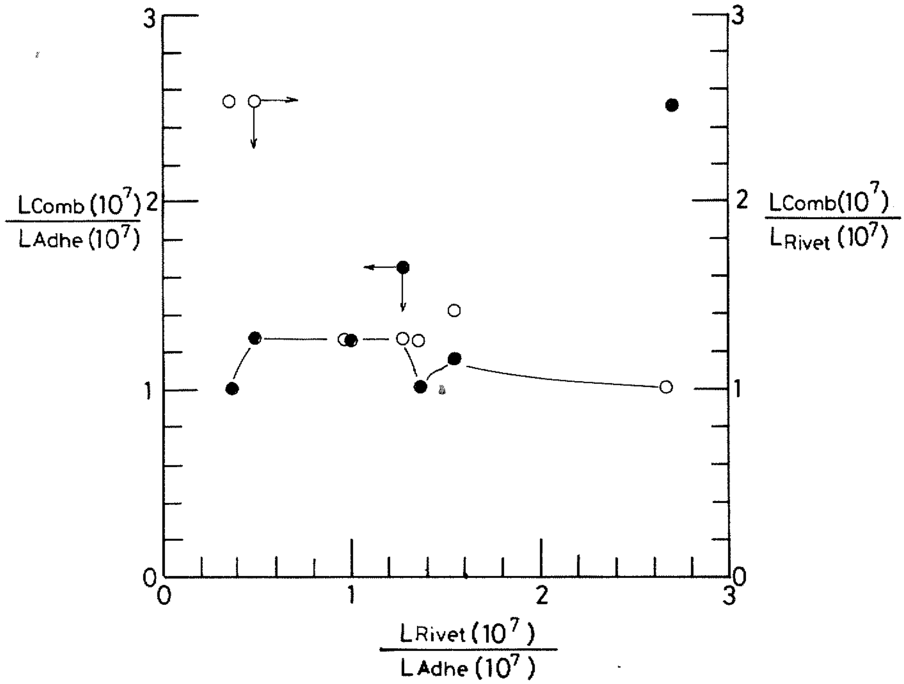


FIGURE 6 Effect of fatigue strength ratio of rivet joint to adhesive joint on the degree of increase in fatigue strength through combination.

joint to the rivet joint on the degree of improvement in fatigue strength of the combined joint. In this figure, the ratio of the fatigue strength at 10^7 cycles of the rivet joint to the adhesive joint, $\Delta L_{\mathrm{Rivet}}(10^7)/\Delta L_{\mathrm{Adhe}}(10^7)$, is shown on the abscissa, and the ratio of fatigue strength of the combined joint to that of the adhesive or rivet joint at 10^7 cycles, $\Delta L_{\mathrm{Comb}}(10^7)/L_{\mathrm{Adhe}}(10^7)$, $\Delta L_{\mathrm{Comb}}(10^7)/\Delta L_{\mathrm{Rivet}}(10^7)$, is shown on the ordinate. The ratio of net increase in joint strength at 10^7 cycles through the combination indicates the lower value, $\Delta L_{\mathrm{Comb}}(10^7)/\Delta L_{\mathrm{Adhe}}(10^7)$ or $\Delta L_{\mathrm{Comb}}(10^7)/\Delta L_{\mathrm{Rivet}}(10^7)$.

From this figure, a net increase in joint strength is observed through adhesive/rivet combination, when the strength of the adhesive joint at 10^7 cycles is nearly equal to, or slightly higher than, that of the rivet joint. The ratio of the fatigue strength of the rivet to that of the adhesive joint is a key parameter in the indication of the degree of improvement in fatigue strength of combined joints.

3.2 Debonding Process

Fatigue crack initiation and propagation behavior of weld and weld-bond joints can be deduced from the strain information obtained from strain gauges bonded onto the adherend plates.[6] Hence, to compare the debonding process at the lap end of the adhesive joint with that of the combined joint, we monitored the strain waves obtained from the strain gauges shown in Figure 3. The change of bias strain was recorded with the passage of time, as it relates to fatigue crack initiation and propagation behavior as follows: Prior to fatigue crack initiation, the bias strains obtained from both gauges, as shown in Figure 7(a), are compression. When fatigue cracks propagate from one or both sides of the lap, the readings obtained from the strain gauges vary as shown in Figure 7(b) and (c), respectively.

Figure 8(a) and (b) shows the bias strain variation of the adhesive and combined joints, with lap width of 60 mm, where epoxy adhesive and 6696 rivet were used. In this figure, the value on the abscissa indicates the life ratio which is obtained by dividing the number of stress cycles by that at failure, and the value on the ordinate is normalized by the absolute bias strain whose life ratio is 0.1. Figure 8(a) shows that, for adhesive joints, the bias strains of both gauges increase rapidly just prior to fracture, irrespective of fatigue strength. For combined joints, the bias strain of one side increases gradually from the early stages of life with a concomitant decrease in that of the other side, as shown in Figure 8(b). The trends in Figures 8(a) and (b) indicate that the fatigue cracks

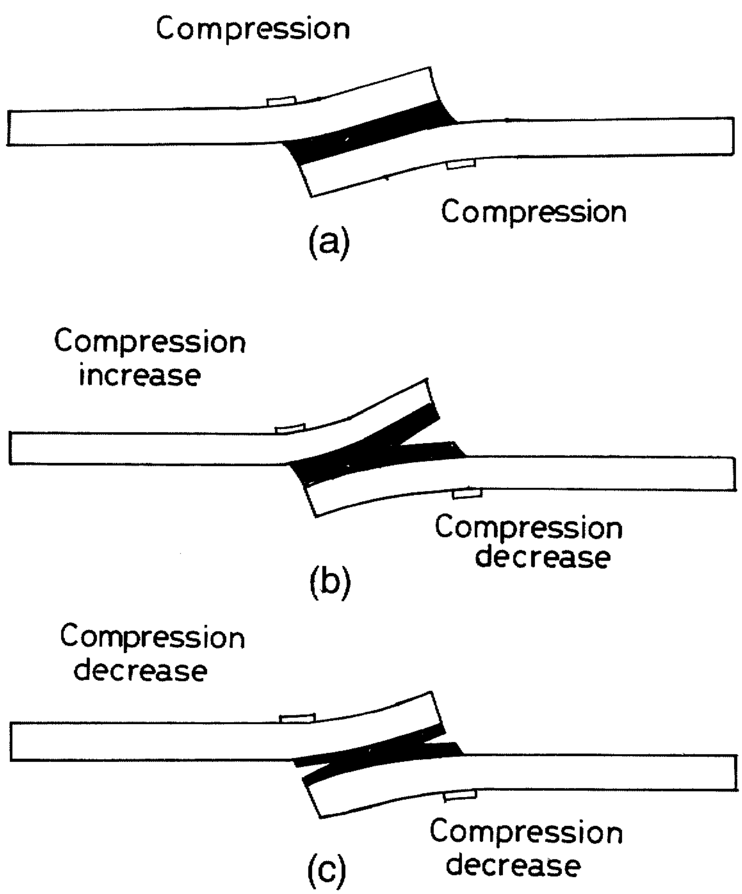
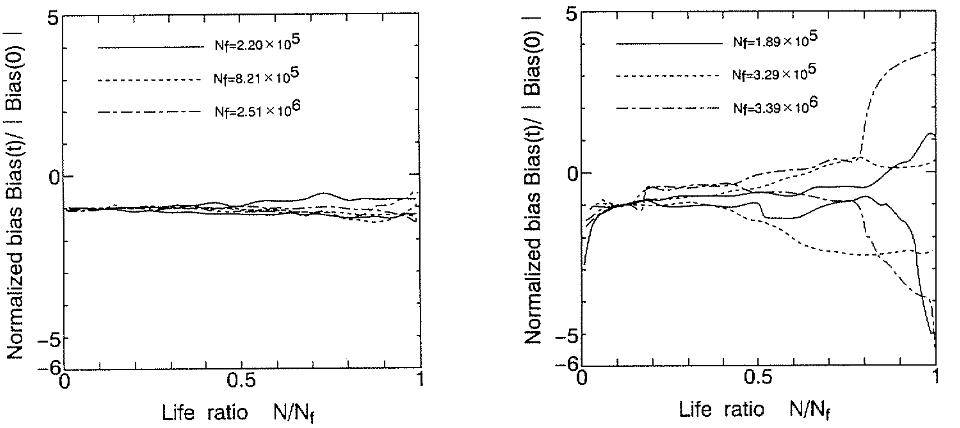


FIGURE 7 Schematic representation of strain changes due to crack propagation.



(a)Strain changes in the adhesive joints (b)Strain changes in the combined joints

FIGURE 8 Relationship between normalized bias strains and life ratio.

in the adhesive joint initiate just prior to fracture, while those of the combined joint initiate in the early stages of the life and propagate gradually.

4. STRESS ANALYSIS

To compare the stress distribution of the combined joint, whose fatigue strength is improved by the adhesive/rivet combination, with that of the adhesive joint, stress distributions in the adhesive layers of the adhesive and combined joints were analyzed by the finite element method using three-dimensional 8-node isoparametric elements. Sizes and bonding conditions of these joints were as follows: The lap length and width of the adhesive and combined joints were 25 mm and 60 mm, respectively. Epoxy adhesive was used for both the adhesive and combined joints, and the 6696 rivet was used for the combined joint.

As the combined joint is symmetric about $x = 0$ axis, half of the joint is modeled. Figure 9 shows the boundary conditions and mesh pattern near the lap end. The finest mesh used at the lap end is $1.0 \times 0.5 \times 0.1$ mm, and the distance from lap end to the Gauss point nearest to the lap end is 0.105 mm. The boundary conditions indicated in Figure 8 are as follows: Displacement in the x direction is constrained (*i.e.*, $x = 0$). Tensile load is applied to the end of the joint. In addition, the tightening load is assumed to be uniformly distributed with the compression load.

Strictly speaking, the tightening load causes plastic deformation of some part of the adherend plates, and the adherend plates are in contact with the rivet. However, to simplify the analysis, the whole joint is assumed to be an elastic material whose material properties are summarized in Table I. Furthermore, the adherend and rivet are treated as one material and the buckled body of the rivet, which is shown in Figure 2, is assumed to have the same shape and sizes as those of the flange.

The tightening load is assumed as follows: As shown in Figure 2, the tightening load caused by the riveter is equivalent to the tensile strength of the mandrel whose tensile

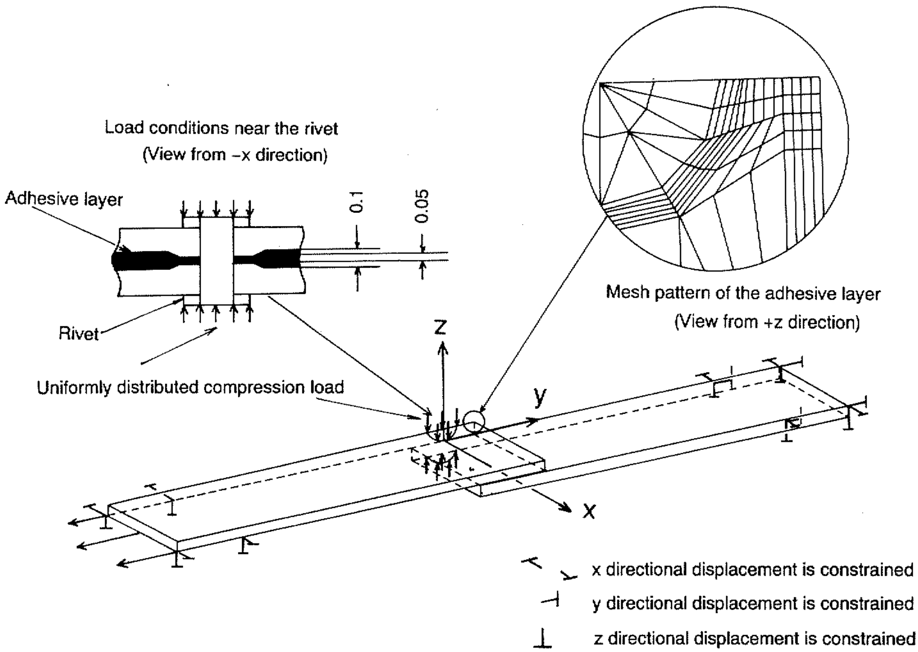


FIGURE 9 Boundary conditions and the mesh pattern of the adhesive layer for FEM analysis.

strength is 4.9 kN. As mentioned above, immediately after pasting with adhesive, the adhered plates were fastened with the rivet, when the adhesive was still in the paste condition. Hence, some of the adhesive under the flange flowed out of the joint. When the curing reaction was completed, the adhesive layer thickness of the combined joint was measured, and was found to have decreased to about 0.05 mm under the flange of the rivet due to the tightening load. Hence, the adhesive layer thickness of the combined joint was modeled as shown in Figure 9. As a result, the tightening load of the combined joint applied to the fatigue test is lower than 4.9 kN due to plastic deformation of the adherend plates, decrease in the adhesive layer thickness and relaxation of the rivet, etc. Therefore, the true tightening load of the combined joint is unknown. Hence, to investigate the effect of pretensioning, the amount of tightening load was varied and stress analysis of the combined joints was conducted for three cases with tightening loads of 4.9 kN, 2.45 kN and 1.225 kN, where 4.9 kN is the upper boundary of the expected value.

The boundary conditions and mesh division of the adhesive joint are the same as those of the combined joint except for the rivet and its compression load and non-uniform adhesive layer thickness.

Figures 10(a) and (b) show normal and shear stress distributions within the adhesive layers of both the adhesive and combined joints, along the AA' section which is the center of the joints, where the tightening load of the combined joint is used as a parameter. The value on the abscissa is normalized with respect to the apparent shear stress, obtained by dividing the applied load by the bonding area. Figure 10(a) shows

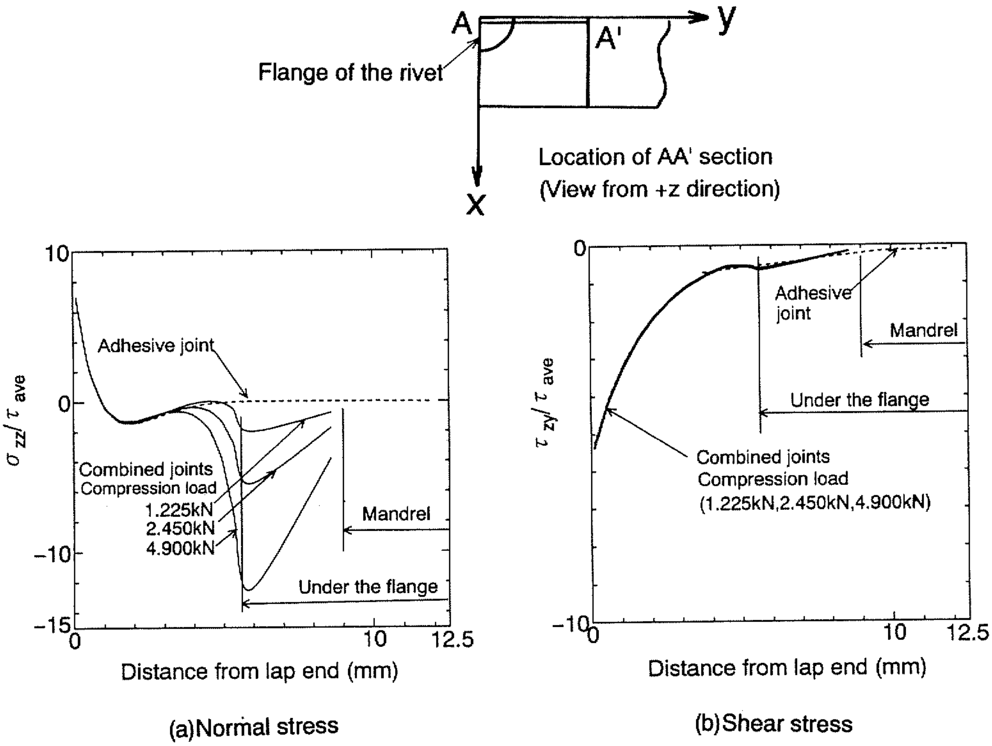


FIGURE 10 Normal and shear stress distributions in the adhesive layer of the adhesive and adhesive/rivet combined joints along AA' section ($x = 0.21$).

that σ_{zz} of both adhesive and combined joints increase rapidly near the lap end, and that σ_{zz} of the adhesive joint near the lap end almost agrees with that of the combined joint, irrespective of the tightening load. However, near and under the flange of the combined joint, compression stress is observed due to the tightening stress of the rivet, and the compression stress increases with the tightening load. Figure 10(b) indicates that the τ_{zy} stress of the adhesive joint approximately matches that of the combined joint, irrespective of the tightening load, throughout the whole range.

Figures 11(a) and (b) show normal stress distributions in both the adhesive and combined joints, along BB' and CC' sections, with tightening loads of 4.9 kN representing the upper boundary within the expected compression load. BB' and CC' sections are located in the middle and near the edge of the joint for y direction, respectively. Furthermore, both BB' and CC' sections are apart from the flange of the rivet. This figure indicates that σ_{zz} of the adhesive joint is almost equivalent to that the combined joint throughout the whole range in both BB' and CC' sections.

As a result Figures 10 and 11 suggest that the compression load affects only the stress distributions of σ_{zz} between the upper and lower flanges and in its vicinity. Hence, there are no real differences in the values of σ_{zz} and τ_{zy} near the lap end between the adhesive and the combined joints.

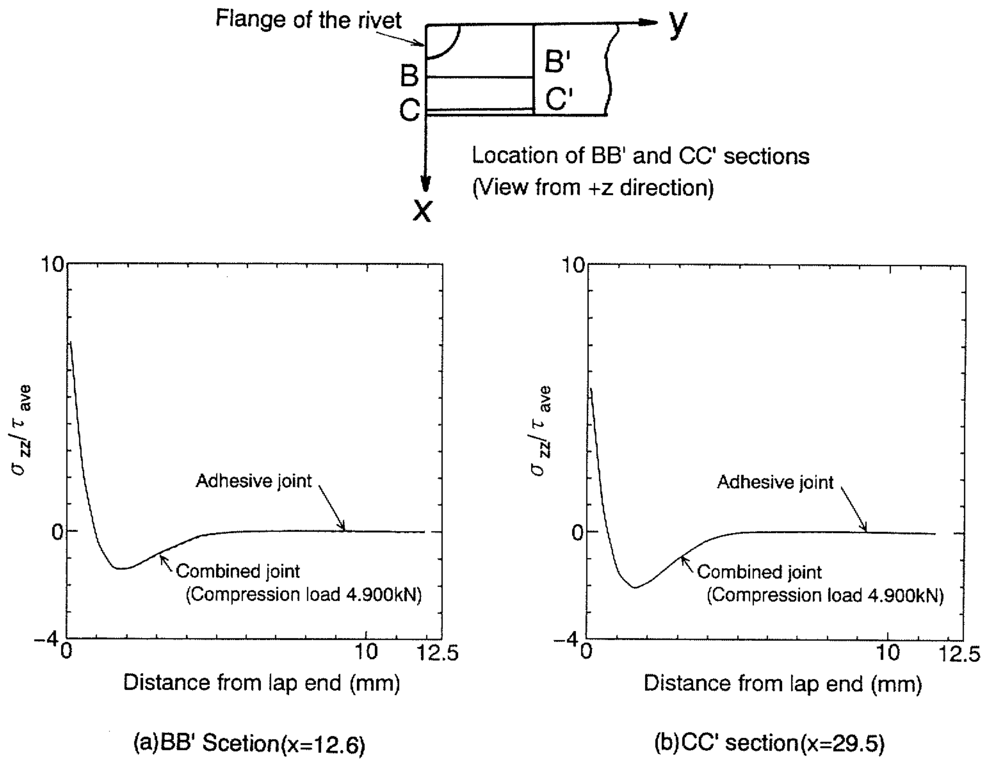


FIGURE 11 Normal stress distributions in the adhesive layer of the adhesive and adhesive/rivet combined joints along *BB'* and *CC'* sections.

5. DISCUSSION

Normal stress in the adhesive layer is considered a key parameter in the estimation of fatigue strength of adhesive bonded lap joints.[7,8] With a lap width of 60 mm, as shown in Figures 10 and 11, the normal and shear stress distributions of the epoxy adhesive joint were approximately equivalent to those of the combined epoxy adhesive/6696 rivet joint near the lap ends. Hence, the fatigue strength of adhesive joints is expected to be constant despite its combination with a rivet. However, the fatigue strength increased through rivet combination as shown in Figure 4(c). Furthermore, the degree of improvement in fatigue strength of the combined joint was confirmed to be affected by the ratio of the fatigue strength of the rivet to that of the adhesive joint, as shown in Figure 6. We also observed that fatigue fracture of the combined joints always occurred in the adhesive layer at the lap end prior to the breaking of the rivet.

Consequently, the cause of the improvement of fatigue strength through rivet combination is assumed to be as follows: When the strength of the adhesive joint is higher or lower than that of the rivet joint, following fracture of the adhesive layer the rivet is broken immediately, or the adhesive layer breaks just after fatigue test commencement. Therefore, fatigue strength is not improved through adhesive/rivet combination in this case. On the other hand, when the strength of the adhesive joint is nearly equal to, or slightly higher than, that of the rivet joint, following fracture of the adhesive layer the rivet is not broken immediately. Furthermore, as shown in Figure 10(a), the normal stress of the combined joint is negative due to the tightening stress of the rivet. Consequently, the opening of a fatigue crack is constrained. Quite recently, the results of FEM analysis revealed that, for a similar adhesive/rivet combined lap joint, the stress intensity factor, K_I, of the adhesive layer was reduced by rivet combination.[5] This is because fatigue cracks in the combined joints propagate more gradually than those of adhesive joints, as shown in Figure 8. For the above reasons, the fatigue strength of the combined joint is improved when the fatigue strength of the rivet joint is nearly equal to, or slightly higher than, that of the adhesive joint.

6. CONCLUSIONS

To clarify which bonding conditions increase the fatigue strength of adhesive/rivet combined joints, fatigue tests were conducted on rivet, adhesive and combined joints with various lap widths and several kinds of adhesives and rivets. In addition, the stress distributions and fatigue crack initiation and propagation behavior of adhesive joints were compared with those of combined joints.

Major conclusions obtained in this study are summarized as follows:

(1) Stress analysis showed that normal and shear stresses near the lap end of the adhesive joints approximately matched those of the combined joints.
(2) The fatigue strength of the adhesive joint can be improved through combination with a rivet whose fatigue strength is nearly equal to, or slightly higher than, that of the adhesive joint.
(3) Fatigue cracks in adhesive joints initiate just prior to fracture, while those in the combined joints initiate in the early stages of life, and crack propagate gradually.

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