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INSPECTING FOR WIDESPREAD FATIGUE DAMAGE: IS PARTIAL DEBONDING THE KEY?

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SUMMARY

Experimental and analytical results indicate that cracks can initiate, grow, and coalesce more rapidly in fuselage lap joints that have experienced partial or complete debonding. Computational analysis in this paper shows that stress concentrations and stress intensity factors at the rivet holes are far less severe when the bond is intact. Debonding hastens the initiation of widespread fatigue cracks and significantly increases crack growth rate. Thus, debonded regions serve as "breeding grounds" for widespread fatigue damage. Therefore, the effectiveness of lap joint inspection programs may be enhanced if detailed inspections are focused on areas in which debonding has been detected.

INTRODUCTION

The Federal Aviation Administration has defined a damage tolerant structure as one "that has been evaluated to ensure that, should serious fatigue, corrosion, or accidental damage occur within the operational life of the airplane, the remaining structure can withstand reasonable loads without failure or excessive structural deformation until the damage is detected [1]." An important aspect of aircraft maintenance, therefore, is to increase the effectiveness of inspections.

Substantial research has been conducted in the area of widespread fatigue damage (WFD). WFD can take the form of multiple site damage (MSD) cracks at rivet holes along the fuselage lap joint [2]. These cracks seem to form predominantly in areas of adhesive bond failure. In the first 291 Boeing 737's manufactured, a cold bond adhesive was used that was found to debond in as few as 3000 cycles [3]. Boeing has also shown experimentally that "the fatigue life of a lap joint with a large area of delamination is reduced [3]."

A fatigue test of a full scale fuselage panel with no adhesive bonding was conducted by Foster-Miller, Inc. [4]. The first detection of damage occurred at approximately 37,000 pressurization cycles. At approximately 73,700 cycles, there were only two cracks more than an inch long. However, over the next 1600 cycles, another crack grew from under one inch to over 50 inches long, resulting in loss of pressurization. A record of the visible damage in that experiment is shown in Figure 1.

The Foster-Miller experiment showed that cracking associated with WFD can advance with disconcerting speed. The 1600 cycles between two relatively small cracks and pressurization failure is less than the normal C-check inspection interval. Nonetheless, we do not regularly see fuselage failures in aircraft with 75,000 flight cycles. A protective mechanism must be at work. That protective mechanism is the action of the adhesive bond. This paper will explore the potential benefits of this form of load transfer in terms of the life needed for WFD crack initiation and growth.

EFFECT OF PARTIAL DEBONDING ON CRACK INITIATION

"Crack initiation" is perhaps an ill-defined term that describes an intuitive series of events. It qualitatively describes the transition from uncoalesced micromechanical damage to a single through-the-thickness crack that grows predictably. The precise definition is not critical to this paper, but, for convenience, it can be defined as that point when the crack tip emerges from under the countersunk rivet head.

Intact adhesive bonds transfer the load between skin panels in small regions at the edge of the joint rather than at the rivet holes. Bonded sheets therefore have similar strain distributions (and, consequently, stress distributions) over most of the joint. Thus, the stress in two equal thickness sheets is essentially equal to half the nominal stress. Little load is actually transferred by the rivets.

In contrast, the top skin in the debonded lap joint carries the entire circumferential load to the first row of rivets. From there, some load is transferred by the rivets into the other sheet and the rest bypasses the first row. Thus, there is one component of the stress concentration factor at the edge of the hole that results from the rivet bearing load and another that arises from the bypass stress, as shown in Figure 2. The magnitudes of these stress concentrations are mitigated somewhat by the biaxial nature of the load on the joint.

The stress concentration factor was calculated by a linear finite element analysis. Three-dimensional 20-noded "brick" elements were used. The three layers (the top and bottom skins and the adhesive layer) were each one element thick. The skins were 0.036 inch thick 2024-T3 aluminum. The adhesive layer was 0.004 inches thick. There were 4356 solid elements. The finite element mesh is shown in Figure 3.

Symmetry boundary conditions were employed such that a periodic repeating pattern was created as shown in Figure 4. Although this configuration of debonding is unlikely in service, it gives an indication of the state of stress experienced in circumstances of interest. Obviously, the calculations are more representative of cases with similar distance from the point of interest to the debond front and approximately the same fraction of debonded area in the vicinity.

The rivet spacing was one inch in both the circumferential and axial directions. The rivet holes were assumed to be cylindrical rather than countersunk. The rivets were modeled with beam elements that were attached to the face of the hole with an array of smaller beam elements. The flexibility of each rivet structure was matched to the value given by the method proposed by Swift [5].

Several configurations of debonding were considered, as shown in Figure 5. Debonding was simulated by limiting the region in which nodes associated with adhesive layer elements and nodes associated with top sheet elements were "merged" at the interface to enforce displacement continuity.

A biaxial load was applied to the model. The tensile circumferential stress was 1000 psi. The tensile axial stress was 500 psi. This 2:1 ratio is the classical value for a pressurized cylinder. The effects of stiffening substructure were not included in this model. Geometric nonlinearities arising from bending and rotation of the lap joint were suppressed.

The maximum stress concentration occurred in the debonded region in the upper row in the top sheet. By the symmetry of the model, the value was repeated at the lower rivet row in the bottom sheet. The maximum stress concentration factor for each case is given in Table 1. There is a factor of 4.55 between the values for the completely bonded and completely debonded cases.

The service life required for crack initiation can be estimated using a model by Broek [6]. He asserts that Miner's cumulative damage, D, can be used to correlate crack initiation. That is, the number of initiated cracks follows a Weibull distribution when plotted against D, where D is defined as:

$$D = \sum \frac{n_i}{N_i} \tag{1}$$

where n_i is the number of cycles experienced at a given nominal stress level and N_i is the corresponding number of cycles to failure of a lap joint specimen at that stress level. In a related report [7], Broek presents data by Hartman [8] as a source for estimates of N_i. From that fatigue failure data for a similar lap joint, it can be seen that there is a factor of approximately six between the number of cycles to failure of lap joints with and without adhesive bonding. The implication is therefore that it will take approximately six times as long to initiate any crack.

Broek [6] assumed a functional fit for N_i of the form:

$$N_i = \exp\left(\frac{A - (\Delta\sigma)_i}{B}\right) \tag{2}$$

If one assumes that the effective change in stress for each cycle is proportional to the stress concentration factor, then estimates of the relative initiation life can be calculated. The initiation lives normalized by the value for the completely bonded case are given in Table 1.

EFFECT OF PARTIAL DEBONDING ON CRACK GROWTH

Crack growth models usually relate the rate of crack extension to the stress intensity factor. A linear finite element analysis was conducted of the lap joint to determine the Mode I stress intensity factor, K_I, of a crack extending from a rivet hole in the upper row. The crack extended from the edge of the rivet hole to the midpoint between the rivets. The mesh is the same as in Figure 3 except that a discontinuity was introduced to model the crack face and singular elements were used at the crack tip. The same five configurations of debonding were studied. In each case, the crack emanated from the hole on the debonded side of the model, as shown in Figure 6. The normalized Mode I stress intensity factor is K_I divided by the nominal value for a center-cracked plate with the same tip-to-tip crack size and uniaxial loading:

$$normalized\ K_I = \frac{K_I}{\sigma \sqrt{\pi\, a}} \tag{3}$$

where σ is the nominal circumferential stress level and a is half the tip-to-tip crack length. The results of the normalized stress intensity factor as a function of the fraction of the bond area intact are given in Table 2. The components of stress intensity factor from the other modes (shearing and tearing) were calculated, but never contributed more than one percent to the total stress intensity factor.

The stress intensity factor increases by a factor of 5.7 when the section has completely debonded. This results both from the increase in stress in the top sheet and from the inability of the adhesive and bottom sheet to act as a "patch" to limit the crack opening displacement. Crack growth models usually assume crack extension per cycle is proportional to the stress intensity factor raised to a power. In Reference 9, the parameters for the Walker model of crack growth in 2024-T3 aluminum include the exponent 4. The calculated increase in crack growth rate would therefore be proportional to the ratio of stress intensity factors raised to the fourth power. These values of stress intensity factor (normalized in this case by the completely bonded value) raised to the fourth power are also reported in Table 2. It is seen that crack growth is accelerated by approximately three orders of magnitude for the completely debonded case.

DISCUSSION

The experimental study of a lap joint with no adhesive bond resulted in fast crack initiation and growth. The fact that such behavior is not commonly observed in service demonstrates that the bond is effective in retarding such damage growth. The analyses in this paper show that moderate bonding can provide substantial benefit.

The computational results illustrate some underlying mechanisms of damage acceleration once the adhesive bond is lost in the lap joint. The load is no longer transferred near the edge of the lap joint. Therefore, the circumferential stress level above the upper row of rivets is the full nominal far field stress rather than half that value. Significant load is transferred by bearing load on the rivets. This raises the stress concentration at the edge of the hole and promotes crack initiation there. Once a crack has formed, the failed adhesive bond can no longer act to limit the maximum crack opening displacement and, therefore, the stress intensity factor. Thus, crack growth rates increase dramatically.

The situation in the fleet is, of course, more complex. The debonded area changes over time and strongly affects crack behavior as it does. There are significant effects of the supporting structure in load redistribution. There is also a need to understand the effect of partial debonding on crack coalescence ("linkup") and any interaction between crack growth and debond growth.

IMPLICATIONS FOR INSPECTION

The implications for maintenance and inspection of fuselage lap joints of these calculations for crack initiation and growth could be significant. If a large section of a lap joint were completely debonded, an incubation period of about 40,000 cycles and a subsequent slow crack growth period of about 30,000 cycles would be followed by extremely rapid growth. Damage tolerance assessments would rely on detecting cracks during the slow growth period. Since cracks are quite small during this phase, detection is not necessarily assured. It would not be conservative for analyses to rely on the existence of intermittent bonded regions to retard or arrest crack growth.

The calculations in this paper indicate that joints with reasonably intact adhesive bonds can expect much longer crack initiation and growth periods. With the rapid growth experienced in the Foster-Miller experiment [4], it is plausible that detection and close inspection of debonded regions before rapid growth begins would be easier and more effective than trying to detect cracks with no regard to the state of the bond. A carefully prepared inspection program might not require frequent detailed inspection of every lap joint rivet.

CONCLUSIONS

The analyses confirm the experimental results that, in a completely debonded lap joint, the stress distribution speeds up the processes of crack initiation and growth. The extent of that acceleration depends on the crack configuration.

This striking contrast in behavior suggests a possible screening during inspection for WFD. If an area inspection can detect debonds with some certainty, then the relative likelihood of WFD formation can be assessed. More informed decisions can then be made about whether a detailed inspection, such as eddy current, is necessary.

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Table I. Results of the Stress Concentration Factor Analyses

Percentage of Lap Joint Area with Intact Bond	Maximum Stress Concentration Factor	Normalized Initiation Life
0	4.96	0.17
25	2.42	0.54
50	1.79	0.73
75	1.34	0.89
100	1.09	1.00

Table II. Results of the Stress Intensity Factor Analyses

Percentage of Lap Joint Area with Intact Bond	Normalized Mode I Stress Intensity Factor	Normalized Crack Growth Rate
0	1.04	1083
25	0.74	275
50	0.52	8.3
75	0.21	1.6
100	0.18	1.0

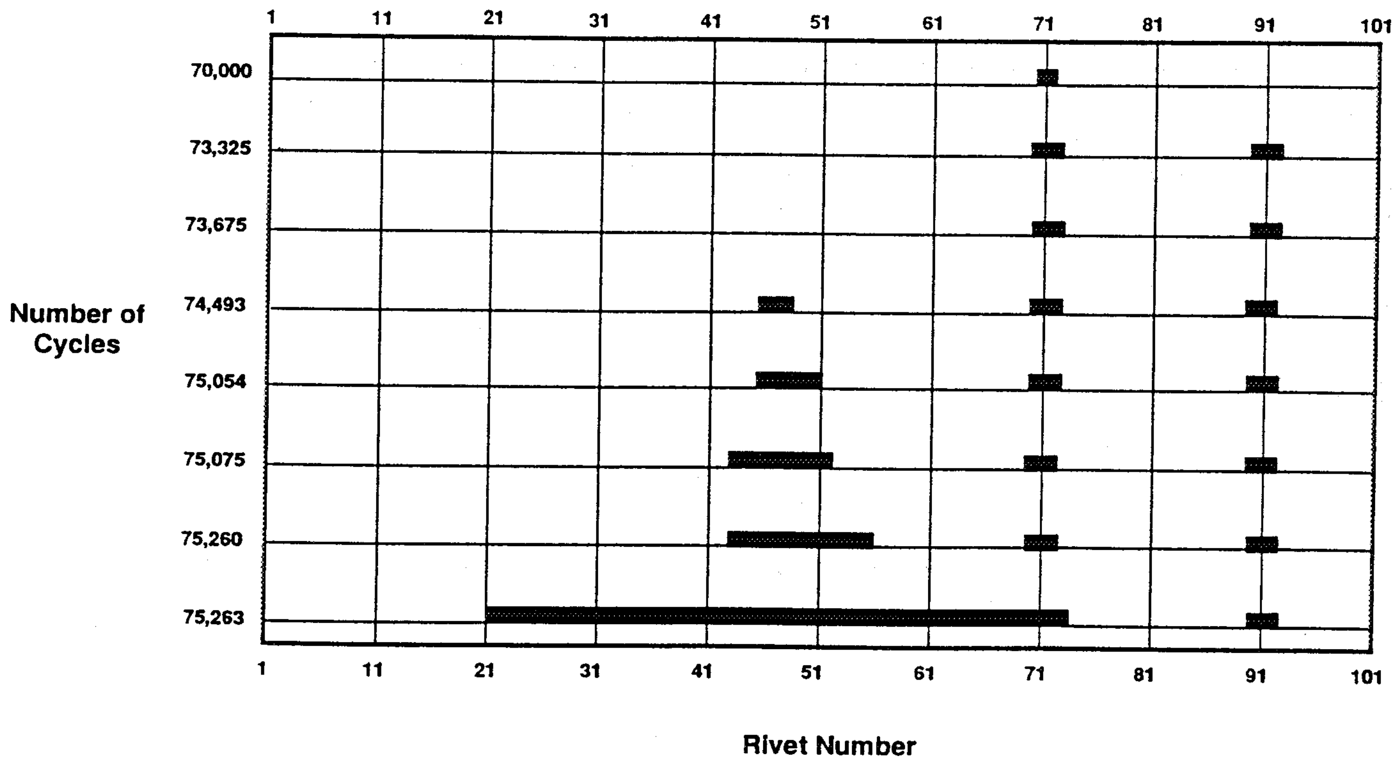


Figure 1. Visible cracks in Foster-Miller experimental full scale fuselage fatigue panel [4].

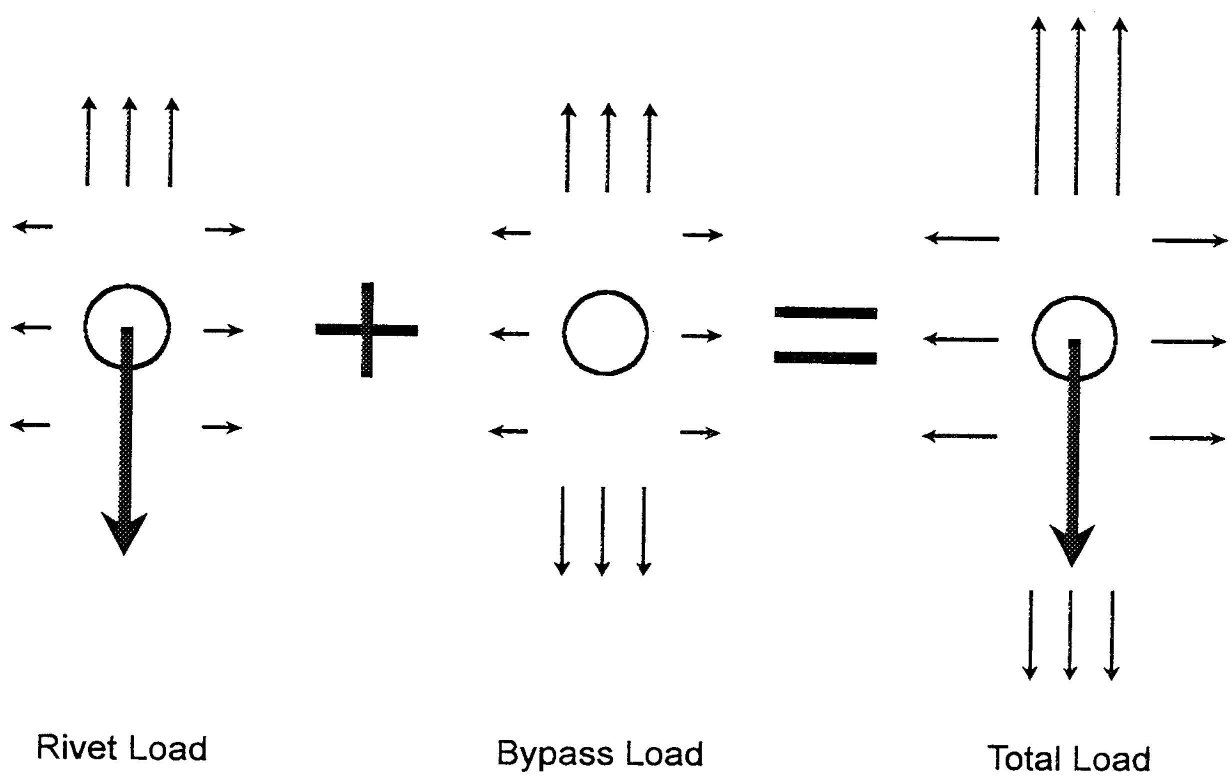


Figure 2. Components of the stress concentration factor.

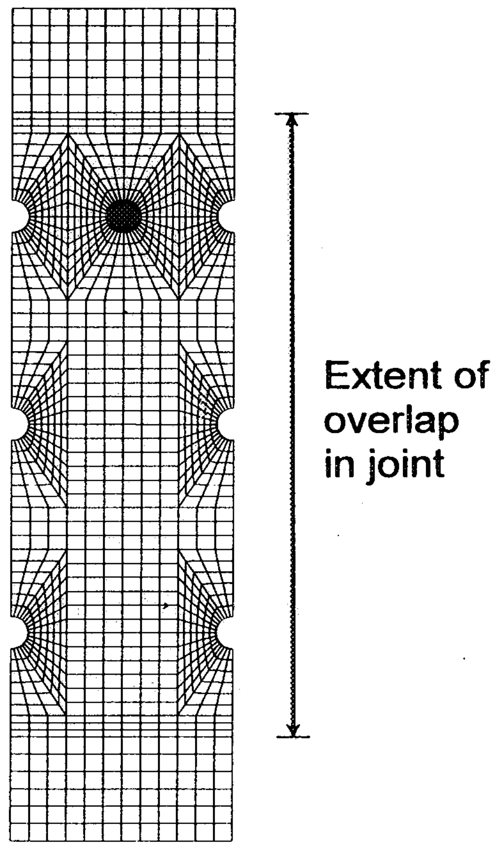


Figure 3. Finite element mesh in the computational analysis.

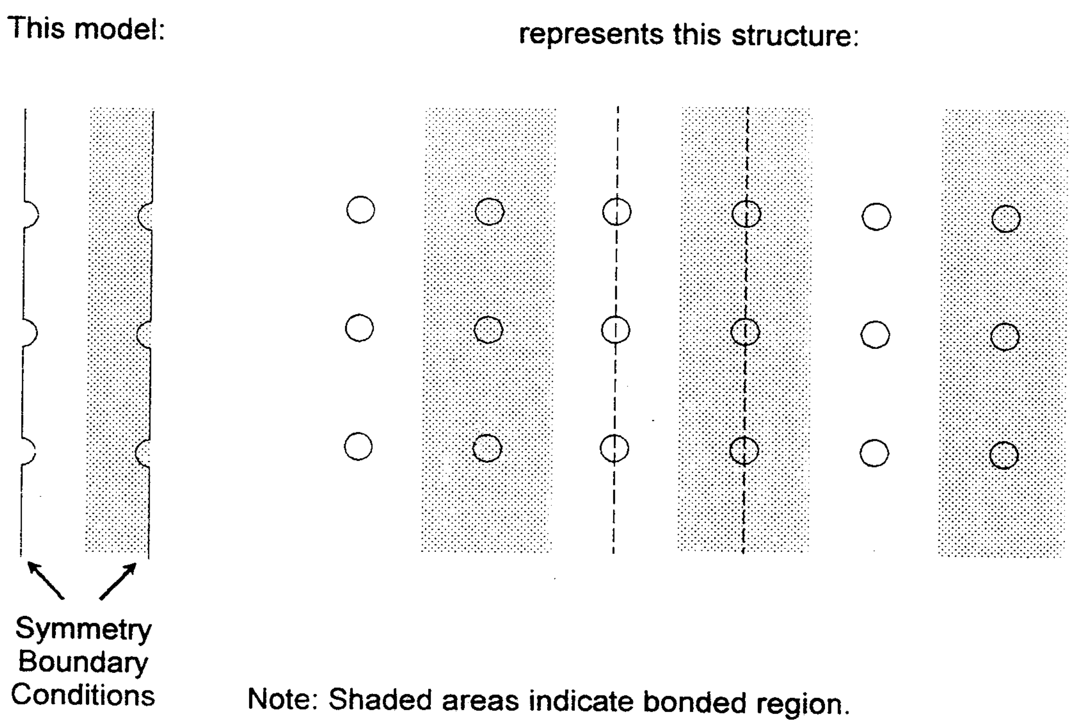
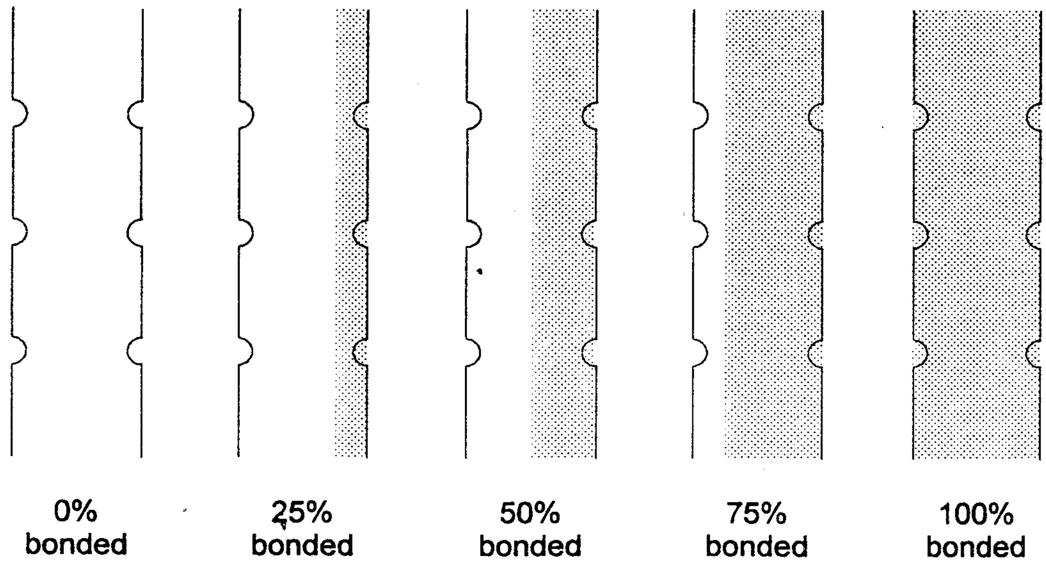
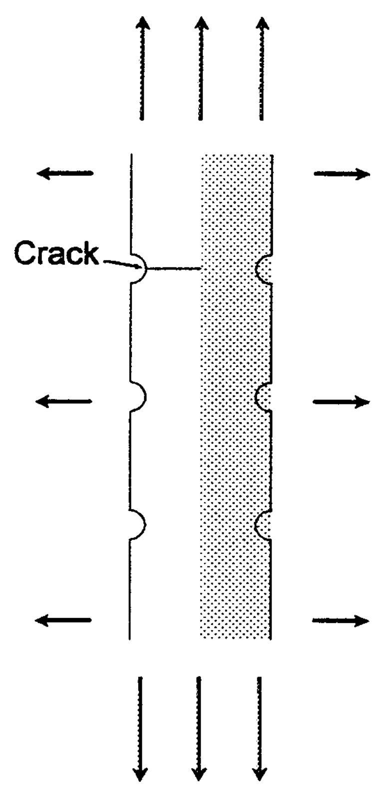


Figure 4. Model of an infinitely repeating strip with symmetry boundary conditions.



Note: Shaded areas indicate bonded regions.

Figure 5. Configurations of debonded areas.



Note: Shaded area indicates bonded region.

Figure 6. Crack location relative to debonded area.