STRESS ANALYSIS AND STRENGTH EVALUATION OF SCARF ADHESIVE JOINTS WITH DISSIMILAR ADHERENDS SUBJECTED TO STATIC BENDING MOMENTS

HE Dan    Toshiyuki SAWA    Atsushi KARAMI
Graduate School of Mechanical Engineering
Hiroshima University
E-mail address: D060663@hiroshima-u.ac.jp

1 Background

One of the merits for adhesive joints is to joint different material adherends easily. Thus, adhesive joints with dissimilar adherends are used as widely as the joints with similar adherends. Some studies have been carried out on the stress and strength evaluation for the adhesive joints with similar adherends, such as butt adhesive joints\cite{1-11}, lapped adhesive joints\cite{12-21}, and scarf adhesive joints subjected to static tensile loadings\cite{22-26}. Furthermore, a lot of researches on the stress analysis and strength estimation for adhesive joints under static loadings have been done in two-dimensional analyses. It is necessary to know the interface stress distributions of adhesive scarf joints in the three-dimensional analyses taking into account the stress distributions in the thickness direction. It is well known that the singular stress occurs at the edges of the interfaces. Thus, the singular stress must be calculated on the joint strength estimation. Suzuki et al. showed the 3-D FEM analysis\cite{23-26}. However, the mesh in their analysis was relatively rough and the detail of the singular stresses at the edges in the thickness direction was not clarified sufficiently. In addition, no research has been carried out on the stress analysis and strength evaluation of scarf adhesive joints with dissimilar adherends. Scarf adhesive joints have been used in aircrafts and so on. However, it is important how to determine the optimum scarf angle and adhesive material properties for better joining. It is necessary to know the interface stress distribution and the estimation of joint strength in the scarf adhesive joints with dissimilar adherends subjected to static bending moments from a reliable design standpoint. In this paper, the stress distributions in the scarf adhesive joints with dissimilar adherends under static bending moments are analyzed using the 2-D and the 3-D finite-element method (FEM) and the difference in the interface stress distributions is shown between the 2-D and the 3-D FEM calculations. The difference in the interface stress distributions between the upper and lower interfaces is also examined. The effects of the adherends and adhesive Young’s modulus, the scarf angle, and the adhesive thickness on the interface stress distributions are examined. In addition, the above characteristics of the joints with dissimilar adherends are compared with those of the joint with similar adherends. For verification of the FEM calculation, the strains in the joints were measured using strain gauges. Furthermore, the joint strength, indicated by the rupture bending moments, is estimated with 3-D FEM calculations in elasto-plastic deformation range by using both the maximum principal stress and the maximum principal strain failure criterion. Experiments to measure the rupture bending moment were also carried out. The numerical results are compared with the experimental results.
2 Method

FEM calculations of interface stress distributions using FEM code ANSYS and experiments measuring strains and joint strengths are carried out. Figure 1 shows a model for the 3-D FEM calculations of scarf adhesive joints. Cartesian coordinates \((x,y,z)\) are used. In addition, coordinates \((s,n)\) along the interfaces are used as shown in Fig.1. Half part of the joint is analyzed because the joint is symmetric with respect to \(z=t_2/2\). The boundary conditions applied are as follows: The lower adherend is fixed in the \(y\)-direction and its freedom of rotation is restricted. A bending moment is applied to the end of the upper adherend. Figure 2 shows an example of mesh divisions in 2-D and 3-D FEM calculations. The smallest element size was chosen as \(5\times5\mu m\) in 2-D FEM calculations and as \(5\times5\times5\mu m\) in 3-D FEM calculations at the interfaces between the adhesive and the adherends. SS400 (JIS) mild steel and brass (C2800) were chosen as the adherend materials and epoxy (SUMITOMO 3M Co., Ltd., Scotch-Weld 1838) as the adhesive. Figure 3 shows the dimensions of the specimens used in the experiments for measuring the strains and the joint strengths of scarf joints subjected to static bending moments. The adhesive thickness \(t_1\) of the specimens was chosen as 0.1 mm, the adhesive length \(l\) as 32mm and the adherend thickness \(t_2\) as 9 mm. The materials of the specimens was the same as in the FEM calculations. The bending experiments were carried out after bonding and solidifying a pair of specimens with different materials for eight hours with the epoxy bond at 60°C. Figure 4 shows the schematic of the experimental apparatus. The four-point bending moments were applied to the test specimen. In the experiments, strains at 3 points at the adhesive
layer were measured using strain gauges (KYOWA Electronic Instruments Co., Ltd., KFC-C1-1) with a length of 1 mm, and the magnitude of the applied load was measured with a load cell. Furthermore, the rupture loading was also measured.

3 Results

Effects of the ratio of Young’s modulus between upper and lower adherends $E_1/E_2$, adhesive Young’s modulus $E_1/E_3$, scarf angle $\theta$ and adhesive thickness $t_1$ on the interface stress distribution are studied using 2-D and 3-D FEM calculations. However, since it can be observed that singular stresses occur near the left side of upper interface and the right side of lower interface. Thus, the following researches about the interface stress distributions will be focused on these two regions. Figures 5-9 show the results of 2-D and 3-D FEM calculations about the effects of above mentioned properties. It is seen that singular stress increases when $E_1/E_2$, $E_1/E_3$, or $t_1$ increases. It is also seen that the singular stress is the minimum when scarf angle is about 60 degree. However the singular stress predicted from 2-D FEM and 3-D FEM is different. It is thought to be due to the stress singularity in the z-direction (the joint thickness direction).

![Fig.5 The effect of adherend Young’s modulus on the interface stress distribution (3-D FEM)](image1)

![Fig.6 The effect of adhesive Young’s modulus on the interface stress distribution (3-D FEM)](image2)
The effect of scarf angle on the interface stress distribution (2-D FEM)

Fig. 7

The effect of scarf angle on the interface stress distribution (3-D FEM)

Fig. 8

The effect of adhesive thickness on the interface stress distribution (3-D FEM)

Fig. 9
Figure 10 shows the comparison of the strains between the numerical results and the experimental results. The black circle ● shows the measured strain. The solid line shows the strain distribution along adhesive layer obtained from the 3-D FEM calculation. In the experiments, the strain (ε_y) was measured at three positions along adhesive layer (as shown in Fig.10), while in the 3-D FEM calculation, the values of ε_y were averaged at the corresponding areas of the glued strain guage along the adhesive layer. It is found that the 3-D FEM results of the strain are in a fairly good agreement with the experimental ones. Figure 11 shows the comparison of the rupture bending moments between the FEM calculated results and the measured results when the scarf angle θ is 52°. The solid line shows the rupture bending moments estimated with FEM approach using the maximum principal strain failure criterion. The dashed line shows the rupture bending moments estimated with FEM approach using the maximum principal stress failure criterion. And the solid circles show the measured bending moments. It can be observed that, the rupture bending moment estimated by use of maximum principal strain failure criterion were in fairly good agreement with experimentally measured results.

4 Conclusions

In this paper, the stress distributions in the scarf joints with dissimilar adherends subjected to static bending moments were calculated using the FEM code ANSYS in the both 2-D and 3-D cases. In addition, the rupture bending moment was predicted. The following results were obtained. 1). The effect of scarf angle of the adherend on the interfaces stress distribution is compared between 2-D and 3-D FEM calculations. The results showed that the singular stress was the smallest at the scarf angle of 60° in both the FEM calculations. It is assumed that the rupture bending moments increased when the scarf angle was 60°. 2). The effect of Young's
modulus of the adhesive, that of the adherends and the thickness of the adhesive layer on the interface stress distributions was investigated with the 3-D FEM calculations. The results show that the stress singularity at the edges of interfaces decreases as the Young's modulus of adhesive increases, the ratio of Young's modulus of adherends decreases, and the thickness of adhesive layer decreases. 3). Experiments measuring the strains on the adherends and the rupture bending moments were carried out. The numerical results were in good consistence with the experimental ones. 4). The rupture bending moments were estimated using both the maximum principal stress failure criterion and the maximum principal strain failure criterion in 3-D FEM calculations in elasto-plastic deformation range. The rupture bending moments estimated using the maximum principal strain failure criterion were in fairly good agreements with the experimental results.

5 References