Evaluation of Fatigue Strength of Adhesive Bonded Box Section Beams

N. TOMIOKA and M. KAKIAGE
Depertment of Mechanical Engineering,College of Science & Technology,Nihon University,
1-8,Kanda-surugadai,Chiyoda-ku,Tokyo,101,Japan

ABSTRACT

To investigate the applicability of the structural adhesive to the automobile body,the works on the fatigue strength of the adhesive bonded box section beams were carried out. Firstly,torsional fatigue tests were conducted on the adhesive bonded box section beams,and the relations between the various factors such as the plate thickness and the dimensions of cross section and the fatigue strength were clarified.Secondly, using the finite element three dimensional elastostatic analysis,the stress intensity factor for interface crack between flange plate and adhesive layer was analyzed.Finally, the results of the fatigue tests were tried to be rearranged by the stress intensity factor range ΔK_{III} obtained by the analyses above.

KEYWORDS

Adhesive Joint; stress intensity factor; fracture mechanics; interface crack; fatigue strength

INTRODUCTION

There has been a growing demand for improved fuel economy of automobiles by reducing the body weight from the aspect of global environment and energy conservation issues. This weight reduction is a technological challenge which must be oriented not for the deterioration but for further improvement in strength, rigidity, safety, etc. of automobile body. Adhesive jointing is expected to be adopted to automobile body construction since it is capable of improving the fatigue strength and rigidity compared with existing spot welding and contributing to weight reduction. It is necessary for putting the adhesive joint structure into practice to understand its fatigue strength characteristics by conducting a series of fatigue tests using structural members which are close to actual members in addition to simple joint test pieces for confirming tensile shear and T-type tensile strength. Also, a method which can uniformly evaluate various adhesive joints for fatigue strength is keenly demanded to be established.

As for the method of strength evaluation based on the stress analysis of adhesive joint, several proposals have been made as introduced in an article by Mori(Mori , 1992) such as: (1) method focusing on local stress, (2) method using specific stress factor, and (3) method based on fracture mechanics. However, it is hard to say that a unified evaluation method has been established. Yuuki *et al.*(Yuuki *et al.* , 1992)have presented that the fatigue strength of adhesive joint such as tensile shear and T-type tensile strength can be uniformly evaluated by using a method based on the interface fracture mechanics and have reported that the method is effective for quantitative evaluation of the fatigue strength of adhesive joint. The authors(Tomioka , 1990)of this paper have evaluated the fatigue strength of various adhesive joints based on the fracture mechanics and obtained a similar result.

To investigate the feasibility of adoption of the evaluation method based on the fracture mechanics to actual structure, we conducted, in this study, torsional fatigue tests of bonded box section beams which were model members of automobile body structure to experimentally confirm the influence of the plate thickness and the size of partition and cross section on the fatigue strength. We further assumed a crack in the adhesive interface and obtained the stress intensity factor by detail finite element three-dimensional elastostatic analysis to examine the fatigue strength evaluation based on the interface fracture mechanics.

METHOD OF EXPERIMENT

Cold rolled sheet steel SPCE for automobiles of 0.8 mm and 1.6 mm in thickness was used as the material for test sample. The chemical composition and mechanical properties of the material are given in Table 1. Adhesive used was of structural one-component epoxy type, and its material characteristics after curing are given in Table 2. The test sample was fabricated, as shown in Fig. 1, by bending a sheet steel to have the cross section of a hat shape. Two shaped steel angles were bonded to each other at its flanges so that a beam having a box cross section was formed. (Double hat beam, shortly DHB) Another type of test sample was prepared by sandwiching a flat sheet steel as partition between the hat shaped steel angles. (Double hat beam with partition, shortly DHBP) To examine the influence of the size of cross sectional area on the fatigue strength, the flange width d was fixed to 15 mm, and the cross section dimensions were made to 2a = 2b = 50 and 35 mm. The overall length L was fixed to 600 mm. To mount the test sample to the testing machine, 6 mm-thick plates were arc welded to the ends of the beam. The adhesive used for bonding the shaped angles was applied over the contacting sides of the flanges leaving 30 mm of flange length at both ends not covered in order to avoid the heat influence of arc welding. The 30 mm portions were spot welded.

Fig. 2 shows an illustrated view of fatigue test. The fatigue test we conducted was displacement controlled in which one end of the test sample was fixed and the other end of it was subjected to vibration at a certain point from the torsional center so that torsional moment was applied it. The test employed completely reversed torsion (R = -1) and the frequency was 25 Hz. The fatigue life was determined when the adhered portions came apart and the torsional moment lowered to 1/2 of the set value.

TEST RESULTS

Fig. 3 shows the result of torsional fatigue test by a moment range △Mt - cycles to fracture Nf chart. Comparison between the test results of test samples with section sizes 50 mm and 35 mm has shown that the test samples of 35 mm section size obviously have lower torsional moment though the flange adhesion area is the same. Fig. 4 shows the influence of plate thickness and partition on the fatigue strength. The samples having 1.6 mm plate thickness tend to show higher fatigue strength compared with those of 0.8 mm plate thickness. The DHBP tends to show higher fatigue strength compared with the DHB. Judging from the results mentioned so far, a great variety of complicated factors seem to give influence on fatigue strength and it is necessary to establish a method which can be used to evaluate the factors in unified and quantitative manner.

EVALUATION BY INTERFACE FRACTURE MECHANICS

The adhesive part analysis models, shown in Fig. 5, which consist of cutouts of the bonded portion are used for conducting a finite element three-dimensional elastostatic analysis of the stress intensity factor of interface cracks. Since the bonded portion of DHB has a symmetrical section with respect to the adhesive layer as shown in Fig. 5 (a), the upper half, separated at the center of the adhesive layer as shown in Fig. 5 (b), was picked by considering the symmetry of the section. As for the boundary conditions, all nodes on the surfaces of this model were provided with the freedom of displacement in only the X direction. However, the nodes on the bottom surface of the adhesive layer were constrained from total degree of freedom. Load P was applied uniformly over the nodes on plane e-j-n-o. Analysis of DHBP was conducted by using the upper half of the beam section separated at the center of the partition thickness under the same conditions as those for DHB.

The stress intensity factor of interface crack was analyzed by using a model shown in Fig. 6 and varying the ratio of c (crack length) to d (flange width) of a hypothetic crack along the adhesive interface extending from the adhesive edge. It is necessary to apply finer element divisions to examine closely the stress specificity at the crack edge. However, the scale of analysis will become immense if fine elements are adopted. To reduce the scale of analysis, a step analysis method(Miyoshi et al , 1976) was employed. Zooming was employed two times in the analysis until the fine elements (0.0025 mm) of step 3 shown in Fig. 6 (b) were obtained to conduct a detailed analysis.

When a bonded box section beam is subjected to torsion, the deformation of the portions near the interface crack tip falls into mode III. When a different material interface crack is subjected to antiplane shear deformation with respect to the crack plane (Fig. 7), the displacement field of the crack tip is known to be represented by the following formula(Yuuki, 1993).

$$u_i = \frac{2K_{III}}{\mu_i}\sqrt{\frac{r}{2\pi}}\sin\frac{\theta}{2} \qquad (i=1,2) \qquad (1)$$

Where, i stands for materials 1 and 2, u_i for the antiplane displacement in respective material, and μ_i for the shear modulus of respective material. According to the above formula, the displacement field in respective material falls into mode III which is the same as the case of homogeneous material. K_{III} is the stress intensity factor of interface crack and determined by the extrapolation of the displacement solution obtained by FEM. The displacement method(Yuuki, 1993) represented by the formula below was used to obtain K_{III}.

$$K_{III}=\frac{1}{2\left[\frac{1}{\mu_1}+\frac{1}{\mu_2}\right]}\lim\sqrt{\frac{r}{2\pi}}\,\Delta u \qquad (2)$$

Where, $\triangle u$ is the relative displacement of the upper and lower surfaces of the crack.

The analysis result of K III for DHB is shown in Fig. 8. Note that K_{III} is divided by the mean shear stress τ_{amean} (τ_{amean} = shear load τ_{mean} thL/adhesive area dL) of the adhesive layer. Members of 1.6 mm plate thickness showed smaller K_{III} compared with those of 0.8 mm plate thickness. The K_{III} value we used in the analysis was obtained by using the method of least squares to obtain a linear approximation expression from the analysis data which showed the linearity away from the crack tip. The linear approximation expression was extended toward the crack tip to find an intersection with r = 0.
Fig.9shows the relationship between K_{III} and the crack length ratio c/d. Fig. 9 is for DHB and shows almost constant K_{III} to the variation of the crack length ratio in a wide range.
The fatigue test results shown in Fig. 3 are rearranged with $\triangle K_{III}$ by using the result of K_{III} analysis, and the result is shown in Fig. 10. However, since K_{III} is almost constant regardless of the crack length ratio c/d, c/d = 0.3 was set as the representative value for the purpose of this analysis. Thus the fatigue data of beams which vary in plate thickness, partition, and section area are arranged within relatively limited dispersion range. Judging from the analysis results obtained so far, it is considered that the fatigue strength of bonded box section beams can be uniformly evaluated by using $\triangle K_{III}$.

CONCLUSION

A torsional fatigue test of bonded box section beams which were employed as the model members for automobile body structure was conducted to examine the influence of the plate thickness and the size of partition and cross section of the beam on the fatigue strength. Then, a crack in the adhesive interface was assumed by using the analysis models and the stress intensity factor was obtained by using a finite element three-dimensional elastostatic analysis to attempt to conduct a quantitative fatigue strength evaluation. The following gives principal conclusions.

(1) The fatigue strength of bonded box section beam is influenced by the size of its cross section. It is influenced a little also by the plate thickness and partition.
(2) A crack in the adhesive interface was assumed and the influence of plate thickness and partition on the stress intensity factor relating to the crack development was described.
(3) The fatigue strength data of bonded box section beam were arranged uniformly by using the stress intensity factor range $\triangle K_{III}$.Judging from the above, we conclude that it is possible to uniformly evaluate the torsional fatigue strength of this beam by using $\triangle K_{III}$.

REFERENCES

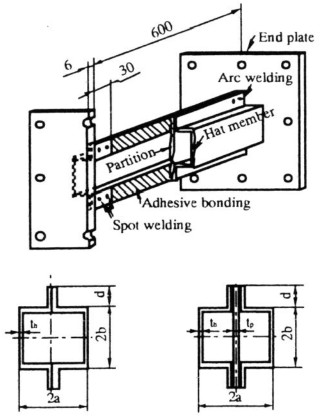
Mori(1995), A review of recent advance in strength evaluation of adhesive joints, J. of the adhesive society of japan, vol.30 No.9, 183-190
Yuuki, et al (1992), J. of material society of japan, vol.41,No.467,1299
Tomioka(1990) ,Evaluation of fatigue strength on steel sheet adhesive joints,Structural adhesive technology for advanced needs , symposium &exhibition, 20-37
Miyosi(1976), Finite element method, jikkyou syuppan, 123
Yuuki(1993), Mechanics of interface, baihuukan, 107

Table 1 Chemical composition and mechanical properties of stell sheets used

	Thickness (mm)	C (%)	Si	Mn	P	S	Al	N	YP (MPa)	TS (MPa)	EL (%)
SPCE	0.8	0.05	0.02	0.23	0.017	0.014	0.058	0.0083	167	304	47
SPCE	1.6	0.05	0.02	0.22	0.013	0.015	0.056	0.0065	157	275	48

Table 2 Material constants of adhesion used

Young's modulus E(GPa)	Poisson's ratio
1	0.38



(a) BHB (b) DHBP

Fig.1 Shape of the adhesive bonded box beams for the test

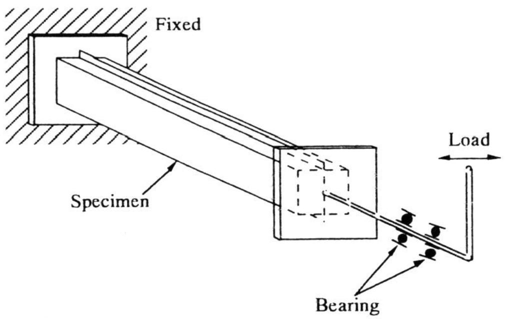


Fig.2 Schematic diagram of fatigue test

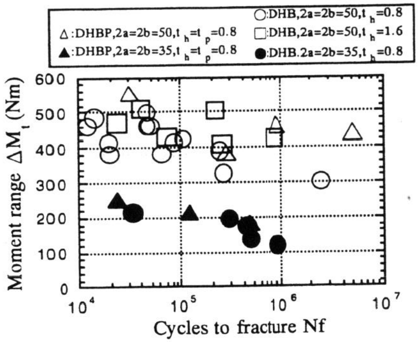
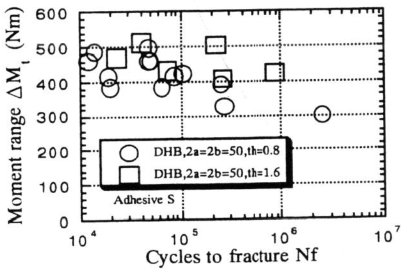
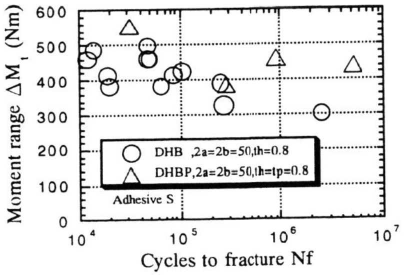


Fig.3 Results of fatigue tests

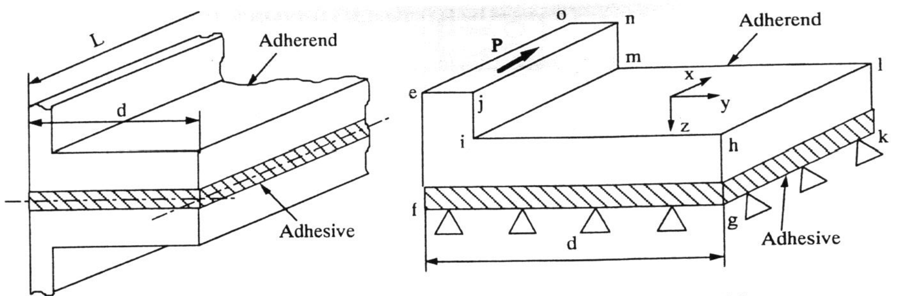


(a)Plate thickness



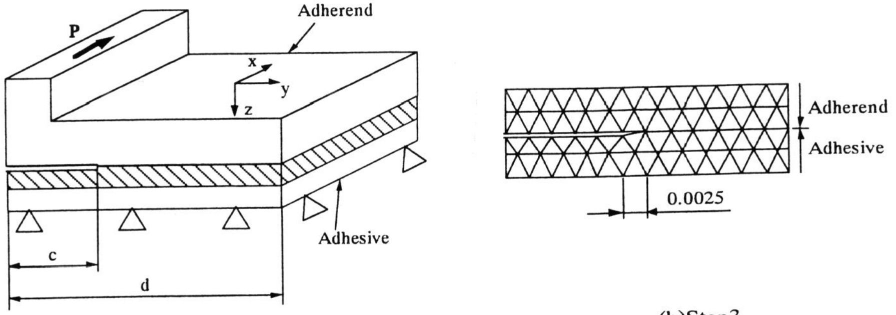
(b)partition

Fig.4 Effect of plate thickness and partition on fatigue strength



(a)Beams (b)Analysis model

Fig.5 Adhesive part analysis model



(a)Step 1 (b)Step3

Fig.6 Analysis model for stress intensity factor

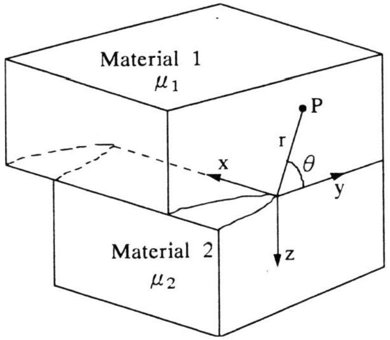


Fig.7 Interface crack under mode K III

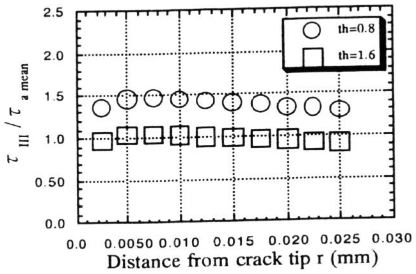


Fig.8 Analytical results of K III

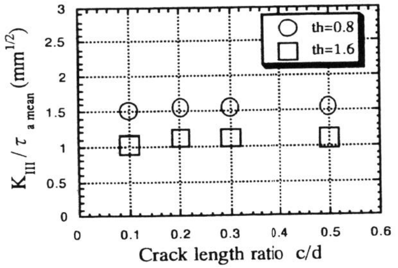


Fig. 9 Relationship between K III and crack length ratio c/d

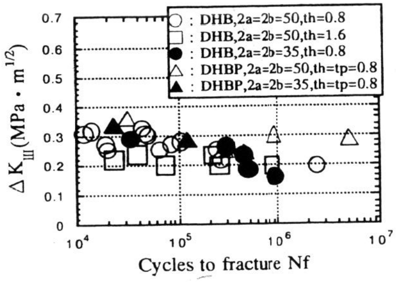


Fig.10 Evaluation of fatigue strength by K III