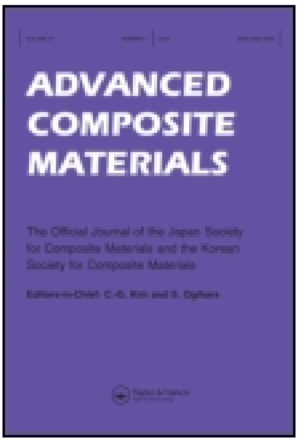

Advanced Composite Materials
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/tacm20

Evaluation of crack growth in cracked aluminum panels repaired with a bonded composite patch under cyclic loading

Y. Shibuya , S. Fujimoto , D. Aoki , M. Sato , H. Shirahata , H. Fukunaga & H. Sekine

Version of record first published: 02 Apr 2012.

To cite this article: Y. Shibuya , S. Fujimoto , D. Aoki , M. Sato , H. Shirahata , H. Fukunaga & H. Sekine (2001): Evaluation of crack growth in cracked aluminum panels repaired with a bonded composite patch under cyclic loading , Advanced Composite Materials, 10:4, 287-297

To link to this article: http://dx.doi.org/10.1163/156855101753415319

Adv. Composite Mater., Vol. 10, No. 4, pp. 287–297 (2001)

Evaluation of crack growth in cracked aluminum panels repaired with a bonded composite patch under cyclic loading

Y. SHIBUYA [1], S. FUJIMOTO [2], D. AOKI [2], M. SATO [3], H. SHIRAHATA [3], H. FUKUNAGA [3] and H. SEKINE [3]

[1] *Department of Mechanical Engineering, Akita University, 1-1, Tegata Gakuen-machi, Akita 010-8502, Japan*
[2] *Graduate School of Engineering, Tohoku University, Aoba-yama 01, Aoba-ku, Sendai 980-8570, Japan*
[3] *Department of Aeronautics and Space Engineering, Tohoku University, Aoba-yama 01, Aoba-ku, Sendai 980-8570, Japan*

Abstract—Crack growth of cracked aluminum panels repaired with a bonded composite patch is analyzed to evaluate the effect of repair. An efficient finite element analysis using Mindlin plate elements is developed. The technique is extended to a three-layer model, which consists of patch, adhesive and plate layers. The crack growth behavior of an aluminum panel with the composite patch is discussed on the basis of the Paris relation.

Keywords: Patch repair; composite patch; aluminum structure; fatigue crack; disbond.

1. INTRODUCTION

Aging aircraft are accumulating fatigue cracks during their operation and are in need of repairs to extend their service life. A repair method using composite patches to reinforce the cracked structure has been promising due to the high specific stiffness and strength of the composite.

Repairs with bonded composite patches have been studied as a possible technique. Rose [1] developed an analytical model to characterize bonded reinforcements. Asymmetric repair of a structure as, for instance, in the use of a single-sided patch causes out-of-plane bending. Mindlin plate finite elements have been used to evaluate the stress intensity factor of the cracked aluminum panel with a single-sided patch [2, 3]. Müller and Fredell [4] presented simple design guidelines for multiple bonded repairs in close proximity. Experimental studies have been carried out to investigate the disbond effect on fatigue crack growth [5] and measurement of stress intensity factor in bonded crack patching [6]. As the patch generates a complex stress field in the panel including the disbond effect, both experimental and analytical studies related to each other are needed to understand the crack growth in the repaired panel under cyclic loading.

In this study, the crack growth in cracked aluminum panels repaired with a bonded composite patch is considered to predict the residual life of the structure. In the case of a single-sided patch, we need to include the effect of out-of-plane bending in the analysis. A finite element analysis using Mindlin plate elements is developed. The method is extended to a three-layer model, which consists of patch, adhesive and plate layers. The adhesive is modeled as a thin elastic layer. The modified crack closure method is used to calculate the stress intensity factor in the cracked panel.

Numerical results on the stress distribution and stress intensity factor are compared with three-dimensional finite element analysis. The effect of disbond on the stress intensity factor is evaluated by three-dimensional analysis. The crack growth behavior of the cracked panel with the bonded composite patch is discussed on the basis of the Paris relation.

2. ANALYTICAL MODEL

Consider a cracked aluminum panel with a bonded circular composite patch as shown in Fig. 1. The crack is located at the center of the panel, and the composite patch over the crack is adhesively bonded to the panel. A Cartesian coordinate system (x, y, z) is placed on the panel. Length of the crack is $2a$, and diameter of the patch is D. Length and width of the panel are $2L$ and $2W$, respectively.

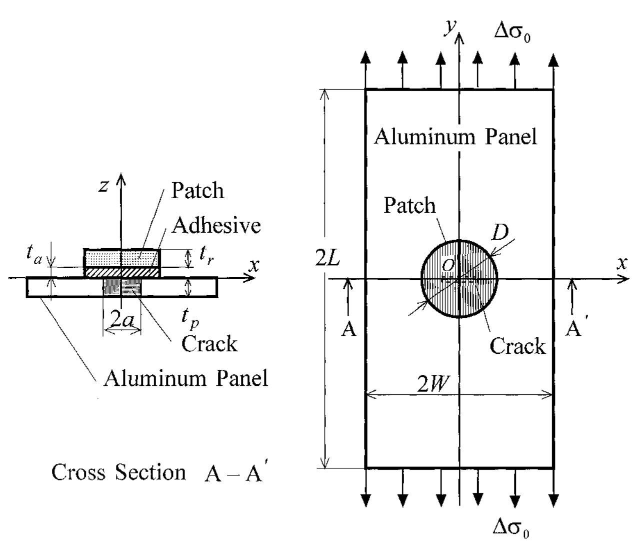

Figure 1. A cracked panel repaired with a bonded circular composite patch.

Thicknesses of the patch, adhesive and panel are t_r, t_a and t_p, respectively. The panel is subjected to cyclic applied stress with amplitude $\Delta\sigma_0$ at $y = \pm L$.

3. FINITE ELEMENT ANALYSIS

3.1. Mindlin plate elements

The structure with a single-sided patch causes three-dimensional stresses due to asymmetry of the structure. Mindlin plate elements are employed as a suitable model to reduce the cost in computation. Figure 2 shows a typical quarter model for Mindlin plate elements, where 4- and 3-noded two-dimensional elements are used. The cracked panel and composite patch are modeled by using Mindlin plate elements, and the adhesive is modeled as an elastic continuum replacing the normal and shear spring elements.

The adhesive layer is modeled by springs for the transverse shear stiffness in the $x-z$ and $y-z$ planes and the axial stiffness in the z direction as shown in Fig. 3. Stresses of the adhesive are proportional to discontinuity of displacements between the patch and panel at the interface. Displacements of the patch and panel at the interface are expressed from Mindlin plate theory as

(a) Interface between the composite patch and adhesive ($z = t_a$):

$$u^{ra} = u^{0r} - \frac{t_r}{2}\theta_x^{0r}, \qquad v^{ra} = v^{0r} - \frac{t_r}{2}\theta_y^{0r}, \qquad w^{ra} = w^{0r}. \tag{1}$$

(b) Interface between the adhesive and panel ($z = 0$):

$$u^{ap} = u^{0p} + \frac{t_p}{2}\theta_x^{0p}, \qquad v^{ap} = v^{0p} + \frac{t_p}{2}\theta_y^{0p}, \qquad w^{ap} = w^{0p}, \tag{2}$$

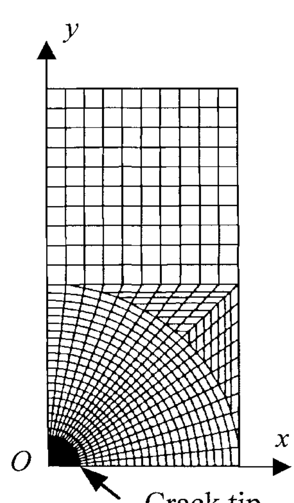

Figure 2. Finite element mesh for calculation by Mindlin plate elements.

where u, v and w are displacements of x, y and z directions, respectively, and θ is the rotation of the panel. Superscripts $0r$ and $0p$ indicate central planes of the patch and panel, and ra and ap indicate interfaces at $z = t_a$ and $z = 0$, respectively.

Stress components in the adhesive τ_{zx}, τ_{zy} and σ_{zz} are related to discontinuity of displacements between the composite patch and panel as

$$\tau_{zx} = \frac{G_a}{t_a}(u^{ra} - u^{ap}), \qquad \tau_{zy} = \frac{G_a}{t_a}(v^{ra} - v^{ap}),$$
$$\sigma_{zz} = \frac{2(1-\nu_a)G_a}{(1-2\nu_a)t_a}(w^{ra} - w^{ap}), \tag{3}$$

where G_a and ν_a are the shear modulus and Poisson's ratio of the adhesive, respectively.

The modified crack closure method [7] is used to calculate the strain energy release rate. In the crack closure method, the virtual crack extension Δa is taken to be small in comparison with the crack length. The strain energy release rate is calculated as the work to close the crack by the total value of displacement. The total strain energy rate $\overline{G}$ is written as

$$\overline{G} = \overline{G}_v + \overline{G}_\theta, \tag{4}$$

where (see Fig. 4)

$$\overline{G}_v = \frac{1}{2\Delta a}[F_y^c(v_{c2} - v_{c1})], \qquad \overline{G}_\theta = \frac{1}{2\Delta a}[M_y^c(\theta_{c2} - \theta_{c1})].$$

Here F_y^c and M_y^c are the nodal force and moment, respectively. The stress intensity factors at crack tip for in-plane stress and pure bending moment are obtained from the strain energy release rate as

$$K_v = \sqrt{\frac{E_p \overline{G}_v}{t_p}}, \qquad K_\theta = \sqrt{\frac{3E_p \overline{G}_\theta}{t_p}}, \tag{5}$$

where E_p is the Young's modulus of the panel. Since the stress intensity factor is linearly distributed over the thickness of the panel, the stress intensity factors at

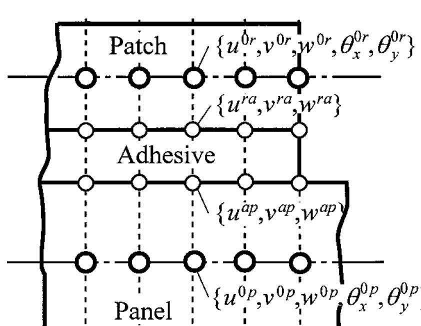

Figure 3. Adhesive layer model.

$z = 0$ and $z = -t_p$ are written as

$$K = K_v - K_\theta \quad (z = 0), \qquad K = K_v + K_\theta \quad (z = -t_p). \tag{6}$$

3.2. Three-dimensional finite element analysis

To validate the three-layer model, three-dimensional finite element analysis is performed. A typical quarter model is shown in Fig. 5a: 20- and 15-noded solid elements are employed in the finite element model, and the numerical calculation for three-dimensional analysis is carried out by using the commercial finite element code MARC. The detail of mesh near the crack tip is shown in Fig. 5b. The stress intensity factor is evaluated by performing the J-Integral.

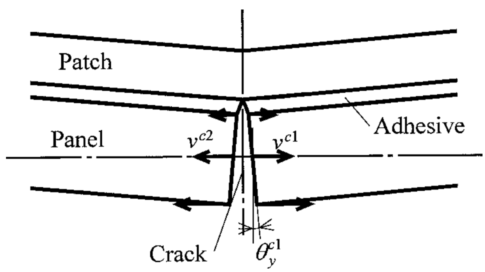

Figure 4. Cross-section of crack tip.

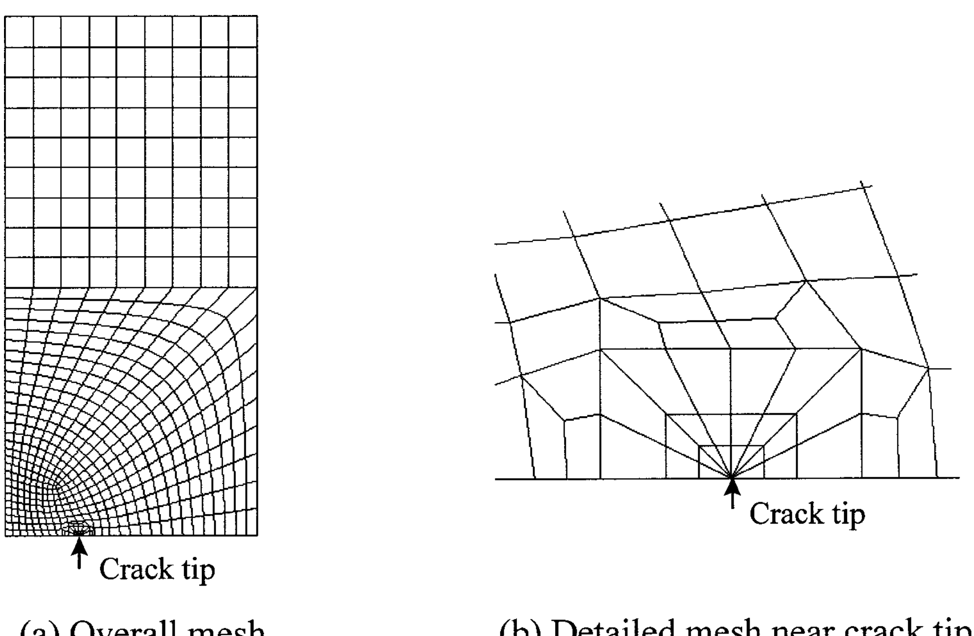

Figure 5. Three-dimensional finite element mesh.

4. NUMERICAL RESULTS AND DISCUSSION

The repaired structure treated in this study is a glass/epoxy composite patch and aluminum panel (2024-T3). The composite patch is a $[0/0/0/\pm 45/0/0]_s$ laminate. The adhesive is AF163-2K. Dimensions and material properties of the panel, adhesive and composite are given as follows:

(a) Aluminum panel: $L = 125$ mm, $W = 60$ mm, $t_p = 2$ mm, $E_p = 72.39$ GPa, $\nu_p = 0.33$.

(b) Adhesive: $t_a = 0.1$ mm, $G_a = 0.439$ GPa, $\nu_a = 0.34$.

(c) Lamina of composite patch: $D = 50$ mm, $t_r/14 = 0.229$ mm, $E_L = 44.12$ GPa, $E_T = 9.65$ GPa, $G_{LT} = 4.13$ GPa, $\nu_{LT} = 0.28$.

The panel is subjected to cyclic applied stress with the amplitude $\Delta\sigma_0 = 58.5$ MPa.

Analyses for Mindlin plate elements and three-dimensional elements are compared in Fig. 6 for the crack length $a = 17.5$ mm and $a = 35$ mm. Solid lines are the result for Mindlin plate elements, and broken lines are that for three-dimensional elements. For the unpatched case, the difference between those analyses is small. The value for three-dimensional elements becomes slightly larger for the patched case. Profile of the distribution over the thickness is similar in both analyses. Since the difference between results for Mindlin plate elements and three-dimensional elements is allowably small, Mindlin plate elements are used in the evaluation of stress intensity factor after this.

Amplitude of stress intensity factors ΔK calculated by using Mindlin plate elements is shown in Fig. 7. Stress intensity factor for the unpatched case is constant over the thickness. As the stress intensity factor for the patched case is linearly distributed over the thickness due to out-of-plane bending, it is indicated at three

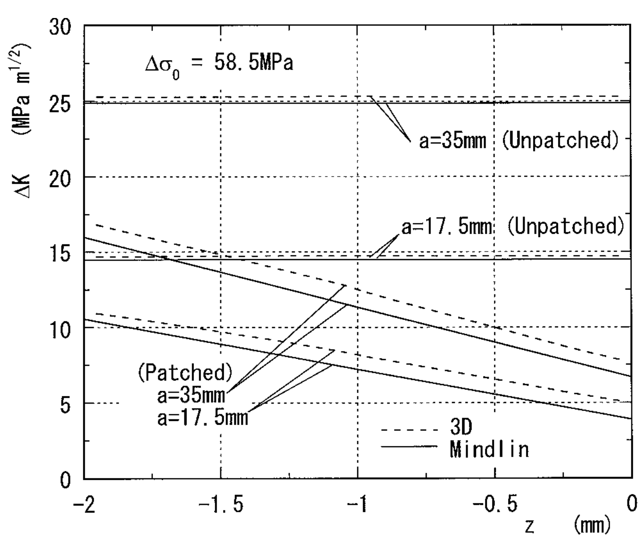

Figure 6. Comparison of analyses between Mindlin plate elements and 3D elements.

planes for free surface ($z = -t_p$), midplane ($z = -t_p/2$) and interface ($z = 0$). The gradient of the stress intensity factor changes near $a = 25$ mm. This length corresponds to the radius of the patch. If the crack extends to the region out of patch, the growth rate can be found to be large from the gradient of the curve.

Stress distribution σ_{yy} of the cracked panel repaired with the patch at the surface $z = 0$ is shown in Figs 8a and b for $a = 17.5$ mm and $a = 35$ mm, respectively. The stress concentration is found at the crack tip. As the crack extends out of the patched region as $a = 35$ mm, the distribution become much complicated. Figure 9 shows the deformed form of the patched panel at the cross-section $x = 0$ for $a = 17.5$ mm and $a = 35$ mm in a similar way to Fig. 8. In the case of $a = 35$ mm, the deflection becomes large due to interaction of the crack and the patch.

We have tried to evaluate crack growth behavior of the cracked panel with the bonded composite patch on the basis of the following Paris relation:

$$\frac{\mathrm{d}a}{\mathrm{d}N} = C(\Delta K)^n, \tag{7}$$

where N is the number of cycles, and C and n are material constants obtained from experiments. Figure 10 shows crack growth behavior under cyclic loading. The marks in the figure indicate experimental data for crack growth. First, a cracked aluminum panel for the unpatched case was tested from initial crack length $2a_0 = 11.5$ mm. Material constants C and n are fitted from these experimental data. The values are $n = 2.60$ and $C = 1.15 \times 10^{-6}(\mathrm{MPa}\sqrt{\mathrm{m}})^{-2.60}\mathrm{mm/cycle}$. Solid lines in the figure are results by solving equation (7) with the Runge–Kutta method numerically for unpatched and patched cases. Stress intensity factor at the midplane of the panel, which is calculated by Mindlin plate elements, is used in the prediction of crack growth. In the case of the unpatched panel, the curve is fitted

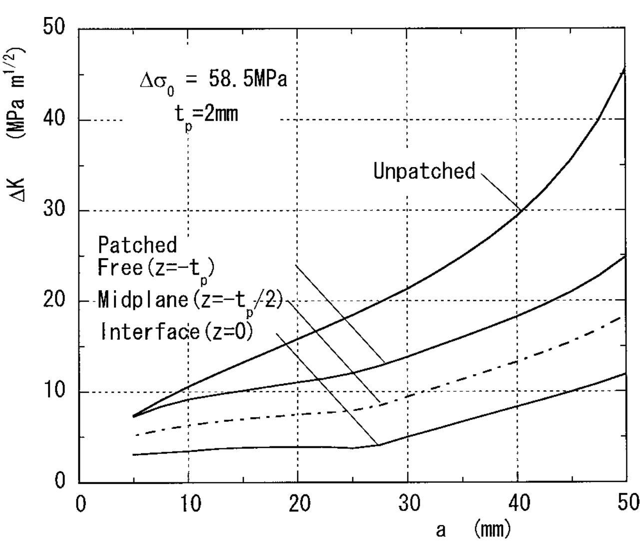

Figure 7. Amplitude of stress intensity factor by Mindlin plate elements.

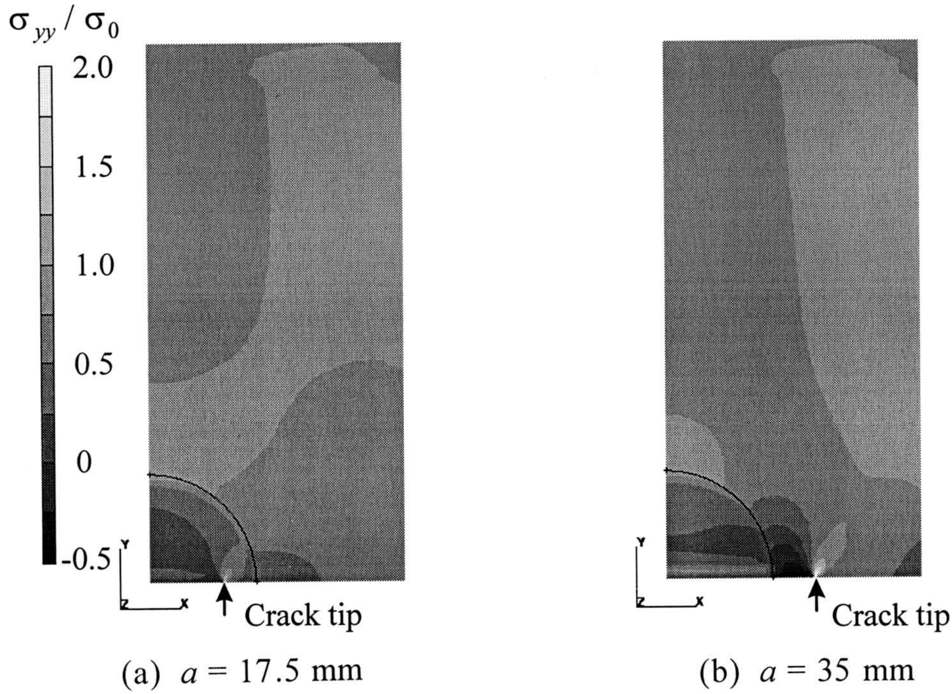

Figure 8. Stress distribution σ_{yy} of aluminum panel at the surface $z = 0$.

well to experimental data. For the patched case, the growth of the crack is slow in comparison with the unpatched case due to the effect of repair. For initial crack length $2a_0 = 21.3$ mm, the predicted result agrees well with the experimental result except for a large number of cycles. The stress intensity factor at large crack length may be underestimated because of extending disbond of patch with crack growth.

To discuss the effect of the disbond on crack growth, the patch was removed from the aluminum panel and the bonded surface was observed after fatigue test. A photograph of a disbond area on the adhesive surface is shown in Fig. 11. The patch was removed at elavated temperature after heating to 190°C for 2 hours [8]. The disbond area is discolored by oxidation during heating and is visible after removing the patch. Figure 12a shows the disbond area contoured clearly by image processing from the photograph. The disbond due to crack growth can be found along the x axis, which corresponds to the crack line. To estimate the disbond effect on the crack growth, a full width disbond model is shown in Fig. 12b. Figure 13 shows the effect of disbond area on the stress intensity factor at crack tip calculated by three-dimensional elements. The stress intensity factors of the crack for $a = 20$ mm are estimated by the model of the patched aluminum panel with disbond as shown in Fig. 12b. In Fig. 10, the difference between prediction and experiment become significant from the length $a = 20$ mm. The stress intensity factor increases with increase of parameter h/D for the disbond area. As the stress intensity factor is

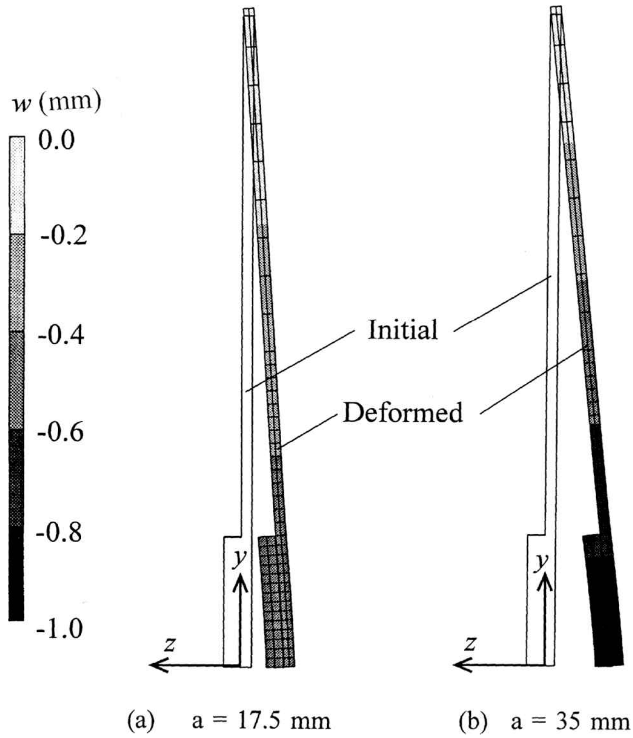

Figure 9. Deformed form of patched panel at $x = 0$.

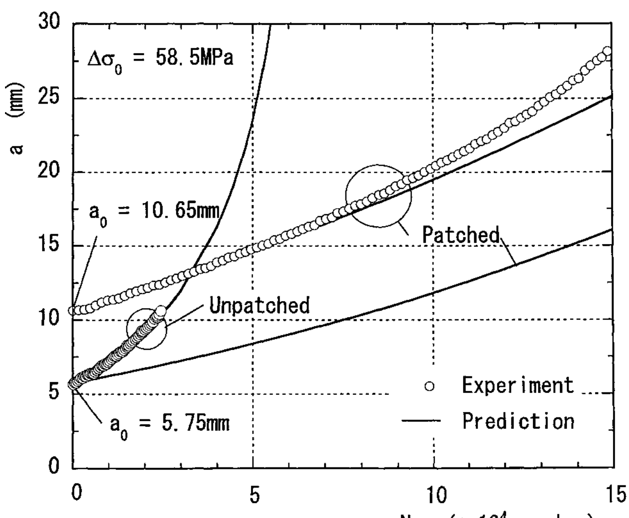

Figure 10. Crack growth behavior under cyclic loading.

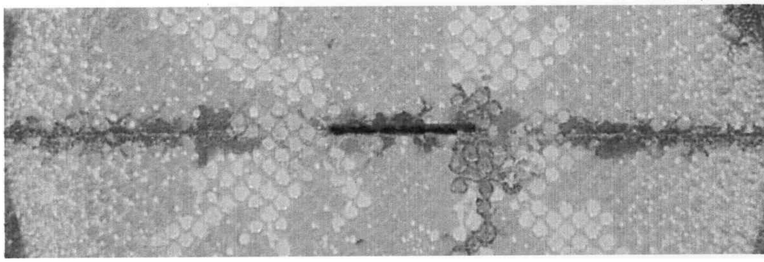

Figure 11. A photograph of a disbond area on the adhesive surface of the patch.

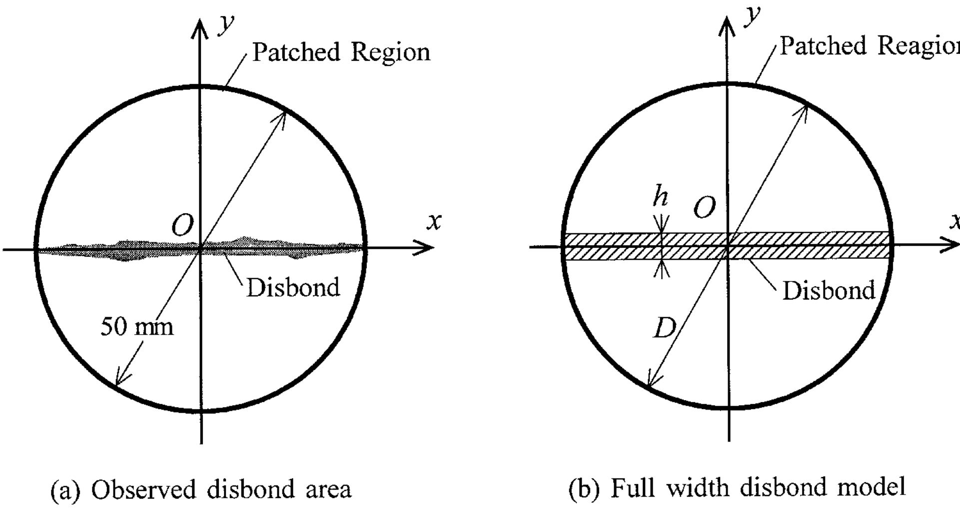

Figure 12. Disbond area on the bonded surface.

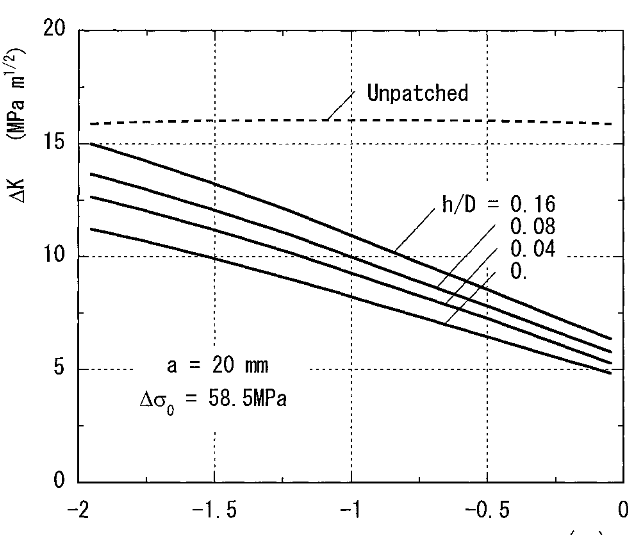

Figure 13. Effect of disbond area on the stress intensity factor of the panel.

underestimated in Fig. 10 by neglecting the disbond, the experimental crack length is larger than the predicted value.

5. CONCLUSIONS

Aluminum panels repaired with a bonded composite patch under cyclic loading are considered. Using Mindlin plate elements, stress intensity factor is evaluated and used to predict the crack growth of the panel. The predicted result agrees well with experimental result except for large number of cycles. The crack length for experiment is larger than that of prediction at large number of cycles due to neglect of the disbond effect, because disbonding of the patch was observed in the experiment.

Acknowledgement

This work was partly supported by Grant for Research and Development Applying Advanced Computational Science and Technology, Japan Science and Technology Corporation.

REFERENCES

1. L. R. F. Rose, A cracked plate repaired by bonded reinforcements, *Intern. J. Fracture* **18**, 135–144 (1982).
2. C. T. Sun, J. Klug and C. Arendt, Analysis of cracked aluminum plates repaired with bonded composite patches, *AIAA Journal* **34**, 369–374 (1996).
3. S. Naboulsi and S. Mall, Nonlinear analysis of bonded composite patch repair of cracked aluminum panels, *Compos. Struct.* **41**, 303–313 (1998).
4. R. Müller and R. Fredell, Analysis of multiple bonded patch interaction simple design guideline for multiple bonded repairs in close proximity, *Appl. Compos. Mater.* **6**, 217–237 (1999).
5. J. J. Denney and S. Mall, Characterization of disbond effects on fatigue cracks growth behavior in aluminum plate with bonded composite patch, *Engineering Fracture Mechanics* **57**, 507–525 (1997).
6. R. Müller, R. Fredell, C. Guijt and J. Dally, Experimental verification of Rose's constant K solution in bonded cracked patching, *Appl. Compos. Mater.* **6**, 205–216 (1999).
7. E. F. Rybicki and M. F. Kanninen, A finite element calculation of stress intensity factors by a modified crack closure integral, *Engineering Fracture Mechanics* **9**, 931–938 (1977).
8. A. A Baker, Repair efficiency in fatigue-cracked aluminium components reinforced with boron/epoxy patches, *Fatigue & Fracture of Engineering Materials & Structures* **16**, 753–765 (1993).