The American Society of
Mechanical Engineers

Reprinted From
PD—Vol. 32, Composite Material Technology
Editors: D. Hui, and T. J. Kozik
Book No. G00513 — 1990

STRENGTH OF ADHESIVE BONDED LAP JOINTS IN HIGH STRENGTH STEEL—EFFECT OF MECHANICAL PROPERTIES OF ADHEREND STEEL ON STATIC AND FATIGUE STRENGTH

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Abstract

Recently, the use of high strength steel plate has been increasing, to reduce the weight of equipment. However, it is diffcult to join these thin steel plates by welding or rivet bonding. Hence, adhesive bonding has been attracting attention in joining these thin steel plates from the viewpoint of high joint efficiency.

In this study, the adhesive bonded lap joints in high strength steel were made from steel plates of different strengths. Using these adhesive bonded joints, strength characteristics were investigated by static tensile and fatigue tests. In addition, stress distributions of adhesive joints were analyzed by finite element methods, considering plastic deformation of adherend steels. The tensile strength was found to increase with steel strength, with fatigue strength being constant irrespective of steel strength. These findings could be explained from the difference of stress distribution between static tensile and fatigue load conditions.

1.Introduction

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

Recently, adhesive bonding has attracted special interest, for it offers the potential advantage of joining thin steel plates arising from a more uniform load distribution in the joints and enhanced fatigue properties of the joints. In order to apply adhesive bonded joints more widely, it is necessary to clarify strength properties of the adhesive joints. Hence, many studies have been conducted to investigate strength and stress distributions of adhesive joints(1-2). Recently, estimation methods of the static(3) and fatige(4) strength of adhesive bonded lap joints have been proposed based on stress distributions of the joints.

It is important to investigate the effect of mechanical properties of adherend plates on joint strength for using higher adherend steels in order to reduce the weight of construction. However, there are few studies to investigate these effects on joint strength(5,6).

In this study, the adhesive bonded lap joints in high strength steel were made from different strength steel plates. Using these adhesive bonded joints, static tensile shear and fatigue strength charactestics were investigated. In addition, stress distributions of these adhesive joints were analyzed by finite element methods considering plastic deformation of adherend steels. As a results, it was found that tensile shear strength increased with increased steel strength, fatigue strength was constant irrespective of the steel strength. These findings could be explained from the difference of stress distribution between static tensile and fatigue load conditions.

2.Test Materials and Adhesive Bonded Specimen

Modified acrylic adhesive(Hard rock C-355, Denkikagaku Co. Ltd.) were adopted as the adhesive component. The adherend materials employed in this study were three kinds of high strength steel plates and a cold rolled carbon steel plate. The shape and sizes of the adhesive bonded lap joints are shown in Fig.1. The adherend plate of HT110 is 1.2 mm thick and the other plates are 1.0 mm thick. The uniaxial tensile stress-strain curves of each of the adherend plates is shown in Fig.2 and the mechanical properties of these are summarized in Table 1.

The adhesive bonded specimens were prepared as follows: The bonding surfaces of the adherend were degreased with acetone. The adhesive bonded joint specimen was allowed to stand 7 days at room temperature and supplied to tensile shear and fatigue tests. Here, the adhesive bonded thickness was controlled by inserting a few resin beads of 0.1mm in diameter between the two adherend endfaces.

Cyclic tensile fatigue tests were conducted with an electro-hydraulic closed-loop fatigue testing

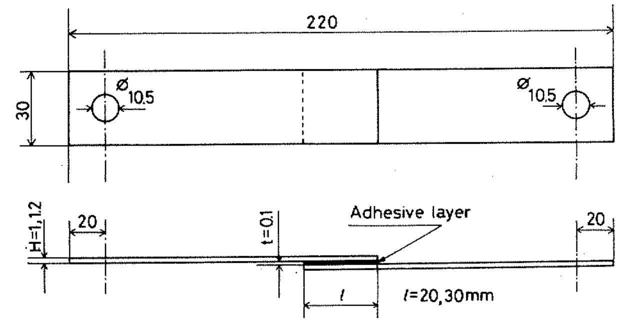


Fig.1 Shape and sizes of the adhesive bonded lap joint specimens.

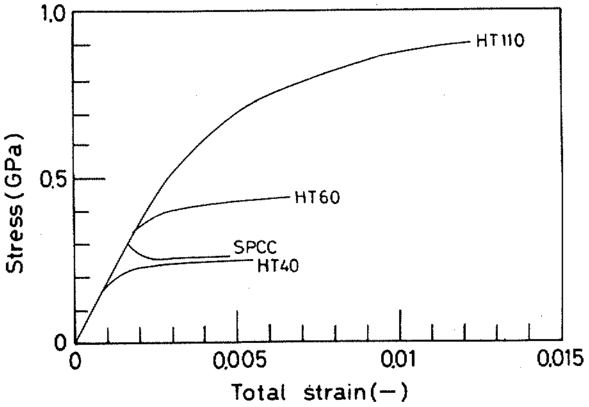
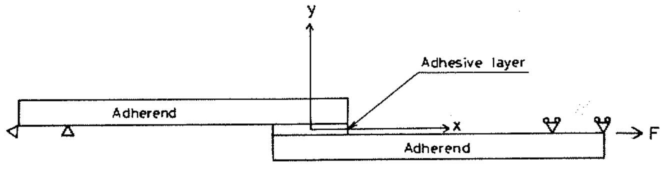
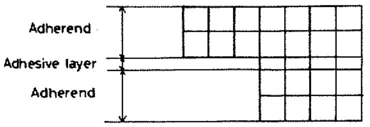


Fig.2 Stress-strain curves of adherend steels.



(a)Boundary conditions.



(b)An example of the mesh pattern.

Fig.3 Boundary conditions and an example of the mesh pattern.

machine with a loading capacity of 30 kN under the conditions of having a stress ratio R=0.1 and a loading frequency of f=30Hz, where the stress ratio, R, was the ratio of the minimum stress to the maxium stress. The tensile shear strength of the adhesive joints was measured on a universal testing machine (Instron Co. Ltd.). The crosshead rate for the tensile test was 5 mm/min.

3.Stress Analysis

The adhesive bonded lap joints were studied with a nonlinear two dimensional finite element analysis. The analysis accounted for the plastic deformation of the adherend steel plates. The computer program in its present form is called MARC. Figure 3 shows the boundary conditions and an example of the mesh pattern for the FEM analysis of the lap joints, where plain strain condition is assumed. The FEM mesh consisted of isoparametric 4-node elements. The adhesive layer was modeled as an elastic material whose shear modulus and possion's ratio were 490MPa and 0.33, respectively. To assess the effect of the adherend plate plasticity on the adhesive joints, the adherend steel was modeled as an elastic-plastic material for which the Von Miese yield criterion was used. After initial yielding, subsequent plastic deformation may occur at increased stress levels owing to work harding. The elastic modulus and work-harding parameters are also shown in Table 1.

Table 1 Mechanical properties of the adherend steels.

Materials	0.2% proof stress or yield strength (GPa)	Tensile strength (GPa)	Enlongation (%)	Young's Modulus (GPa)	Work-harding parameter H' (GPa)
HT110	0.76	1.09	11.2	183	302 ($0 < \varepsilon_p < 0.0008$) 73 ($0.0008 < \ \ < 0.0024$) 30 ($0.0024 < \ \ < 0.0056$) 16 ($0.0056 < \ \ < 0.0104$) >0.0104)
HT60	0.42	0.64	25.2	175	158 ($0 < \varepsilon_p < 0.00036$) 18 (>0.00036)
HT40	0.24	0.39	34.2	188	148 ($0 < \varepsilon_p < 0.00032$) 19 ($0.00032 < \ \ < 0.016$) 3 (>0.016)
SPCC	0.30	0.36	37.6	176	0 ($0 < \varepsilon_p$)

(ε_p is plastic strain.)

3-1 Stress Distributions.

Figures 4 and 5 show the distributions of the tensile and shear stresses in the adhesive layer at y=0.289. In both figures, the abscissa was normalized by the lap length. Figures 4 and 5 show the tensile and shear stress distributions in the adhesive layer, with the lap length l=30 and 20mm, by taking the applied load as a parameter. These figures show that both the tensile and shear stresses take maximum values near the lap end and that the gradient of the tensile stress near the lap end is steeper than that of the shear stress. Furthermore, the higher the applied load, the greater the increase ratio of the maximum tensile and shear stresses. That is, the non-linearity between maximum stresses and applied load appears in high applied load ranges.

In order to investigate this nonlinearlity in more detail, Figures 6 and 7 show the variation of the maximum tensile and shear stresses with average shear stress which is obtained by dividing applied load by bonding area. Furthermore, the relation between the average shear stress and maximum Miese stress is also shown in Fig.8, because the Miese stress has been most commonly used as a paremeter for evaluating static strength. In Figs. 6-8, the applied load is also scaled on the abscissa and the maximum stresses are taken with the stresses located 0.1 mm from the lap end.

Figures 6 and 7 show the maximum tensile and shear stresses with lap length l=30 mm and 20 mm over a range of joint loading. This figure indicates that in low average shear stress ranges both the maximum tensile and shear stresses increase proportionally to the average shear stress, and the gradients of the curves is constant irrespective to the strength of the

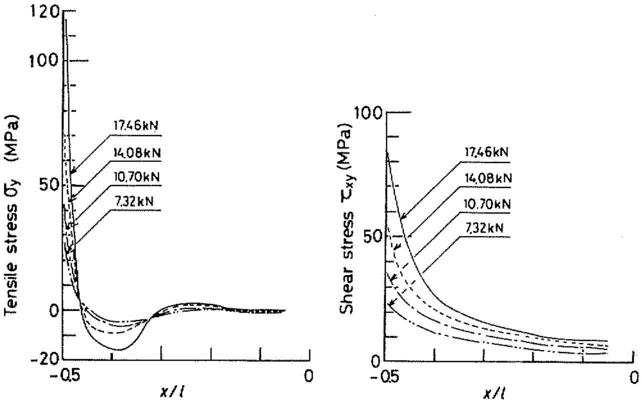


Fig.4 Stress distributions of the adhesive layer with HT60 adherend(lap length l=30mm).

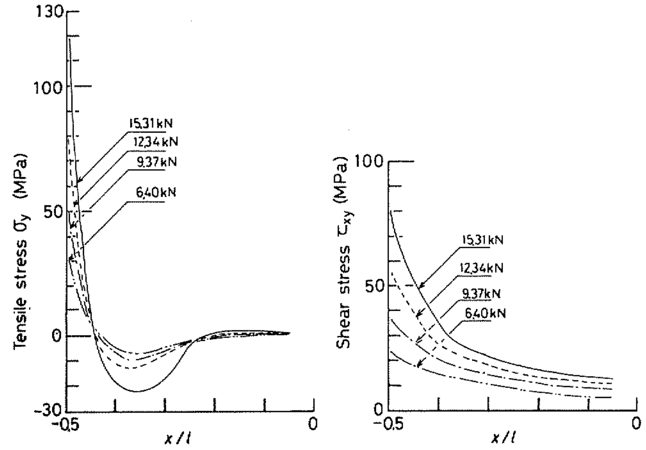


Fig.5 Stress distributions of the adhesive layer with HT60 adherend(lap length l=20mm).

adherend. However, as the average shear stress increases, these curves deviate from the lineality due to plastic deformation of the adherend plate. With the weaker strength of the adherend plate, the deviation points from the linearity shift to the lower side in the average stress.

When the results of Fig.6 with that of Fig.7 are compaired, the gardient of the curves in low average stress i.e. the stress concentration factors for the joint l=30mm are higher than those with a 20mm lap length one.

Figure 8 shows the relation between the maximum Miese stress and the average shear stress. Compared with the results of the tensile and shear stresses as shown in Figs. 6 and 7, the gradients of the curves are higher than the curves arranged by maximum tensile and shear stresses.

Therefore, at low average shear stress ranges, before adherend yielding, the maximum stresses increase proportionally to average shear stress. However, at higher average shear stresses, linear elastic analysis underpredicted the maximum stresses of the adhesive layer compared with the results of non-linear analysis which accounted for the plastic deformation of the adherend.

4.Experimanral Results and Discussions

4-1 Results of tensile shear tests.

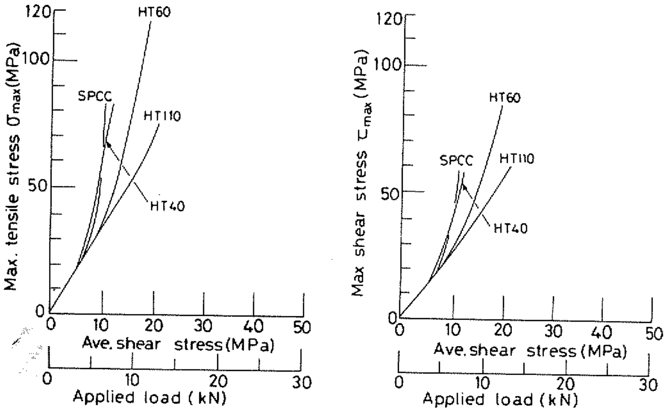


Fig.6 Variation of the maximum tensile and shear stresses of the adhesive layer with an average shear stress or an applied load with various adherends(lap length l=30mm).

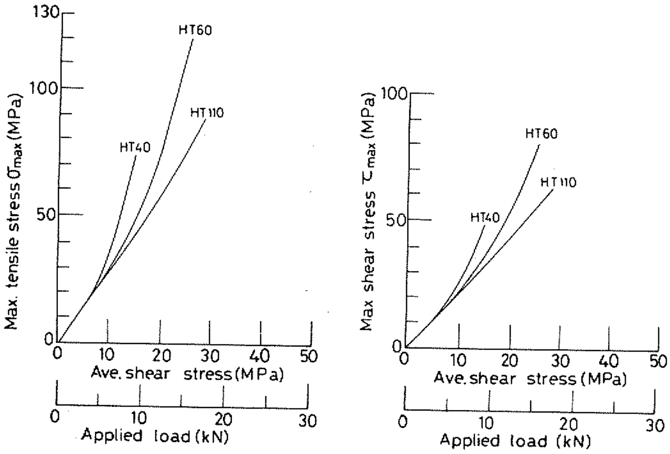


Fig.7 Variation of the maximum tensile and shear stresses of the adhesive layer with an average shear stress or an applied load with various adherends(lap length l=20mm).

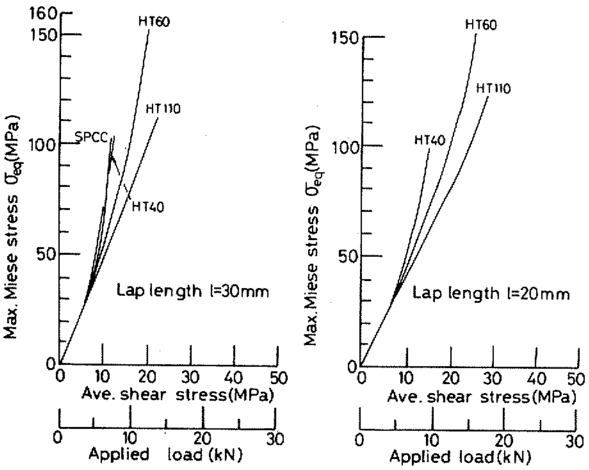


Fig.8 Variation of the maximum Miese stress of the adhesive layer with an average shear stress or an applied load with various adherends.

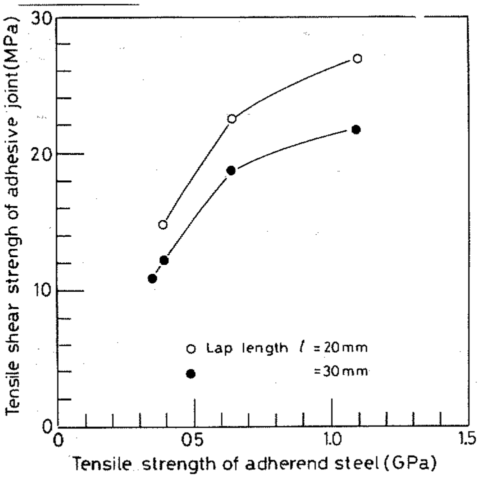


Fig.9 Effect of adherend strength on tensile shear strength of adhesive joints.

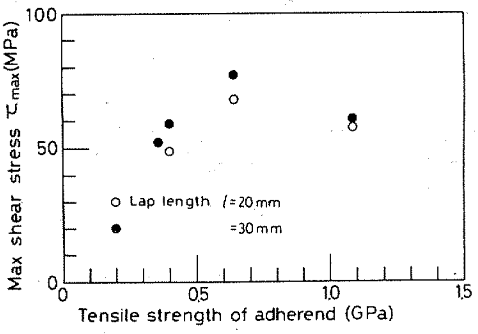


Fig.10 Arrangement of the tensile shear test data with the maximum tensile stress of the adhesive layer.

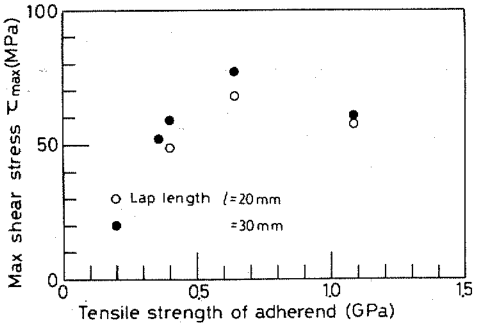


Fig.11 Arrangement of the tensile shear test data with the maximum shear stress of the adhesive layer.

Table 2 Coefficient of variation of tensile shear strength arranged by averaged shear and maximum stresses.

	Average shear stress	Max. tensile stress	Max. shear stress	Max. Miese stress
Coefficient of variation (%)	30.6	13.7	14.5	12.6

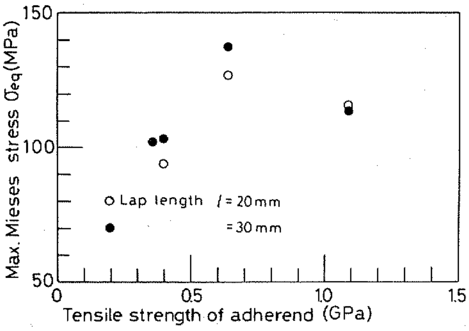


Fig.12 Arrangement of the tensile shear test data with the maximum Miese stress of the adhesive layer.

Figure 9 shows the effect of adherend steel strength on the tensile shear strength of an adhesive bonded lap joint, which is obtained by dividing fracture load by bonding area. This figure indicates that joint strength of lap length l=20 mm is higher than that of l=30 mm and the joint strength increases with increased of steel strength. These trends can be explained. The former corresponds to the increase of stress concentration with the increase of lap length, and the latter to the increase of maximum stress with the decrease of steel strength as shown in Figs. 6-8.

In the case of the lap joint, both the values of the tensile and shear stresses increase rapildy near the lap end. Furthermore, these stresses take different values depending on the shape of joint as defined by the lap length and the mechanical properties of the adherend steel as defined by the steel strength or plastic deformation. In order to estimate the tensile shear strength of the lap joint, the difference of joint strength shown in Fig.9 must be standarized to eliminate the effect of steel strength and lap length by adopting an appropriate stress component.

It has been shown that the maximum tensile and Miese stresses are adequate paremeters for estimating the fatigue and static strength of adhesive joints(2,3,7). Hence, in order to standardize the effect of steel strength and lap length on tensile shear strength, these data have been rearranged by the maximum tensile and Miese stresses at the lap end which can been read from Figs.6-8. Furthermore, standardization has also been conducted by maximum shear stress for comparison.

Figures 10-12, respectively show the correlation of the tensile shear strength data with the maximum tensile, shear and Miese stresses. These figures indicate a similar tendency, that is, the data points are scattered irrespective to tensile strength of adherend and lap length. In order to evaluate the extent of this scattering of these data, coefficents of variation are shown in Table 2 arranged by average shear and three types of maximum stresses. From this table, it can be seen that the coefficent of variation arranged by average shear stress is more than double those arranged by maximum stresses. Furthermore, the coefficent of variation arranged by maximum Miese stress is the lowest in those arranged by maximum stresses, however, the difference in the different kinds of maximum stresses is 2% at the most.

4-2 Fatugue test.

The S-N relations of the lap joints with lap length l=20mm are shown in Fig.13. The value of the ordinate is the apparent shear stress range. This

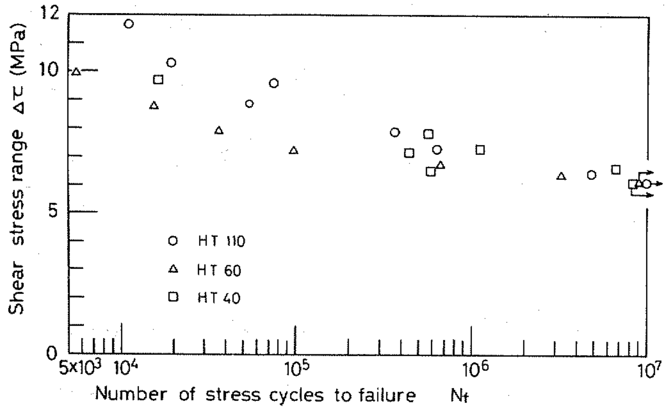


Fig.13 S-N relations of the adhesive joints.

figure indicates that in low stress cycles range the fatigue strength with HT110 is slightly higher than those with HT60 and HT40. However, in high stress cycles range the difference with the adherend strength becomes smaller and the fatigue strengths of the adherends agree at 10^7 stress cycles.

There is an adequate correlation between the static strength and fatigue strength for several materials. The fatigue strength of the adhesive joints were evaluated based on static strength(8). Furthermore, these fatigue strengths of the adhesive joints of different sizes can be standardized based on the ratio of the fatigue strength to the static strength(9,10). However, in this study the fatigue strength of the lap joints with thin adherend steel had no connection with the static strength. The reason to be considered as follows.

It can be seen from in Fig.13 that the average shear stress range is less than 7MPa in the range above 10^6 stress cycles. From Figs. 6-8, it was revealed that in average shear stress ranges below 7MP, maximum shear, tensile and Miese stresses at the lap end increase linearly with shear stress regardless of the adherend strength. Therefore, the fatigue strength in high cycles range agrees irrespective to the adherend strength.

As a result, the fatigue strength of adhesive bonded lap joints with thin adherend steels should not be estimated based on the static strength of the joint but rather on the maximum stress of the adhesive layer. Furthermore, it was also confirmed that elastic-plastic analysis, to account for plastic deformation, is needed for estimating the static strength of lap joints, however only elastic analysis is sufficient for estimating the endurance limit of the lap joint.

5.Conclusion

Adhesive bonded lap joints in high strength steel were made from steel plates of different strengths. Using these adhesive bonded joints, the effect of steel strength on the tensile shear and fatigue strength of adhesive bonded joints was investigated based on the stress distribution in the adhesive layer.

The majior conclusions obtained in the study are summarized as follows:

1)Both the tensile and shear stresses take maximum values near the lap end and the gradient of the tensile stress near the lap end is steeper than that of the shear stress.

2)In the low average shear stress range, maximum tensile, shear and Miese stresses increase proportionally to the average shear stress, and the gradients are constant irrespective to the kind of adherend steels. However, as the average shear stress is increased, these relations between the maximum stress and the average shear stress are no longer linear due to plastic deformation. The weaker the strength of the adherend plate, the lower the average shear stress range at which the curves are no longer linear.

3)Tensile shear strength of lap joints increases with increased adherend strength and decreased lap length.

4)Tensile shear strength of the lap joints with different lap lengths and adherend strengths can be standardized based on the maximum tensile, shear and Miese stresses. As for stress parameters, there was no significant difference in the types of maximum stresses.

5)In low stress cycles range, the fatigue strength of the lap joints increases with increased adherend strength. However, in high stress cycles range, the difference with adherend strength becomes smaller and the fatigue strengths at 10 stress cycles agree irrespective to the adherend strength.

It is necessary for estimating static strength of lap joints to account for plastic deformation of the adherend. However, only elastic analysis is sufficient for estimating the endurance limit of the lap joint.

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