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EVALUATION OF ADHESIVE STRENGTH BASED ON THE INTENSITY OF SINGULAR STRESS FIELD OF SINGLE LAP JOINT

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Abstract: In this study, the adhesive strength for single lap joint is investigated based on the intensity of singular stress field. First, the critical intensity of singular stress at the adhesive dissimilar joint is calculated by using finite element method (FEM) based on the experimental result. It is found that the adhesive strength can be expressed as the critical intensity of singular stress field. Then, a suitable evaluation method of adhesive strength is investigated focusing on the intensity of singular stress field. The effect of specimen geometry on the intensity of singular stress is considered. The results show that the intensity of singular stress field decreases with increasing the adherend thickness, the minimum intensity of singular stress can be obtained when the adherend thickness is large enough. The results of the deformation angle at the interface corner edge show a similar trend as in intensity of singular stress field, and the minimum deformation angle can be obtained when the adherend thickness is large enough. The usefulness of the method is investigated focusing on the deformation angle at the interface corner edge.

Keywords: Stress intensity factor; Interfaces; Deformation angle; Single lap joint

1 INTRODUCTION

Since adhesively joints are economical, practical and easy to be used; thus they have been widely used in a variety of industries. A number of studies of adhesive joints have been made so far [1-4]. The authors investigated the adhesive butt joint strength in Fig. 1 by changing the adhesive thickness and material combination [5,6]. It is found that the adhesive strength can be expressed as the critical intensity of singular stress field as $K_{nc} = \text{const}$ based on the experimental results. The adhesive strengths of the single lap joint (see Fig. 2(a)) and double lap joint (see Fig.2(b)) were also investigated previously [7]. In this result, the adhesive strength of double lap joint is not equal to the one of single lap joint as expected and is almost twice larger than the one of single lap joint. Compared with double lap joint, single lap joint testing is more stable and used conveniently. The testing method and experimental adhesive strength are prescribed by Japanese Industrial Standards (JIS) [8]. However, since the debonding strength is defined as the magnitude of the load, the strength is affected by the specimen dimension and difficult to be applied to other geometries. Therefore, it is necessary to find a suitable method to evaluation the debonding strength of single lap joint testing.

In this paper, first, the debonding strength of single lap joint will be investigated based on the experimental results [9] by using the evaluation method shown in [6]. Then, a suitable evaluation method of adhesive strength will be evaluated focusing on the intensity of singular stress field and the deformation angle appearing at the end of interface.

Fig.1 Adhesive strength expressed as $K_{nc} = \text{const}$ for butt joint.  
Fig.2 Single and double lap joints.
2 ADHESIVE STRENGTH EXPRESSED AS A CONSTANT CRITICAL INTENSITY OF SINGULAR STRESS $K_{\sigma_c}$ FOR SINGLE LAP JOINT WITH VARYING ADHESIVE GEOMETRY $l_{ad}$ AND $t_{ad}$

Figure 3 shows the schematic illustration of the analysis models. It has been reported that the singularity exists near the interface corner, and the singularity depending on the singular indexes $\lambda_1$ and $\lambda_2$ at the interface [10]. In this paper, $\lambda_1=0.6062$, $\lambda_2=0.9989$. The stress $\sigma_\theta$ at $r$ direction ($\theta=0$) can be expressed as follows. The notation $r$ denotes the radial distance away from the corner singular point O.

$$\sigma_\theta = \frac{K_{\sigma_1,\lambda_1}}{r^{1-\lambda_1}} + \frac{K_{\sigma_2,\lambda_2}}{r^{1-\lambda_2}} \equiv \frac{K_{\sigma,\lambda}}{r^{1-\lambda}} \left(1 + C_\sigma r^{\lambda-1} \right)$$

(1)

Here, $K_{\sigma_1,\lambda}$ and $K_{\sigma_2,\lambda}$ are the intensities of the singular stress field. The intensities of singular stress field can be obtained based on our previous study[11,12] by using Reciprocal Work Contour Integral Method[13] (RWCIM). The intensities of the singular stress field can be represented with only $K_{\sigma,\lambda}$ since $C_\sigma$ is almost constant expressed as $C_\sigma = -5.2387 \pm 0.2659$.

In this study, the thick specimens used by Park [9] in Fig.3 are analyzed where the adherends aluminum alloy 6061-T6 (Young’s modulus $E = 68.9$ [GPa], Poisson’s ratio $\nu = 0.3$) are bonded with adhesive FM73 M epoxy (Young’s modulus $E = 4.2$ [GPa], Poisson’s ratio $\nu = 0.45$). The typical force-displacement curves of the adhesive joints show nearly linear behavior. A drop in load was used to detect a failure. The total length of the specimen is 225mm, adherend thickness $t_1=7mm$, $d=10mm$, adhesive thickness $t_{ad}=0.15-0.9mm$, adhesive length $l_{ad}=20-50mm$, $L=50mm$, $\sigma_{ad}=1MPa$ ($P = 14.15N$).

Fig.4 shows the $K_{\sigma_c}$ with different $l_{ad}$ and $t_{ad}$ under $P = P_{0j}$. Here, $P_{0j}$ is the fracture load, “A25” means $l_{ad}=25mm$ and $t_{ad}=0.15mm$, “A25-30” means $l_{ad}=25mm$ and $t_{ad}=0.30mm$, and so on. It is found that the average value of $K_{\sigma_c}$ is 4.030 MPa.m$^{-1/2}$, and the $K_{\sigma_c}$ values are almost constant independent of the $l_{ad}$ and $t_{ad}$. It is seen that the adhesive strength can be expressed as $K_{\sigma_c}$=const.

![Fig. 3 Analysis model and boundary condition.](image)

![Fig. 4 Adhesive strength expressed as $K_{\sigma_c}$=const for $t_{ad}=0.15-0.9mm$ and $l_{ad}=20-50mm$ under fixed $t_1=7mm$, $L=50mm$.](image)

3 PURE SHEAR TESTING TO MINIMIZE $K_{\sigma_c,\lambda}$

The butt joint in Fig.1 is used to obtain the adhesive strength under pure tension [5, 6] and the single lap joint in Fig.2 is used to obtain the adhesive strength under pure shear. However, due to the deformation of single lap joint during testing, peeling force as well as shearing force is applied to the adhesive region. Then, the intensity of singular stress $K_{\sigma_c,\lambda}$ is also affected by the peeling force due to the deformation. Since the single lap joint testing should be done under pure shear loading, smaller $K_{\sigma_c,\lambda}$ is desirable. The fracture load $P_{0j}$ increases with increasing the adhesive length $l_{ad}$ as described in [9], and the adhesive strength can be expressed as $K_{\sigma_c}$=const independent of adhesive geometry $l_{ad}$ and $t_{ad}$. This means that
when $K_{\sigma, A}$ is small, the fracture load $P_{af}$ is large. Therefore, in order to minimize $K_{\sigma, A}$, the effect of specimen geometry is considered under the same adhesive geometry and load $P$. In this section, we assume $P = 14.15N$, the adhesive length $l_{ad} = 25mm$, and adhesive thickness $t_{ad} = 0.15mm$. Then, the effects of specimen geometries $t_i$ (adherend thickness) and $L$ (fixed boundary length) on the intensity of singular stress field $K_{\sigma, A}$ are discussed.

Figure 5 shows the relationship between the intensity of singular stress field $K_{\sigma, A}$ and adherend thickness $t_i$ under different fixed length $L$. The dashed line shows the minimum value of $K_{\sigma, A}$. Here, JIS* means only the adherend thickness $t_i = 1.5mm$ and fixed boundary length $L = 50mm$ in JIS K6850 are used as shown in Fig.3. As can be seen from Fig.5, the $K_{\sigma, A}$ decreases with increasing $t_i$ and $L$. The $K_{\sigma, A}$ value becomes constant if $t_i$ is large enough. The $K_{\sigma, A} |t_i = 1.5mm$ (JIS K6850) is 5 times larger than the one of $K_{\sigma, \text{min}}$, and the $K_{\sigma, A} |t_i = 7mm$ [9] is more than twice than that of $K_{\sigma, \text{min}}$. It is seen that the specimen in [9] is better than the JIS, but it is more desirable to use larger adherend thickness.

![Fig. 5. Effect of $L$ and $t_i$ on $K_{\sigma, A}$ under fixed $l_{ad}$ and $t_{ad}$ (JIS*: Only $t_i = 1.5mm$ and $L = 50mm$ in JIS K6850 are used as shown in Fig.3).](image)

**4 DEFORMATION ANGLE AT THE INTERFACE CORNER**

As shown in section 3, the intensity of singular stress $K_{\sigma, A}$ decreases with increasing the adherend thickness $t_i$. It is found that the minimum $K_{\sigma, A}$ can be obtained when $t_i$ is large enough. In this section, the deformation angle at interface corner is considered by changing the distance $l_p$.

Fig. 6 shows the deformation example near the interface corners. In order to obtain the deformation angle, two target points are considered. For the deformation angle $\theta_{ad}$ at interface corner O, two target points are points O and A with the distance $l_p$. For the deformation angle $\theta_{ab}$ at interface corner O, two target points are points O and B with the distance $l_p$. Fig. 7 shows the deformation angles $\theta_{ad}$ and $\theta_{ab}$ vs. $l_p$ under $t_i = 7mm$. It is found that the values of $\theta_{ad}$ and $\theta_{ab}$ both increase with increasing $l_p$, and the difference between $\theta_{ad}$ and $\theta_{ab}$ increases with decreasing $l_p$. Therefore, we cannot obtain the maximum deformation angle at corner O. Fig. 8 shows the deformation angle $\theta_c$ vs. $l_p$ under $t_i = 7mm$. It is seen that the value of $\theta_c$ increases initially with increasing $l_p$ and then decreases. Then, the maximum $\theta_c$ can be obtained when $l_p = 1/33mm$. Thus, in this study, the deformation angle will be considered by using the maximum deformation angle at corner C rather than at corner O.
As can be seen from Fig. 5, the minimum $K_{\sigma.c}$ can be obtained when $t_1$ is large enough. Similar to the variation trend of $K_{\sigma.c}$, the minimum $\theta_C$ can be obtained when the adherend thickness $t_1$ is large enough.

5 CONCLUSION

In this study, the adhesive strength for single lap joint is investigated based on the intensity of singular stress field. Since the experiments are often time-consuming and costly, the analysis method shown in this paper can help to predict the strength of adhesive joint accurately and conveniently. The conclusions can be summarized in the following way.

(1) In this paper, the critical intensity of singular stress field $K_{\sigma.c}$ is investigated by using the analysis method presented. It is seen that the adhesive strength can be expressed as $K_{\sigma.c}=\text{const}$.

(2) The effects of specimen geometries $t_1$ (adherend thickness) and $L$ (fixed boundary length) on the intensity of singular stress field $K_{\sigma.c}$ are discussed. The results show that the $K_{\sigma.c}$ at the interface corner decreases with increasing the $t_1$, and the minimum intensity of singular stress field $K_{\sigma.min}$ can be obtained when $t_1$ is large enough.

(3) The deformation angle at the interface corner is investigated by using the maximum deformation angle at interface corner C. It is found that the minimum deformation angle $\theta_C$ can be obtained when the adherend thickness $t_1$ is large enough.

6 REFERENCES


