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A mesh-independent technique to evaluate stress singularities in adhesive joints

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ABSTRACT

As adhesive joining becomes widely used in industrial production, the evaluation of adhesive joint strength becomes increasingly important. Singular stress fields exist at the extremes of interfaces of adhesive joints. The intensity of singular stress can be used to evaluate the strength of the adhesive joint; however, it is difficult to measure strength directly by the finite element method (FEM) because of the singularity. In this paper, a new method is proposed, in which only the first element stress values at the end of interface were used to obtain the intensity of the singular stress. The method was proved to be valid by comparing the peeling stresses between numerical results and experimental results from other papers. The effects of material combinations and the adhesive thickness on the intensity of singular stress in adhesive joints under tension and bending were discussed. It was found that the change rate of the intensity of singular stress depended on the combinations of adhesive and adherent materials, and the intensity of singular stress increased with increasing adhesive thickness until the adhesive thickness equaled the total width. The joint strengths under tension and bending were compared based on the intensity of the singular stress, and it depended on material combinations, differently from the case of a bonded strip. Moreover, the interaction between singular stress fields in the upper and lower interfaces was also investigated for the adhesive joint with dissimilar adherents.

1. Introduction

Due to their low manufacturing cost and ease of maintenance, adhesive joints are most frequently used in numerous industrial sectors, such as automobile, shipbuilding, and aeronautics, to replace or supplement traditional joining technologies, such as welding or riveting. With the extensive use of adhesive joining, research has been conducted to evaluate its strength through experimental data [1–3]. However, as the experiments are often time-consuming and costly, finite element analysis (FEA) of adhesive joints is preferred, which can help to investigate the strength of adhesive joints as a function of varying geometrical features and material properties that can be changed numerically [4]. Most research concentrates on numerical methods, and the validity of these studies has been proved through experimental results [5–8].

The mismatch of different material properties may cause stress singularities at the end of an interface, which easily leads to failures from the bonded interface. Therefore, it is important to analyze the stress singularity to evaluate the strength of adhesive joints. Much valuable research has been conducted to analyze the stress singularity at the end of the interface between adhesive and adherent sections, such as Koguchi et al. [9], Kilic et al. [10], Van Tooren et al. [11], and Goglio and Rossetto [12]. Da Silva et al. made a detailed and comprehensive comparison review about the studies of adhesive joints [13,14]. Moreover, Mintzas and Nowell [15] presented the fracture criterion and its validation for adhesive joints on the basis of the intensity of singular stress K_σ as the fracture initiation parameter, which was similar to the stress intensity factor K of a crack. The critical values of the intensity of singular stress $K_{\sigma c}$ were obtained under various material combinations, and geometries, as well as mechanical and thermal loadings [16–20].

However, the intensity of singular stress is difficult to obtain directly from stress values of elements in the singular stress field, as these values are sensitive to element mesh sizes. Previously, the intensity of singular stress was calculated by extrapolation, in which needed a fine mesh size to ensure its precision. However, results were still not particularly accurate. In this paper, a new method is proposed, in which only the first element stress values at the end of the interface are used to obtain the intensity of singular stress. This method was proved to be valid by comparing the peeling stresses between numerical and experimental results. The intensity of the singular stress values was obtained with different material combinations for the adhesive joint under tension (Fig. 1(a)) and bending (Fig. 1(b)).

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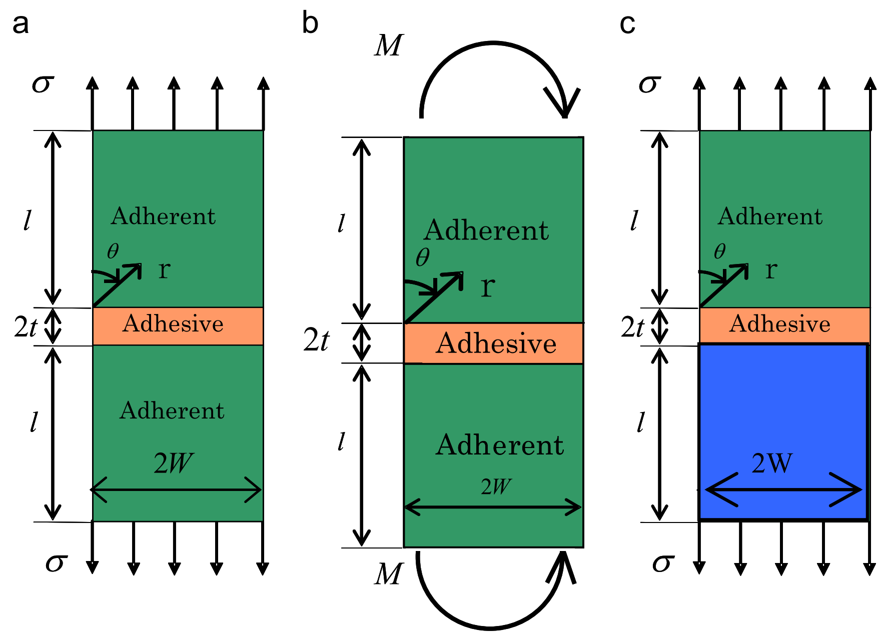

Fig. 1. Adhesive joint under (a) tension, (b) bending, and (c) tension with dissimilar adherents.

Additionally, the effect of the adhesive thickness on the intensity of the singular stress was discussed. The joint strength under tension and bending is compared based on the intensity of singular stress. Moreover, the interaction between singular stress fields of the adhesive joint with dissimilar adherents (Fig. 1(c)) was investigated.

2. Analytical method

For the adhesive joint shown in Fig. 1, it is known that the interface stress $\sigma_{ij}(ij=rr,\theta\theta,r\theta)$ goes to infinity at the end of the joint and has a singularity of $\sigma_{ij}\propto 1/r^{1-\lambda}$ when $\alpha(\alpha-2\beta)>0$. Here, α and β are Dundurs' parameters, which depend on Poisson's ratio v and the shear modulus G. Moreover, when $\theta=\pi/2$, the stress singularity index λ could be expressed by the following equations [21,22]:

$$\left[\sin^2\left(\frac{\pi}{2}\lambda\right)-\lambda^2\right]^2\beta^2+2\lambda^2\left[\sin^2\left(\frac{\pi}{2}\lambda\right)-\lambda^2\right]\alpha\beta$$
$$+\lambda^2\left(\lambda^2-1\right)\alpha^2+\frac{\sin^2(\lambda\pi)}{4}=0 \qquad (1)$$

$$\alpha=\frac{G_1(\kappa_2+1)-G_2(\kappa_1+1)}{G_1(\kappa_2+1)+G_2(\kappa_1+1)}\quad \beta=\frac{G_1(\kappa_2-1)-G_2(\kappa_1-1)}{G_1(\kappa_2+1)+G_2(\kappa_1+1)}$$
$$\kappa_j=\begin{cases}\frac{3-\nu_j}{1+\nu_j}(\text{plane stress})\\ 3-4\nu_j(\text{plane strain})\end{cases},\kappa_j=\ (j=1,2) \qquad (2)$$

It is found that $\lambda>1$ when $\alpha(\alpha-2\beta)<0$; $\lambda=1$ when $\alpha(\alpha-2\beta)=0$; and $\lambda<1$ when $\alpha(\alpha-2\beta)>0$.The strength of adhesive joints with interfaces depends on the singular stress fields, which exist at the end of interface, and it is often evaluated by the parameter of intensity of singular stress K_σ. Furthermore, $K_{\sigma,T}$ refers to the case of tension and $K_{\sigma,M}$ to bending

$$K_{\sigma,T}=\lim_{r\to 0}\left[r^{1-\lambda}\times\sigma_{\theta|\theta=\pi/2,T}(r)\right] \qquad \text{(for tension)}$$
$$K_{\sigma,M}=\lim_{r\to 0}\left[r^{1-\lambda}\times\sigma_{\theta|\theta=\pi/2,M}(r)\right] \qquad \text{(for bending)} \qquad (3)$$

The dimensionless intensities of the singular stress $F_{\sigma,T}$ and $F_{\sigma,M}$ are defined by

$$F_{\sigma,T}=\frac{K_{\sigma,T}}{\sigma(2W)^{1-\lambda}}=\frac{\lim_{r\to 0}[r^{1-\lambda}\sigma_{\theta|\theta=\pi/2,T}(r)]}{\sigma(2W)^{1-\lambda}} \qquad \text{(for tension)}$$
$$F_{\sigma,M}=\frac{K_{\sigma,M}}{(3M/2W^2)(2W)^{1-\lambda}}=\frac{\lim_{r\to 0}[r^{1-\lambda}\sigma_{\theta|\theta=\pi/2,M}(r)]}{(3M/2W^2)(2W)^{1-\lambda}} \qquad \text{(for bending)}$$
$$(4)$$

where σ is the tension stress, M is the moment per unit length at the adhesive joint, and $\sigma=3M/2W^2$ is the maximum bending stress (stress at the furthest point from the neutral axis) caused by M equals the tensile stress σ.

In this paper, the adhesive thickness t/W in the analytical model varies from 0.001 to 4 (0.01, 0.1, 0.5, 1, 2, and 4), and the actual width of the FEM model, which does not affect the results, is W=1000 mm. The length is l=2W, because it is known that the interface stresses do not change for length values of more than twice the width.

It is difficult to obtain the values of the intensity of singular stress ($K_{\sigma,T},K_{\sigma,M}$) directly from FEM calculations, as the stresses go to infinity at the end of the interface due to the singularity. In this paper, the ratios of the intensity of the singular stress ($K^1_{\sigma,T}/K^2_{\sigma,T}$, $K^1_{\sigma,M}/K^2_{\sigma,M}$) will be considered. Here, the superscripts 1 and 2 refer to different thickness to width ratios (t/W); the adhesive thickness t/W has two cases. As shown in Eqs. (3) and (4), the dimensionless intensity of singular stress is related to the distance r, the singularity index λ, the applied load (σ or M), the width W and the limiting stress $\lim_{r\to o}\sigma_{\theta|\theta=\pi/2,T}$ or $\lim_{r\to o}\sigma_{\theta|\theta=\pi/2,M}$. Two models with different adhesive thicknesses (t_1,t_2) are considered (problem 1 and problem 2), both of which have the same applied load at infinity σ or M, the same model width W, and the same material combinations (which means that the singularity index is $\lambda_1=\lambda_2$). Therefore, the ratios of intensity of singular stress ($K^1_{\sigma,T}/K^2_{\sigma,T},K^1_{\sigma,M}/\ K^2_{\sigma,M}$) are only related to the ratios of stress $\lim_{r\to o}(\sigma^1{}_{\theta|\theta=\pi/2,T}/\sigma^2{}_{\theta|\theta=\pi/2,T})$, $\lim_{r\to o}(\sigma^1{}_{\theta|\theta=\pi/2,M}/\sigma^2{}_{\theta|\theta=\pi/2,M})$, which only depend on the adhesive thickness t. The ratios of intensity