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Photoelastic Investigation of the Stresses in Cemented Joints*
(3rd Report, Stresses on the Butt Bonded Boundary)

By Ichiro TUZI**

The stresses in composite models with application to cemented joints, especially those by butt bonding, were studied by using the photoelastic and interferometric methods. The models were made of epoxy-poly sulfide copolymers. Tests were carried out under tension on a composite bar bonded at various interlayer breadths. The results of experiments revealed that the stresses near the bonded boundary were not uniform and that in the joints with a soft adhesive layer, the stress concentrations were found on the end or center of bonded boundary in hard adherends, and they were almost reduced depending upon the decrease in the value of the breadth of adhesive layer. And in those with a hard adhesive layer, they were found on the end of bonded boundary in the hard adhesive layer, and they were increased depending upon the decrease in the value of the breadth of adhesive layer.

1. Introduction

Analysis of stress distribution and mechanical behaviors in the vicinity of bonded boundary of the cemented joints which consist of two materials having different mechanical properties is essential in studying not only the mechanical behavior of composite heterogeneous materials but also the yield behavior of homogeneous isotropic materials, for example, welded joints, compound materials, and grain boundary of metals.

Though the theoretical and experimental works on this problem have been presented previously by several authors⁽¹⁾⁻⁽²⁾, no attention is paid in these works to the effects of adhesive layer's breadth and thickness of specimen on the above mentioned distribution and behavior.

2. Nomenclature

h : thickness of adhesive layer and adherends, mm
 t : breadth of adhesive layer, mm
 P : applied tension load, kg
 E_a : Young's modulus of adhesive layer, kg/mm²
 E : Young's modulus of adherends, kg/mm²
 ν_a : Poisson's ratio of adhesive layer
 ν : Poisson's ratio of adherends
 α : photoelastic sensitivity, mm/kg, wave length of light used $\lambda = 5461 \text{ \AA}$
 β : interferometric stress sensitivity, mm/kg
 σ_1, σ_2 : principal stresses, kg/mm²
 σ_0 : nominal axial stress, kg/mm²

: principal strains

n_p : fringe order of isopachic line
 n_{po} : fringe order of isopachic line on the section far away from the jointed boundary

n_c : fringe order of isochromatic line
 n_{co} : fringe order of isochromatic line on the section far away from the jointed boundary

Subscripts

A : indicate the material of adherends
 B : indicate the material of adhesive layer

3. Model construction

Fig. 1 shows the shapes and dimensions of the test pieces. Epoxy-polysulfide copolymers were employed as model materials, and the variations in copolymerization ratio of the materials provided any desired Young's moduli. The values of E and ν for the harder material were shown at 270 kg/mm² and 0.36, and for the softer material were shown at 135 kg/mm² and 0.38. The breadth t of adhesive layers was changed to six types (2.5, 5.0, 10.0, 20.0, 30.0 mm and ∞). In I series, the softer materials were employed as the adhesive layers and the harder materials were employed as the adherends. In II series, the materials were employed reversely. They were bonded with the same materials of adhesive layers at room temperature $25 \pm 0.5^\circ\text{C}$ and the curing time was about 150 hours.

4. Test procedure

The experiments were carried out under tension to obtain the principal stresses and strains by using the photoelastic and interferometric methods at constant test temperature $25 \pm 0.5^\circ\text{C}$.

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** Assistant Professor,
Miyagi University of Education,
Sendai.

A He-Ne gas laser was used for the source of monochromatic light of wave length 6328 Å in the Mach-Zehnder interferometer. Nisida and Saito⁽³⁾ calculated the light intensity in the pattern where the light passed through the test pieces was joined with the other light and they obtained the following Eq. (1)

$$J' = \frac{1}{2} + \frac{1}{2} \cos \left[\frac{2\pi}{\lambda} \cdot \frac{A' + B'}{2} (\sigma_1 + \sigma_2)t \right] \times \cos \left[\frac{2\pi}{\lambda} \left\{ \frac{C}{2} (\sigma_1 - \sigma_2)t \right\} \right] \quad (1)$$

Equation (1) shows that the intensity of isopachic lines which tell the distribution of $(\sigma_1 + \sigma_2)$ is modulated by the variation of intensity of isochromatic lines which tell the distribution of $(\sigma_1 - \sigma_2)$. It follows from this, that with the values of $(\sigma_1 + \sigma_2)$ and $(\sigma_1 - \sigma_2)$ obtained by Eq. (2), direct determination of σ_1 and σ_2 becomes possible by adding the two and subtracting one from the other.

$$\begin{aligned} \sigma_1 + \sigma_2 &= \frac{n_p}{\beta t} \\ \sigma_1 - \sigma_2 &= \frac{n_c}{\alpha t} \end{aligned} \quad (2)$$

The isochromatic lines were obtained by photoelasticity as these lines obtained by interferometric method were not clear.

$$\begin{aligned} \frac{\sigma_1 + \sigma_2}{\sigma_0} &= \frac{n_p}{n_{po}} \\ \frac{\sigma_1 - \sigma_2}{\sigma_0} &= \frac{n_c}{n_{co}} \end{aligned} \quad (3)$$

so that

$$\begin{aligned} \frac{\sigma_1}{\sigma_0} &= \frac{1}{2} \left(\frac{n_p}{n_{po}} + \frac{n_c}{n_{co}} \right) \\ \frac{\sigma_2}{\sigma_0} &= \frac{1}{2} \left(\frac{n_p}{n_{po}} - \frac{n_c}{n_{co}} \right) \end{aligned} \quad (4)$$

and

$$\begin{aligned} \frac{\epsilon_1}{\sigma_0} &= \frac{1}{E} \left(\frac{\sigma_1}{\sigma_0} - \nu \frac{\sigma_2}{\sigma_0} \right) \\ \frac{\epsilon_2}{\sigma_0} &= \frac{1}{E} \left(\frac{\sigma_2}{\sigma_0} - \nu \frac{\sigma_1}{\sigma_0} \right) \end{aligned} \quad (5)$$

5. Results and discussion

Fig.2 shows the values of σ_1 / σ_0 and σ_2 / σ_0 on the bonded boundary DD' for series I. It shows that for the A side the values of σ_1 / σ_0 are larger than one and for the B side they are smaller than one. And it shows that for the A and B sides that the values of t are smaller than 10 mm, the values of σ_1 / σ_0 are smaller on the free boundary than on the center line, but for the values of t are larger than 20 mm, they are larger on the free boundary than on the center line. Fig.3 shows the values of σ_1 / σ_0 and σ_2 / σ_0 on the bonded boundary DD' for series II. It shows that for the B side the values of σ_1 / σ_0 are larger than one and for the A side they are smaller than one. And it shows that for the A and B sides the values of σ_1 / σ_0 are larger on the free boundary than on the center line.

Fig.4 shows the values of σ_1 / σ_0 on the free boundary FF' for series I. It shows that for the A and B sides the val-

ues of σ_1 / σ_0 at the point D reduce depending upon the decrease in the value of t . Fig.5 shows the values of ϵ_1 / σ_0 on the free boundary FF' for series I and it shows that the values have similar tendency to those in Fig.4. Fig.6 shows the values of σ_1 / σ_0 on the free boundary FF' for series II. It shows that the values of σ_1 / σ_0 at the points D and C increase depending upon the decrease in the values of t for the B side and for the A side they are changeless approximately. Fig.7 shows the values of ϵ_1 / σ_0 on the free boundary FF' for series II and it shows that the values have similar tendency to those in Fig.6. Fig.8 shows the values of σ_1 / σ_0 versus t at the points C and D on the free boundary FF' for $h = 4, 6$ mm and series I, II. It shows that for series I the values of σ_1 / σ_0 increase depending upon the increase in the values of t at the points C and D of A and B, and they approach to the constant values for $t = \infty$, and the values of σ_1 / σ_0 at the point D of A increase depending upon the increase in the values of h and at the points C and D of B they decrease depending upon the increase in the values of h . For series II the values of σ_1 / σ_0 at the points C and D of A and B reduce depending upon the increase in the values of t , and they approach to the constant values for $t = \infty$ and the values of σ_1 / σ_0 at the point D of A reduce depending upon the increase in the values of h and at the points C and D of B they increase depending upon the increase in the values of h .

Fig.9 shows the values of σ_1 / σ_0 on the center line OO' for series I. It shows that the stress concentration occurs at the point D of A and the values of σ_1 / σ_0 at the point D of B are smaller than those at the point C. Fig.10 shows the values of ϵ_1 / σ_0 on the center line OO' for series I and it shows that the values have similar tendency to those in Fig.9. Fig.11 shows the values of σ_1 / σ_0 on the center line OO' for series II. It shows that the values of σ_1 / σ_0 reduce at the point D of A and the maximum value occurs at the point distant a little from the point D and the stress concentration occurs at the point D of B and the values of σ_1 / σ_0 reduce at the point C. Fig.12 shows the values of ϵ_1 / σ_0 on the center line OO' for series II and it shows that the values have similar tendency to those in Fig.11. Fig.13 shows the values of σ_1 / σ_0 versus t at the points C and D on the center line OO' for $h = 4, 6$ mm and series I, II. It shows that for series I the values of σ_1 / σ_0 reduce depending upon the increase in the values of t at the point D of B and they increase at the point C of B and D of A and they approach to the constant values for $t = \infty$, and the values of σ_1 / σ_0 at the point D of B reduce depending upon the increase in the values of h and at the point D of A they increase depending upon the increase in the values of h . For series II, the values of σ_1 / σ_0 at the points C and D of B

reduce depending upon the increase in the values of t and they approach to the constant values for $t = \infty$, and at the point D of A they increase depending upon the increase in the values of t and they approach to the constant values for $t = \infty$, and the value of σ_1 / σ_0 at the point D of A reduce depending upon the increase in the values of h and at the point D of B they increase depending upon the increase in the values of h .

Fig.14 shows the values of σ_2 / σ_0 on the center line OO' for series I. It shows that the values of σ_2 / σ_0 at the point D and the minimum value point of A and at the points C and D of B increase depending upon the increase in the values of t . Fig.15 shows the values of σ_2 / σ_0 on the center line OO' for series II.

It shows that the values of σ_2 / σ_0 at the point D and maximum value point of A and at the points C and D of B reduce depending upon the decrease in the values of t . Fig.16 shows the values of σ_2 / σ_0 versus t at the points C and D on the center line OO' for $h = 4, 6$ mm and series I, II.

It shows that for series I the values of σ_2 / σ_0 reduce depending upon the increase in the values of t at the point D of A and at the points C and D of B, and they approach to the constant values for $t = \infty$, and the values of σ_2 / σ_0 at the point D of A increase depending upon the increase in the values of h and at the point D of B they reduce depending upon the increase in the values of h . For series II, the values of σ_2 / σ_0 at the point D and the maximum value point of A and at the points C and D of B increase depending upon the increase in the values of t and they approach to the constant values for $t = \infty$, and the values of σ_2 / σ_0 at the point D of A reduce depending upon the increase in the values of h and at the point D of B they increase depending upon the increase in the values of h .

6. Conclusion

Principal stress distribution in the vicinity of jointed boundary of the composite bars with various breadth of adhesive layer was investigated using the photoelastic and interferometric methods, and the following results were obtained.

(1) The stress distribution in the vicinity of jointed boundary of the composite bars is different to the stress distribution of uniform bar. The maximum or minimum value appears in the free boundary or center line on the bonded boundary or near. And the stress concentration occurs in the free boundary and center line on the bonded boundary of harder material.

(2) As the value of h is constant, the values of σ_1 / σ_0 increase depending upon the increase in the values of t at the points C and D of A and B for series I and they approach to the constant value for $t = \infty$. For series II, the values of σ_1 / σ_0

reduce depending upon the increase in the values of t at the points C and D of A and B and they approach to the constant values for $t = \infty$.

(3) In the increase of the value h , the values of σ_1 / σ_0 and σ_2 / σ_0 reduce on the soft material side and increase on the hard material side.

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Fig.1 Sketch showing the test piece

Fig.2 The values of σ_1 / σ_0 , σ_2 / σ_0 on the bonded boundary DD' (Series I, $h = 6$ mm)

Fig.3 The values of σ_1 / σ_0 , σ_2 / σ_0 on the bonded boundary DD' (Series II, $h = 6$ mm)

Fig. 4 The values of σ_1/σ_0 on the free boundary FF' (Series I, $h = 6$ mm)

Fig. 5 The values of ϵ_1/σ_0 on the free boundary FF' (Series I, $h = 6$ mm)

Fig. 6 The values of σ_1/σ_0 on the free boundary FF' (Series II, $h = 6$ mm)

Fig. 7 The values of ϵ_1/σ_0 on the free boundary FF' (Series II, $h = 6$ mm)

Fig. 8 The values of σ_1/σ_0 versus t on the free boundary FF'

Fig.9 The values of σ_1/σ_0 on the center line OO'
(Series I, $h = 6$ mm)

Fig.11 The values of σ_1/σ_0 on the center line OO'
(Series II, $h = 6$ mm)

Fig.10 The values of ϵ_1/σ_0 on the center line OO'
(Series I, $h = 6$ mm)

Fig.12 The values of ϵ_1/σ_0 on the center line OO'
(Series II, $h = 6$ mm)

Fig.13 The values of σ_1 / σ_0 versus t on the center line $00'$

Fig.15 The values of σ_2 / σ_0 on the center line $00'$ (Series II, $h = 6$ mm)

Fig.14 The values of σ_2 / σ_0 on the center line $00'$ (Series I, $h = 6$ mm)

Fig.16 The values of σ_2 / σ_0 versus t on the center line $00'$