International Journal of Adhesion & Adhesives 44 (2013) 166–173

Contents lists available at SciVerse ScienceDirect

International Journal of Adhesion & Adhesives

journal homepage: www.elsevier.com/locate/ijadhadh

FEM stress analysis and strength prediction of scarf adhesive joints under static bending moments

Hiroko Nakano [a], Yasuhisa Sekiguchi [b], Toshiyuki Sawa [b,*]

[a] Center for Collaborative Research and Community Cooperation, Hiroshima University, 3-10-31 Kagamiyama, Higashi-Hiroshima, Hiroshima 739-0046, Japan
[b] Graduate School of Engineering, Hiroshima University, 1-4-1 Kagamiyama, Higashi-Hiroshima, Hiroshima 739-8527, Japan

ARTICLE INFO

Article history:
Accepted 7 February 2013
Available online 20 February 2013

Keywords:
Stress analysis
Interface stress distribution
Singular stress
FEM
Adhesive
Bending moment
Joint strength
Scarf adhesive joint

ABSTRACT

The stress distributions at the interfaces in the scarf adhesive joints under static bending moments were analyzed using two-dimensional and three-dimensional finite element (FEM) calculations. The effects of the scarf angle, adhesive Young's modulus and the adhesive thickness on the interface stress distribution were examined. It was found that the singular stress at the edges of the interfaces decreased as the adhesive Young's modulus increased and the adhesive thickness decreased. The singular stress at the edges of the interfaces obtained from the 3-D was larger than that from the 2-D FEM. The joint strength was also predicted using the elasto-plastic 3-D FEM calculations. For verification of the FEM calculation results, the strains in the adherends and the joint strengths were measured. The measured results of the strains and the joint strengths were fairly consistent with the results obtained from the 3-D FEM calculations and indicated that the rupture bending moment (joint strength) was the maximum when the scarf angle was around 60°.

1. Introduction

Recently, as the performance of adhesives has been enhanced, adhesive joints are used in various industrial fields including mechanical structures, automobiles, aerospace, electronics devices and so on. However, the adhesive has been considered not suitable for application to key mechanical components due to its large variance in adhesive joint strength. It is necessary and important to understand the stress distribution and to predict strength for the adhesive joints under different types of external loadings for effective future application of the adhesive joints. Some studies have been conducted on the stress and strength prediction for butt adhesive joints[1–10], lapped adhesive joints[11–18], scarf adhesive joints [20–25] and stepped-lap adhesive joints [26,27] subjected to static tensile loadings. Suzuki [20,21] investigated on the interface stress distributions in scarf adhesive joints under tensile loadings using two-dimensional (2-D) FEM calculations and they reported that singular stresses vanished when the scarf angle of the joints under tensile loads was about 52°. While it is presumed that the bending moment as well as a tensile loading affects scarf adhesive joints, few investigations have been carried out on the stress analysis and strength prediction of adhesive joints subjected to static bending moments. Moreover, no studies on the three-dimensional (3-D) interface stress distributions for the adhesive joints except some studies [19,23–25] on the stress analysis and strength prediction of the scarf adhesive joints under static tensile loadings using the 3-D FEM.

It is necessary to understand the interface stress distribution and to predict the joint strength in scarf adhesive joints subjected to static bending moments from a reliable design standpoint. It is also important to understand the differences in characteristics related to the interface stress distribution and strength in scarf adhesive joints subjected to static bending moments.

Some researches [20,21] on the stress analysis and strength prediction for scarf joints under static loadings were conducted using two-dimensional analyses. A few investigations [23,25] were carried out on the singular stresses at the edges of the interfaces in scarf adhesive joints using the three dimensional analyses. It is, however, necessary to know the interface stress distributions of the joint in the three-dimensional analyses taking into account the stress distributions in the thickness direction. Furthermore, it is important in designing the scarf adhesive joints to know the difference in the stress characteristics in the joints between the two-dimensional and the three-dimensional analyses.

In the present paper, the stress distributions in scarf adhesive joints of similar 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 identified between the 2-D and the 3-D FEM calculations. The effects of the scarf angle, adhesive Young's modulus and adhesive thickness on

* Corresponding author. Tel.: +81 82 424 7577; fax: +81 82 422 7193.
E-mail address: sawa@mec.hiroshima-u.ac.jp (T. Sawa).

0143-7496/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.ijadhadh.2013.02.010

the interface stress distributions are examined using the 3-D FEM calculations and compared with those under static tensile loadings. For verification of the 3-D FEM calculations, the strains in the joints are measured. Furthermore, the joint strengths are predicted using elasto-plastic 3-D FEM calculations and the predicted results are then compared with the measured joint strengths.

2. FEM calculations

Fig. 1 shows a model for the 3-D FEM calculations for a scarf adhesive joint. The upper and lower adherends are the same in dimensions and materials, and are subjected to a static bending moment. Cartesian coordinates (x,y,z) are used as shown in Fig. 1. The origin of the coordinates is denoted by o. In addition, the coordinates (s,n) along the adhesive layer are used as shown in Fig. 1. Young's modulus of the adherends is denoted by E_1, Poisson's ratio by ν_1, the width by w, and the thickness in the z direction by t_2. Young's modulus of the adhesive is denoted by E_2, Poisson's ratio by ν_2, the length by l and the thickness by t_1. The scarf angle is denoted by θ. Only half of the joint is analyzed because the symmetry of the joint is taken into consideration with respect to the plane $z=0$. The boundary conditions are as follows: all nodal positions at the bottom of the lower adherend are fixed in the y direction and those of the center is fixed in the x direction, and a bending moment M is applied to the top of the upper adherend as shown in Fig. 1. The maximum bending stress due to bending moment M is designated as σ_0 as shown in Fig. 1.

Fig. 2(a) shows an example of mesh divisions for a scarf adhesive joint in the 2-D FEM calculations (plain strain). The FEM code employed is ANSYS. The total number of nodes and elements are 1891 and 1800, respectively. The smallest element size is 5 μm × 5 μm at the edges of the interfaces between the adhesive and the adherends, and 8 node hexahedron elements are used. Fig. 2(b) shows an example of mesh divisions for the scarf adhesive joint in the 3-D FEM calculations. The stress distributions at the interfaces, in particular, the distributions close to the edges of the interfaces are examined by changing the minimum mesh size as 20 μm, 10 μm, 5 μm and 2 μm. As the results, the difference in the stress distributions is found to be the smallest between the case of 5 μm and 2 μm. Thus, the minimum mesh size is chosen as 5 μm taking into account the FEM calculation time. The total number of nodes is 30,256 and the total number of elements is 27,000. The smallest element size is 5 μm × 5 μm × 5 μm at the edges of the interfaces. Mild steel (SS400 (JIS)) was selected as the adherend material and the epoxy as the adhesive.

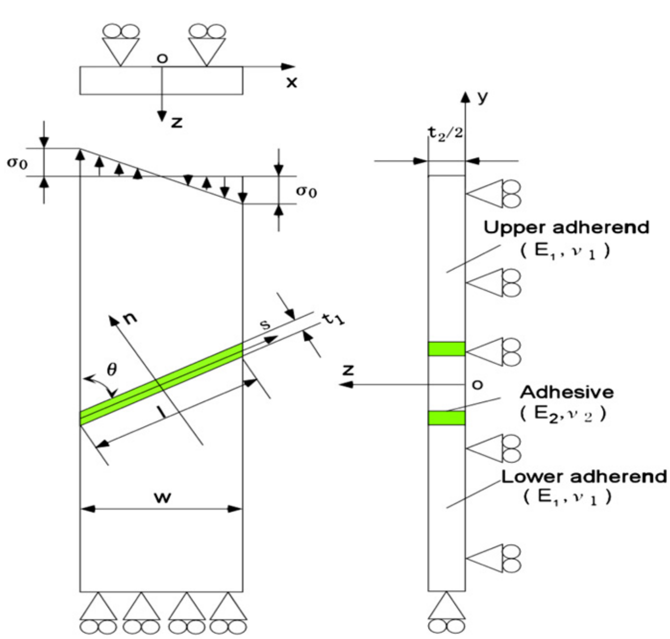

Fig. 1. Model of scarf adhesive joint subjected to bending moment for 3-D FEM calculations.

3. Experimental details

Fig. 3(a) shows the dimensions of the specimens used in the experiments to measure the strains and the joint strengths of scarf joints subjected to static bending moments. The adhesive thickness t_1 of the specimens is set as 0.1 mm, the adhesive length l as 32 mm and the adherend thickness as 9 mm. The material of the adherends is the mild steel (SS400, JIS). Its Young's modulus and Poisson's ratio, E_1 and ν_1, are 209 GPa and 0.29, respectively. The material of adhesive is epoxy (SUMITOMO 3M Co., Ltd., Scotch-Weld 1838). Its material constants E_2 and ν_2, are 3.34 GPa and 0.38, respectively. The scarf angle θ is chosen as 45°, 52°, 60° and 90°.

The test specimens were fabricated by wire cut except the specimens with the scarf angle 90° (butt joint specimens). The surface roughness at the bonded interface was measured. The calculated average roughness R_a obtained was less than 5 μm.

The interfaces of both adherends were degreased using butanone. Epoxy adhesive were pasted at the interfaces of the adherends and the joints were pushed with some compressive forces. The bonded joints were left for 10 h at an ambient temperature. After that, the bonded joints were cured for 2 h in an oven at 60 °C and then at the ambient temperature for 24 h. Then, the four-point bending experiments were carried out.

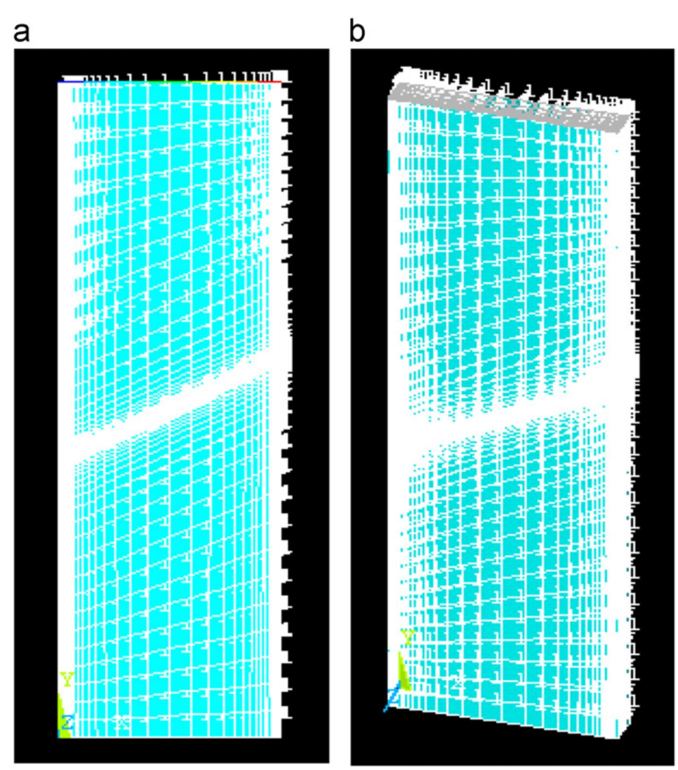

Fig. 2. Examples of mesh divisions in the 2-D and the 3-D FEM calculations (a) 2-D FEM calculations (b) 3-D FEM calculations.