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Intensity of singular stress field over the entire bond line thickness range useful for evaluating the adhesive strength for plate and cylinder butt joints

Nao-Aki Noda[a,*], Fei Ren[a], Rei Takaki[a], Zefeng Wang[a], Kazuhiro Oda[b], Tatsujiro Miyazaki[c], Yoshikazu Sano[a]

[a] *Department of Mechanical Engineering, Kyushu Institute of Technology, 1-1, Sensui-cho, Tobata-Ku, Kitakyushu-Shi, Fukuoka 804-8550, Japan*
[b] *Oita University, 700 Dannoharu, Oita-Shi, Oita 870-1192, Japan*
[c] *University of the Ryukyus, 1 Senbaru, Nishihara, Nakagami, Okinawa 903-0213, Japan*

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ABSTRACT

Our previous research has indicated that the bonded strength can be expressed in terms of the intensity of the singular stress field (ISSF). Since the ISSF is quite useful for evaluating the bonded strength, in this study, the variation of the ISSF is investigated over the entire bondline thickness range of plate and cylinder butt joints. Here, an effective mesh-independent technique combined with a standard FEM approach is used to obtain the ISSFs under arbitrary material combinations. A reference solution of simply bonded plate is used to eliminate FEM error since the exact ISSF is available. This paper clarifies the differences between the fracture behaviors of the bonded plate and cylindrical butt joints.

1. Introduction

Adhesive joints are widely used in numerous industrial sectors, such as automobile, shipbuilding and aeronautics [1–3]. Compared with the other traditional joints, adhesive joints have advantages of light weight, low cost and easy to process. However, different material properties cause singular stress at the interface end, which may lead to debonding failure in structures [4–12]. The bonded strength can be expressed in terms of the intensity of the singular stress field (ISSF). The ISSF K_σ and the normalized ISSF F_σ can be determined from the interface stress as shown in Eq. (1) [13,14] by using the local polar coordinate (r, θ) indicated in Fig. 1(a), (b).

$$\text{ISSF } K_\sigma = \lim_{r\to 0}[r^{1-\lambda} \times \sigma_\theta(r)|_{\theta=\pi/2}],\ \text{Normalized ISSF } F_\sigma = \frac{K_\sigma}{\sigma W^{1-\lambda}} \quad (1)$$

Since the singular index $\lambda \neq 0.5$ different from the singular index for cracks $\lambda = 0.5$, the term ISSF (=Intensity of Singular Stress Field) is used instead of SIF (=Stress Intensity Factor) usually used for cracks generally.

Fig. 2(a) shows the adhesive joint strength for plate butt joint expressed as the critical remote tensile stress σ_c [15]. It is known that the debonding stress increases with decreasing the adhesive thickness [15–19]. In Ref. [19], the effect of joint component mechanical properties and adhesive layer thickness on stress concentration was discussed for a bonded cylindrical specimen. In Ref. [7–9] the ISSF is considered under arbitrary material combinations for $h/W = 0.1$ and 0.001. Our previous studies have indicated that the normalized ISSF decreases with decreasing the bondline thickness as shown in Fig. 2(b) under tension [7] and under bending [8,9]. From the critical remote tensile stress shown in Fig. 2(a), (b), the critical ISSF can be calculated when the debonding occurs. As shown in Fig. 3, the debonding strength can be expressed as a constant value of ISSF [12,20].

From the above discussion, it is seen that the solution for ISSF shown in Fig. 2(b) is quite useful for evaluating the adhesive strength. For large adhesive thickness h, the normalized ISSF F_σ becomes constant as shown in Fig. 2(b), and therefore can be estimated easily for any material combination (see Appendix A [14]). However, for small bondline thickness h, which is necessary for evaluating normal adhesive layers, the normalized ISSF F_σ decreases with decreasing h and does not become constant. In this paper, therefore, the ISSF vs. h relation will be clarified mainly focusing on the small adhesive thickness. As a three-dimensional fundamental solution, the cylindrical butt joint in Fig. 1(c) is also considered to be compared with plate butt joint. The aim of this paper is to provide the solutions of ISSFs useful for evaluating the adhesive joint strength. In this study, arbitrary material combinations will be considered for the future use of adhesive joint in wide engineering fields.

* Corresponding author.
E-mail address: noda@mech.kyutech.ac.jp (N.-A. Noda).

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Nomenclature

E	Young's modulus
$e_{\min}$	Minimum element size
F_σ^C	ISSF of bonded cylinder normalized by W, $= K_\sigma^C/\sigma W^{1-\lambda}$
F_σ^{C*}	ISSF of bonded cylinder normalized by h, $= K_\sigma^C/\sigma h^{1-\lambda}$
F_σ^P	ISSF of bonded plate normalized by W, $= K_\sigma^P/\sigma W^{1-\lambda}$
F_σ^{P*}	ISSF of bonded plate normalized by h, $= K_\sigma^P/\sigma h^{1-\lambda}$
G	Shear modulus
K_σ^C	ISSF for bonded cylinder
K_σ^P	ISSF for bonded plate
$K_{\sigma c}$	Critical ISSF at debonding fracture
h	Bondline thickness
r	Distance from the interface end
u_{r0}^{CYL}	Real radial displacement of bonded cylinder
W	Plate width and radius of bonded cylinder
α, β	Dundurs' parameters
$\varepsilon_{j0,FEM}^C$, $\gamma_{rz0,FEM}^C$	FEM strain of bonded cylinder at interface end
$\varepsilon_{i0,FEM}^P$, $\gamma_{xy0,FEM}^P$	FEM strain of bonded plate at interface end
θ	Angle from the corner on the interface
λ	Singular index
ν	Poisson's ratio
σ_c	Adhesive tensile strength
σ_j^C, τ_{rz}^C	Real stress of bonded cylinder
σ_i^P, τ_{xy}^P	Real stress of bonded plate
$\sigma_{i0,\,FEM}$, $\tau_{xy0,\,FEM}$	FEM stress at interface end
$\sigma_{j0,FEM}^C$, $\tau_{rz0,FEM}^C$	FEM stress of bonded cylinder at interface end
$\sigma_{i0,FEM}^P$, $\tau_{xy0,FEM}^P$	FEM stress of bonded plate at interface end
$\tilde{\sigma}_{j0,FEM}^C$, $\tilde{\tau}_{rz0,FEM}^C$	Non-singular FEM stress of bonded cylinder at interface end
σ^{real}	Real stress at interface end
σ_y^∞, σ_z^∞	Uniform applied stress

1.1. Mesh-independent technique to evaluate the ISSF of plate butt joint

In this section, a mesh-independent technique will be explained for the readers to understand how to obtain accurate ISSFs although similar methods have been used in [9,12,20]. In the first place, a plate butt joint as shown in Fig. 1(a) is considered. When the bondline thickness h is significantly less than the adhesive width $W\,(h/W \to 0)$, the solution may be regarded as the bonded semi-infinite plate as shown in Fig. 1(b). It is known that the interface stress $\sigma_{ij}\,(ij = rr, r\theta, \theta\theta)$ at the edge can be expressed in the form $\sigma_{ij} \propto 1/r^{1-\lambda}$ when $\alpha(\alpha - 2\beta) > 0$. Notations α and β denote Dundurs' parameters [21] expressed by Poisson's ratio ν and shear modulus G, and notation λ denotes the singular index at the interface expressed as the root of the following equations [22,23].

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

$$\alpha = \frac{G_1(\kappa_2 + 1) - G_2(\kappa_1 + 1)}{G_1(\kappa_2 + 1) + G_2(\kappa_1 + 1)},\quad \beta = \frac{G_1(\kappa_2 - 1) - G_2(\kappa_1 - 1)}{G_1(\kappa_2 + 1) + G_2(\kappa_1 + 1)} \tag{3}$$

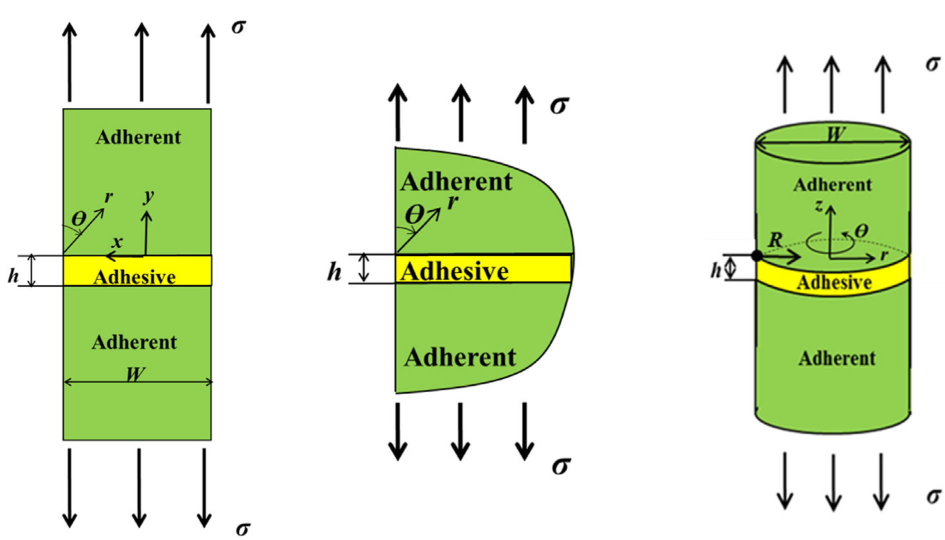
$$\kappa_j = \begin{cases} \frac{3-\nu_j}{1+\nu_j} \text{ (plane stress)} \\ 3 - 4\nu_j \text{ (plane strain)} \end{cases} \quad (j = 1, 2) \tag{4}$$

The ISSF K_σ at the adhesive dissimilar joint end is defined from the real interface stress σ_y^{real} as shown in Eq. (5).

$$\text{ISSF } K_\sigma = \lim_{r\to 0}[r^{1-\lambda}\sigma_y^{real}(r)],\ \text{ but ISSF } K_\sigma \neq \lim_{r\to 0}[r^{1-\lambda}\sigma_y^{FEM}(r)] \tag{5}$$

However, the ISSF cannot be easily determined by FEM since real interface singular stress σ_y^{real} is different from the FEM stress σ_y^{FEM}, which is largely depending on the mesh size. In the previous papers [8,9,12], therefore, the FEM stress ratio $\sigma_y^{FEM}/\sigma_{y(\mathrm{Ref})}^{FEM}$ was considered by using a reference problem which has been solved very accurately in the previous study. It should be noted that the FEM stress ratio of the unknown reference problems is independent of the mesh size if the same FEM mesh is applied. This is because the FEM errors of two problems are nearly the same. As the reference solution, a simply bonded plate can be used since the ISSF has been analysed very accurately by using the body force method [14] (see Appendix A). Since the FEM stress ratio and the reference solution are very accurate, the new results also can be obtained very accurately.

In this study, the ISSF of a simply bonded plate will be used as the reference problem, as is shown in Eq. (6).



(a) Plate butt joint (b) Semi-infinite butt joint (c) Cylinder butt joint

Fig. 1. Adhesive butt joints (Fig. 1(b) is equivalent to Fig. 1(a) when $h/W \leq 0.01$ in Fig. 1(a)).