

Bonded Composite Patch Geometry Effects on Fatigue Crack Growth in Thin and Thick Aluminum Panels¹

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Abstract: Effects of various geometric factors on the crack growth behavior of thin and thick aluminum panels repaired with asymmetric boron/epoxy bonded composite patch were investigated. Two widths, three patch lengths, three panel thicknesses and several patch-to-panel stiffness ratios were considered. Asymmetric repair introduces initial thermal curvature (or bending) in the repaired panels. The radius of curvature decreased with increase in the patch length in the thicker plates (6.350 or 4.826 mm thickness). On the contrary, the radius of curvature in the thin plate (i.e. 3.175 mm thickness) increased with increase in the patch length. The effects of stiffness ratio and patch width on the initial curvature of the asymmetrically repaired panel depended upon the length of the bonded patch, thickness of the repaired panel and stiffness ratio. There was increase in the fatigue life of the repaired panel with increase of stiffness ratio at a given patch length for all three thicknesses. For repairs of stiffness ratio equal to 1.0, the patch length had practically no or small effect on fatigue life of the repaired thick panels, but increase in patch length improved the fatigue life of the repaired thin panel. Overall, the effects of stiffness ratio and patch length on the fatigue life improvement of the repaired panel are complex which require further studies. The crack growth rate in the thick repaired panels (6.350 or 4.826 mm thickness) up to crack length before any debond occurred was not affected by the patch length. On the other hand, the longer patch decreased in the crack growth rate relative to the shorter patch in the thin repaired panel (3.175 mm). The higher stiffness ratio provided the lower crack growth rate or longer fatigue life for both thin and thick repaired plate for

¹ The views expressed in this article are those of the authors and do not reflect the official policy or position of the United States Air Force, Department of Defense, or the U.S. Government

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a given patch length. Finally, there was no effect of the patch width on the crack growth rates up to crack length equal to the uniform width of patch. There was similar growth pattern of debond (i.e. only near the immediate area of the crack), regardless of patch length and width as well as stiffness ratio up to the crack length either equal to uniform width of the patch (i.e. before patch taper portion) or when it would have grown unstable in the unrepaired specimen. Thereafter, a significant debond growth occurred.

1 Introduction

The need for efficient repair techniques for cracked aerospace metallic structures is a continual effort. Bonded composite repairs reduce stress intensity factor through the alteration of load path, and bridging of the crack thus preventing/retarding, re-initiation or further growth. Additionally, these repairs do not introduce additional stress risers caused by standard repair methods of bolting or riveting repairs to existing structure. Specimen durability and damage tolerance improvements using these bonded reinforcements have also been demonstrated. Although several studies involving both experimental and analytical techniques have investigated the mechanics of bonded composite repairs on cracked thin metallic structures of about 3 mm or less thickness, debate still persists on 'best' or 'optimal' configuration, material, stiffness ratio of the bonded patch [1-5]. Thermal and three-dimensional effects due to differences in coefficient of thermal expansion between repaired panel and bonded patch can be significant and should be included in the consideration of patch repair [6-9]. Repairs of thick plates have also been investigated, rather in limited amount, under different configurations both numerically and experimentally [10-12]. Few studies performed in this arena showed the difference in crack growth rates between both unrepaired and repaired thin and thick components [13-15]. Their analyses also showed significant discrepancies between the computed crack growth behavior and experimental counterparts in the repaired thick panels due to the bending effects [13-15]. These bending effects have been included in the analytical method [16], or restricting/eliminating them during experiments which simulated the repair of aircraft's components that may not experience bending due to stiffening, e.g. from spars and longitudinal stiffeners. [11, 17].

The curing process required to adhesively bond composite patch to cracked structure, produces residual (thermal) stresses due to the coefficient of thermal expansion mismatch between the aluminum and boron/epoxy repair. Additional change in temperature during the service/operation of aerospace structures can further exaggerate this effect. For asymmetric repairs, bending stresses are also generated from the applied load in the plate/patch combination. This complicates the problem of predicting the effectiveness of the repair on thick panels by creating a condition

that opens the crack on the patched face and closes the unpatched face crack. Thermal stresses increase the stress intensity factor on the patched face of the panel and reduce the opening stresses on the unpatched face due to thermal bending. Patch configurations, temperature, and three dimensional effects influence both initial and loaded plate geometric non-linearity as the plate thickness increases. These phenomena produce the variation of stress intensity factor, and thus uneven (or non-self-similar) crack growth through the repaired panel's thickness. A thorough understanding of the thick panel repaired with bonded composite patch is therefore needed. This study is a step in this direction.

The specific objectives of the present study were to experimentally examine the geometry effects of patch (i.e. patch length, patch width and patch-to-panel stiffness ratio) of the asymmetric bonded repair on the fatigue behavior of cracked aluminum plate in an unrestricted condition. This was investigated by characterizing the influences of these geometric factors on the fatigue life, crack growth rate and debond behavior. For this purpose, pre-cracked (center crack) 3.175, 4.826 and 6.350 mm thick plates repaired with full and finite width unidirectional boron/epoxy composite patch having three lengths, two patch widths and different patch-to-panel stiffness ratios were tested. These repairs were bonded using FM-73 sheet adhesive. Cracked baseline panels (i.e. unrepaired) were also tested for the comparison.

2 Specimen and Test Details

The material, used in this study, was 2024-T3 sheet (unclad) aluminum. The composite patch was unidirectional boron/epoxy. Material properties, in the loading direction (fibers in composite patch were oriented in the loading direction), for the plate and patch are shown in Table 1. Specimens were configured as described in previous studies [18, 19] with a single center crack (nominal length of 25.4 mm) and rectangular patch as shown in Figure 1. Several specimens were prepared to examine a range of geometric parameters, as mentioned previously, that might influence fatigue crack growth in the repaired specimens. All patches had unidirectional lay-up, $[0]_n$ (n is the number of plies) with fibers oriented in the loading direction. Three patch lengths (102, 68 and 51 mm), two widths (full and finite), and several stiffness ratios are examined in this study. The patch to panel stiffness ratio, S , is defined as:

$$S = \frac{E_r t_r}{E_p t_p} \quad (1)$$

where E is Young's Modulus, t is thickness, and r and p are subscripts designating the repair patch and plate, respectively. Due to fixed prepreg layer thicknesses of the boron/epoxy, stiffness ratios as close as possible to 0.46, 0.69, 1.0 and 1.3 were

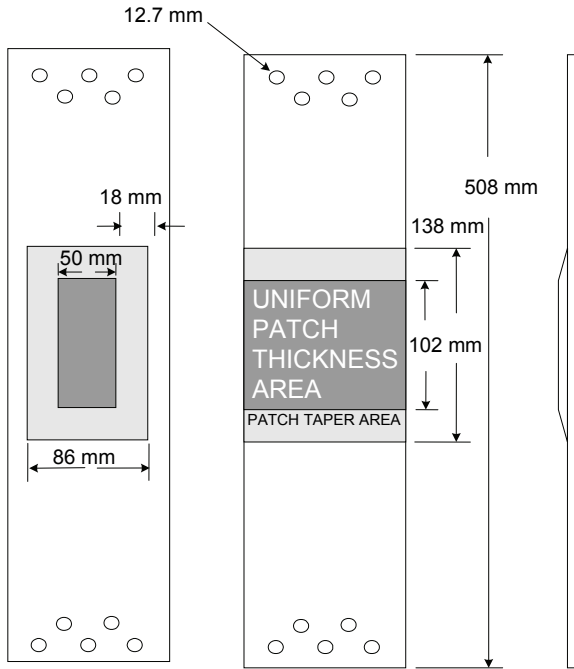


Figure 1: Repaired specimen details

Table 1: Material Properties

	2024-T3 Aluminum	Boron/Epoxy (Single Ply $\nu_f = 0.5$)
E (GPa)	72.4	200
σ_{ult} (MPa)	441	1550
σ_y (MPa)	290	-
ν	.33	.17

fabricated. Thus, patch stiffness ratios in this study are referred to by the closest rounded numbers. All patches were configured in a decreasing ply size orientation (from bond surface to top) terminated with cover plies. Edge tapers of patches had a constant nominal length of 18 mm with uniform ply drop-off dependent on the total number of plies. The full width repairs had tapers on the longitudinal ends (load direction) only. Finite width patches had tapers on four sides. Three patch lengths, 102, 68 and 51 mm, were chosen to investigate the effects of patch length in this

study. Two patch widths, full and finite, were used. The finite patch width was 86 mm (50 mm of uniform thickness plus two 18 mm tapers). The full patch had uniform width of 153 mm (i.e. equal to width of repaired specimen). The schematic view of patch details is shown in Figure 2. Patch sizes (lengths and widths) will be referred to by the size of the uniform patch thickness area (i.e. excluding tapers) in this study. Patches were pre-cured before bonding to specimen using a portable autoclave (porto-clave). The pre-curing process enhances the storability of the patch prior to bonding for repair. The specimen surfaces were grit blasted and silane treated for bonding including a spray with CIAP primer (BR-127). The patches were wrapped (both sides, like a band-aid) in a nontreated resin rich peel ply, which was peeled-off immediately prior to bonding. The patches were secondarily bonded to the specimen with the film adhesive (1 ply).

The unpatched side of specimen was polished using standard metal polishing method to allow crack measurement optically by a travelling microscope during the fatigue tests. All fatigue tests were conducted at a constant maximum stress equal to 120 MPa with stress ratio of 0.1 at a cyclic frequency of 10 Hz. The debond growth was also monitored periodically during the fatigue tests through an ultrasonic technique (C-scan) by stopping test and removing the specimen from the fatigue test machine. In order to have a baseline data with which to compare the repaired specimens' behavior, unrepaired panels with a central crack of nominal length of 25.4 mm were also tested.

3 Results and Discussion

3.1 Thermally Induced Curvature

A three-dimensional digitizing system, which measures the surface topography in x, y, z-coordinate spatial grid, was used to characterize the out-of-plane displacements in the patched area of the repaired specimens caused by thermal residual stresses. These stresses are caused by the difference in coefficient of thermal expansion during cool down of the specimen after heat curing of the FM73 sheet adhesive during patch bonding. Figure 3 shows typical out-of-plane displacements of unpatched and repaired specimen. It should be noted that the temperature drop was 100° C during the cool-down phase of the bonding procedure. The initial curvature of each specimen was measured and verified as 'flat' (i.e. no initial curvature) prior to repair, also shown in Figure 3. The deviations from 'flat' (or initial curvature), measured as out-of-plane displacements, after repair patches were bonded to plates, were then plotted and the resulting data points were fitted with a parabolic curve of the equation:

$$x = h \pm \sqrt{4P(y - k)} \quad (2)$$

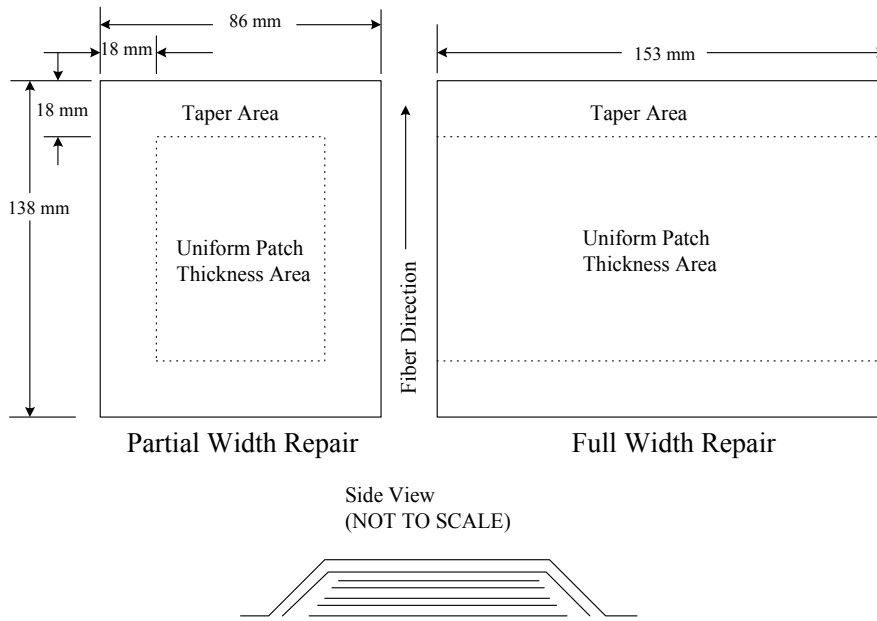


Figure 2: Patch details

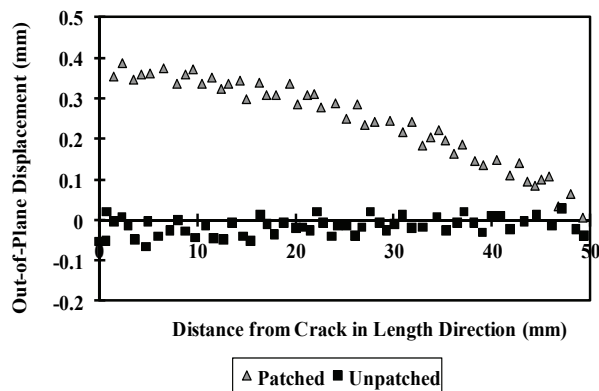


Figure 3: Out-of-plane displacement before and after patch repair

The parabolic parameters, h and k , define the coordinates of the parabola's vertex, P is the distance from the vertex to apex and the parabola's axis is the y-axis. In this study, each fit was optimized for the range of points, falling within ± 50 mm of the crack, along the centerline of the panel. Figure 3 shows an example of the curve-fit compared to the measured out-of-plane displacements. Radius of curvature, ρ , is defined as $\frac{1}{k}$, where

$$k = \frac{|y''|}{[1 + (y')^2]^{\frac{3}{2}}} \tag{3}$$

Using Equation 2 and solving for the radius of curvature, ρ :

$$\rho = 2P \left[1 + \left(\frac{x-h}{2P} \right)^2 \right]^{\frac{3}{2}} \tag{4}$$

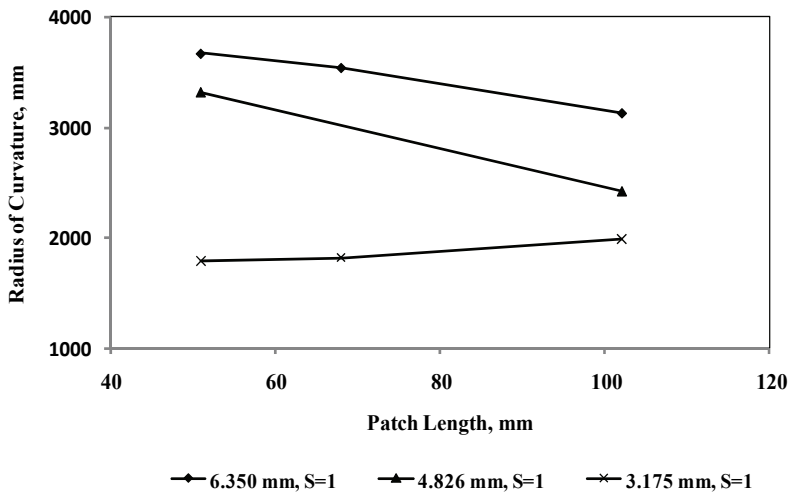


Figure 4: Effect of patch length on radius of curvature

Figure 4 shows the measured radius of curvature for three thicknesses of repaired panels with full width patch (153 mm) and for patch to panel stiffness ratio, $S=1.0$ as a function of patch length. The thinner plate had a consistently lower radius of curvature than the thicker plate for a given patch length. This dependency of the radius of curvature on the panel thickness is consistent with simple beam theory; i.e. increased plate thickness results in increased radius of curvature. However,

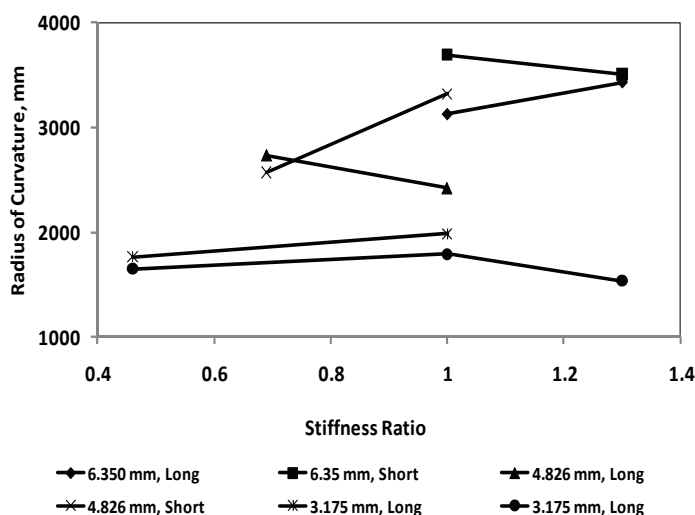


Figure 5: Effect of stiffness ratio on radius of curvature

the initial thermal curvature did not show a consistent trend with the variation of patch length. In the thicker plates, the radius of curvature decreased with increase in the patch length and it is consistent with beam theory as well as with Rose's analysis [20]. On the contrary, the radius of curvature in the thin plate (i.e. 3.175 mm thickness) does not coincide with the expected trend from the beam theory and Rose's analysis. Therefore, prediction of thermal induced curvature effects need more sophisticated analysis than simple beam theory or simple analysis. Further, this dependence of curvature on the patch length and other parameters would have a significant effect on stress intensity factor and hence on the crack growth rate behavior in repaired panels. The latter is investigated experimentally in the study.

Besides the plate thickness and patch length, the stiffness ratio would also have effects on the initial curvature from the curing of bonded patch. Figure 5 shows radius of curvature as a function of stiffness ratio for two patch lengths. Two patch lengths were: long one having 102 mm length and short one having 51 mm length. Stiffness ratio (S) change from 1.0 to 1.3 for the 6.350 mm plate with the long patch (102 mm length) increased radius of curvature by about 10% than that of the $S=1.0$ repair. Similar comparison for the short patch repair (51 mm length) for the same stiffness change showed about 5% decrease in radius of curvature. Examining the results of 3.175 mm plate with $S = 0.46, 1.0,$ and 1.3 for the short (51 mm) repair, it can be seen that $S = 0.46$ had about 8% smaller radius of curvature than the $S = 1.0$

repair. The $S = 1.3$ repair also had a smaller radius, about 14% less than the $S = 1.0$ repair. On the other hand, the long patch (102 mm) repair on the 3.175 mm panels resulted in an 11% smaller radius for the $S=0.46$ specimen over that of the $S=1.0$ specimen. The 4.826 mm panels were also examined with $S = 0.69$ and $S = 1.0$. Measurements showed that the $S = 0.69$ repair with the short patch (51 mm length) resulted in about 22% smaller radius of curvature than the $S = 1.0$ while the $S = 0.69$ repair on the 4.826 mm plate with long patch showed about 13% larger radius than the $S = 1.0$ specimen. These data, even though limited, clearly suggests that the effect of stiffness ratio on the initial curvature of the asymmetric repair would depend upon the length of the bonded patch and thickness of the repaired panel, and there is no simple trend among these parameters.

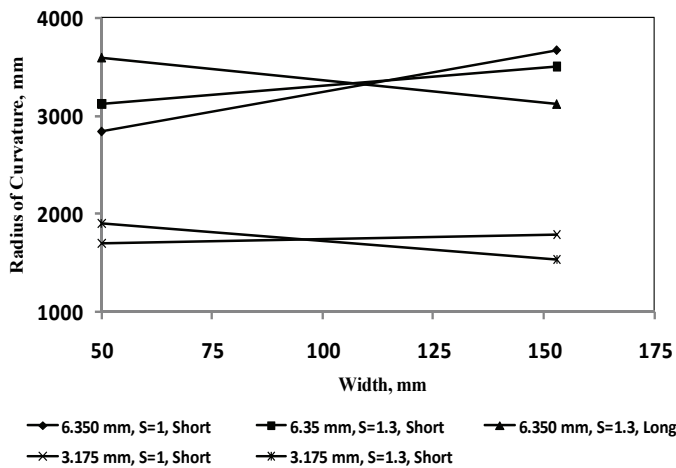


Figure 6: Effect of width on radius of curvature

The effect of the patch width on the initial curvature is shown in Figure 6. Examination of the effect of width patch on post-repair plate curvature shows two trends. First, for the long patch (102 mm) repair on the thick plate with $S = 1.3$, there was increase of about 10% in radius of curvature with a finite width patch (50 mm) relative to the full width patch (153 mm). Second, for the same thickness but with a short patch (51 mm), there was about 10 ~ 15% decrease in radius of curvature with a finite width relative to the full width for both stiffness ratios of 1.0 and 1.3. The change in the radius of curvature of repaired thin plate (3.175 mm) with short patch and $S = 1.0$ follows the same trend as the thick panel. On the other hand, the higher stiffness (1.3), short and finite width patch on the thin plate (3.175

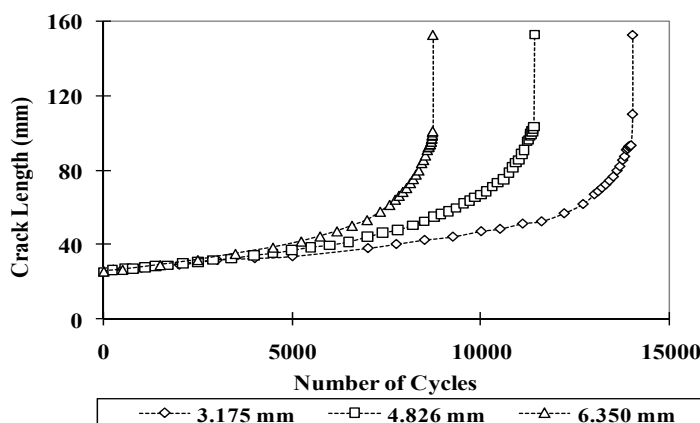


Figure 7: Crack length versus cycle relationship for unrepaired panels

mm) resulted in about 20% increase in radius of curvature relative to the full width. These data, even though limited, again suggest that the effect of the patch width on the initial curvature of the asymmetric repair would depend upon the length of the bonded patch, thickness of the repaired panel and stiffness ratio.

In summary, although limited data are available at present to characterize the effects of stiffness ratio, plate thickness, patch length and patch width on the initial radius of curvature, it clearly shows that it is complex interdependence. Therefore, lot more work is needed in experimental arena to establish the interrelationships or trends among these four parameters.

3.2 Fatigue Life

Figure 7 shows the crack length versus fatigue cycle relationships of unrepaired panels for three thicknesses: 6.35, 4.826 and 3.175 mm. Fatigue life decreased with increase of thickness. This dependence of fatigue life on the thickness was also observed by Broek and Schijve [21]. Fatigue life of unrepaired thin panel (3.175 mm) was about 1.6 times longer than that of the unrepaired thick panel (6.35 mm) as seen in Figure 7. The repaired thin panels also showed considerable improvement after repair, i.e. longer life (in the range of 2 ~ 3) relative to the repaired thick panels with similar patch configuration (i.e. same stiffness ratio, length and width) as discussed in the following. Thin panel versus thick panel repairs display different response to repair and crack growth mechanisms. Therefore, a thorough understanding of the fatigue behavior of the repaired panels is needed in order to further improve their fatigue lives. This study is a step in this direction.

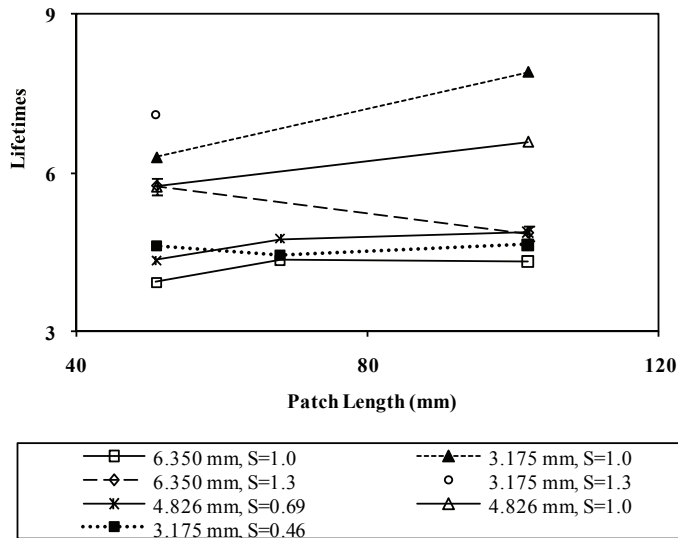


Figure 8: Effect of patch length on fatigue lifetime

Figure 8 shows the combined effects of stiffness ratio and patch length on the life improvement which is the ratio of repaired panel’s total life to the corresponding unrepaired panel’s total life for all three thicknesses. This is for the full width patch (153 mm). It is interesting to note that there is increase in the life improvement with increase of stiffness ratio at a given patch length for all three thicknesses. For repairs of stiffness ratio equal to 1.0, the patch length had practically no or small effect on fatigue life of the repaired thick panels, but increase in patch length improved the fatigue life of the repaired thin panel. But, with stiffness ratio of 1.3, the longer patch length on the thick panels decreased the fatigue life in comparison to the shorter patch. Therefore, there is practically no benefit or even a possible detrimental effect of the increased patch length on the fatigue life during the repair of thick plates. Thus, the current guidelines for the thin panel repairs that recommend the use of a longer patch are not directly applicable to the thick panel repairs. Therefore, the effects of stiffness ratio and patch length on the fatigue life improvement of the repaired panel are complex which require more studies. However, asymmetric repair of cracked panels with bonded composite patch increased their fatigue lives by at least four times relative to the unrepaired panels and in some cases even much more.

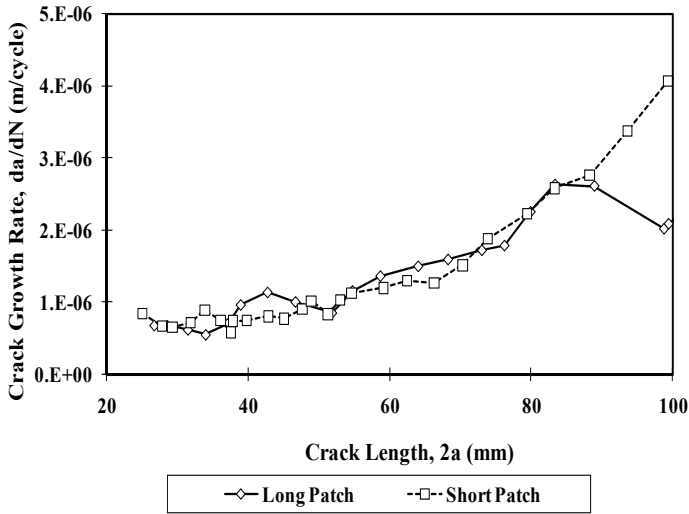


Figure 9: Crack growth rate versus crack length, 6.350 mm, S = 1, long versus short patch

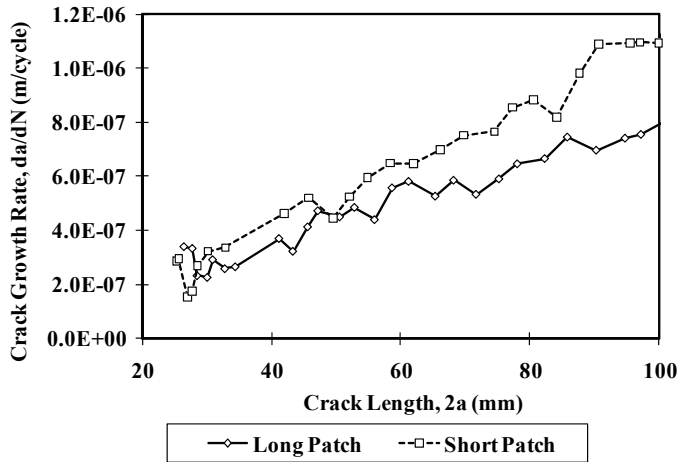


Figure 10: Crack growth rate versus crack length, 3.175 mm, S = 1, long versus short patch

The fatigue life would depend upon not only patch parameters but also on many other factors including debond. If there is no debond, the fatigue life would depend directly on the crack growth rate determined by opening stresses at the crack front for a given set of patch parameters. As discussed in the following, debond did not occur until the total crack length, $2a$ was in the range of 90 to 100 mm in all specimens with full width patch or when it exceeded the patch width in the finite width case. So, the comparison of crack growth, until significant debond occurred, would provide a direct and better comparison of the effects of different patch parameters.

4 Crack Growth Behavior

As mentioned above, an initial curvature in the repaired panel is present after the asymmetric bonding of the patch. With this initial curvature, the applied load causes out-of-plane displacement, i.e. curvature due to offset of the neutral axis. These two curvatures would act in the opposite direction. It should be noted that the curvature from the applied load would depend not only on the patch parameters but also on the load magnitude, and this curvature would cause the crack on the patched face to close and on the unpatched face to open. Further, these curvatures would cause non-uniform stresses along the thickness of the specimen, and hence variation in the stress intensity factor at the crack front along the thickness of the repaired panel. Thus, the crack growth behavior is expected to depend on the cumulative effects of both curvatures (i.e. from thermal stresses and applied load) that would then depend on various patch parameters at a given load level. In the following, the crack growth rates on the unpatched face of the repaired panel will be discussed to characterize the effects of different patch parameters.

4.1 Patch Length Effect

Bending, caused by the shift of neutral axis, in asymmetric repair decreases with the increase of the patch length. Therefore, the bonded repair guidelines recommend the use of longer patch length. However, these guidelines were primarily based from experiences with thin panel repairs where the initial curvature from bonding is minimal. Figure 9 compares the crack growth rates for the long and short repairs in thick panel of 6.350 mm with stiffness ratio of 1.0 up to crack length, $2a = 100$ mm, i.e. until any noticeably debond occurred. The increase in patch length had practically no impact on the crack growth rates in the thick panel repaired with the stiffness ratio of 1.0. This was expected since residual thermal stresses increased the bending effects and the loading reversed the bending to a certain extent with the longer patch, thus reducing these effects by offsetting each other. Similar behavior was observed in thick panel of 4.826 mm with stiffness ratio of 1.0 up to the crack

length, $2a = 100$ mm, and hence these data are not shown for the sake of brevity. In other words, patch length had practically no effect on the crack growth rates before any debond occurred in the thick panels. On the other hand, the longer patch (i.e. 102 mm length) shows a definitive improvement in the crack growth rates over the shorter patch (i.e. 51 mm length) in the thin repaired panel (3.175 mm) with the stiffness ratio of 1.0 as shown in Figure 10. It should be mentioned here that there was about 20% increase in the total fatigue life in this case. However, comparison of long patch (102 mm) with short patch (51 mm) in the thick repaired panel (6.35 mm) with the stiffness ratio of 1.0 had only about 2% difference in the total fatigue life. The effect of patch length on the crack growth rate up to the crack length, $2a = 100$ mm, i.e. before any debond occurred, was almost similar with higher stiffness ratio of 1.3 in the thick plate as with stiffness ratio of 1.0 in the thin plate. Figure 11 shows this phenomenon with thick repaired panel of 6.350 mm thickness with stiffness ratio of 1.3.

Thus, it is observed that crack growth rate in the thick repaired panels up to crack length before any debond occurs is not affected by the patch length, and it can be attributed to the fact that increase in patch length had opposite effect on the curvature due to thermal stress and the bending from the offset of the neutral axis. On the contrary, there is an effect of patch length on the crack growth rate in the thin repaired panel up to crack length before any debond occurs such that increase in patch length decreases the crack growth. However, once the debond occurs, the stress state at the crack front becomes very complex, and effects of patch length on the crack growth also becomes complicated, and therefore no simple dependence of the crack length on the crack growth can be deduced easily. Therefore, the current bonded repair guidelines to use the longer patch length are not directly applicable to the thick panels.

4.2 Stiffness Ratio Effect

The effect of the stiffness ratio (1.0 versus 1.3) on the crack growth rates is shown in Figure 12 for the thick repaired panel for the longer patch (102 mm length). The crack growth rates for the higher stiffness ratio of 1.3 were in general slightly lower than those with a stiffness ratio of 1.0 for crack lengths less than 90 mm long, i.e. before any debond occurred. This is expected since higher stiffness ratio increased curvature after bonding (or less bending from thermal stresses), and hence reduced radius of curvature due to the neutral axis offset from application of the load. These effects would decrease the stress intensity factor with increase of stiffness ratio and hence the crack growth rate. Similar phenomenon was also observed with the smaller patch length (51 mm), i.e. the crack growth rates were again less for the higher stiffness ratio patch as shown in Figure 13. Exactly similar

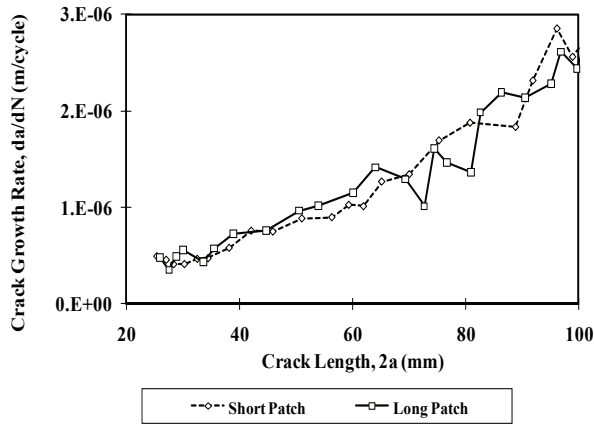


Figure 11: Crack growth rate versus crack length, 6.350 mm, $S = 1.3$, long versus short patch

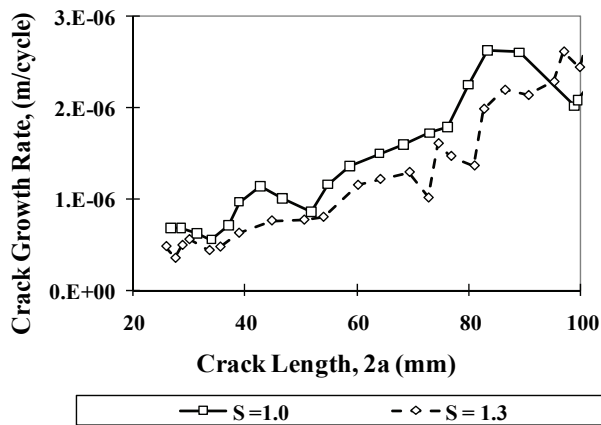


Figure 12: Crack growth rate versus crack length, 6.350 mm, long patch $S=1.0$ versus $S = 1.3$

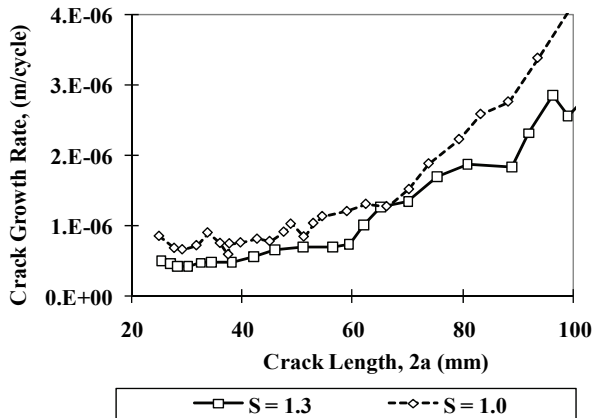


Figure 13: Crack growth rate versus crack length, 6.350 mm, short patch, S = 1.3 versus S = 1.0

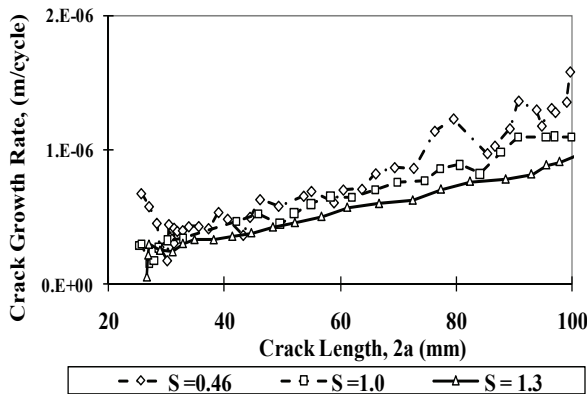


Figure 14: Crack growth rate versus crack length, 3.175 mm, short patch, effect of stiffness

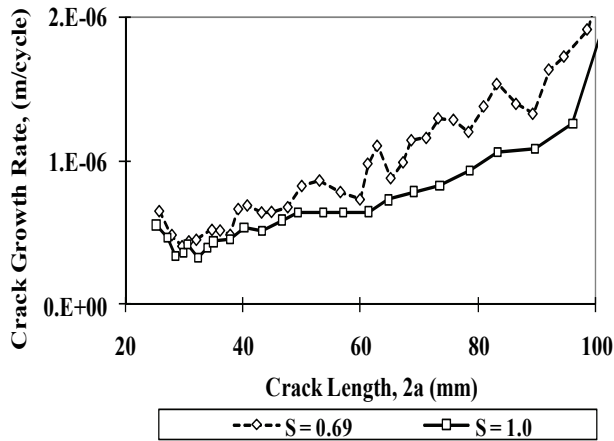


Figure 15: Crack growth rate versus crack length, 4.826 mm, short patch, effect of stiffness ratio

feature was observed with the thin panels (3.175 mm) as shown in Figure 14 where crack growth rates for three stiffness ratios, 0.46, 1.0 and 1.3 are shown for patch length of 51 mm. Finally, Figure 15 displays the same phenomenon with intermediate panel thickness of 4.826 mm with patch length of 51 mm for stiffness ratios: 0.69 and 1.0. Here again higher stiffness ratio provided slower crack growth rate and hence longer fatigue life. Thus, it appears that higher stiffness ratio provides the lower crack growth rate or longer fatigue life for both thin and thick repaired plate for a given patch length. Furthermore, it is interesting to note from Figures 12, 14, and 15 that reduction in the crack growth rate decreased with increase of the panel's thickness for a given increase in stiffness ratio. Thus, it appears that benefit of increasing stiffness ratio depends on thickness of the repaired panel. Hence further studies are also needed in this direction to utilize this benefit in the repaired panels.

4.3 Patch width Effect

Crack growth rates in the repaired panels with finite width patch, 50 mm wide (i.e. width of the patch up to which thickness was uniform) were compared with counterparts with the full width (153 mm) patch. The crack growth rates of all finite width repairs were equal to their counterparts from the full width repair up to crack length equal to the width of the finite patch, i.e. it was not affected by plate thickness, patch stiffness and patch length. For example, Figure 16 shows the

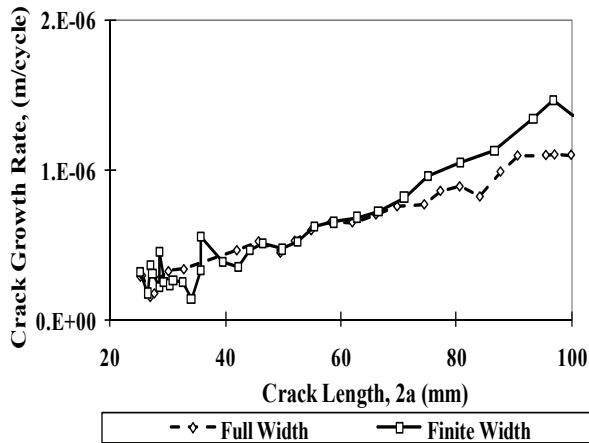


Figure 16: Crack growth rate versus crack length, 6.350 mm, long patch, full width versus finite width

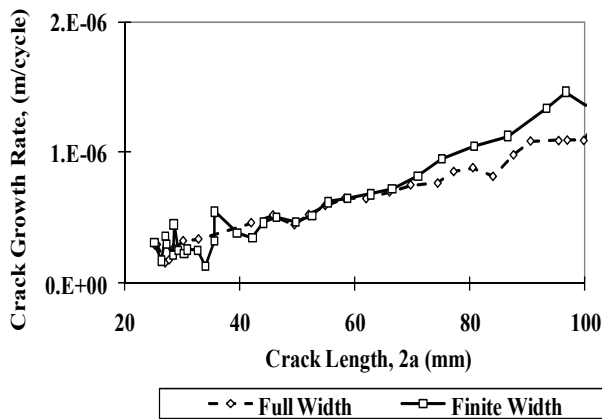


Figure 17: Crack growth rate versus crack length, 3.175 mm, long patch, full width versus finite width

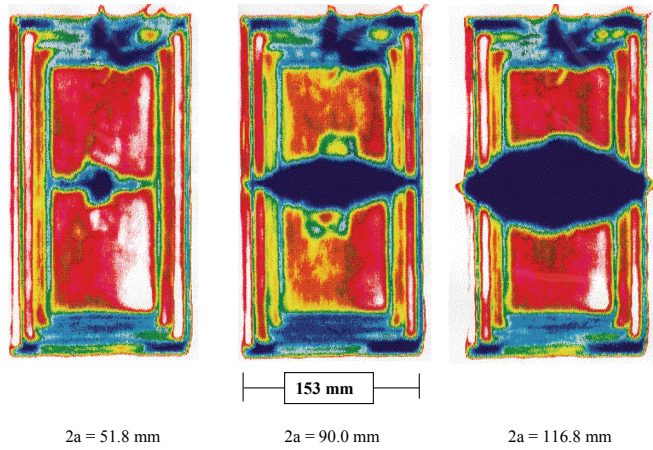


Figure 18: Debond growth

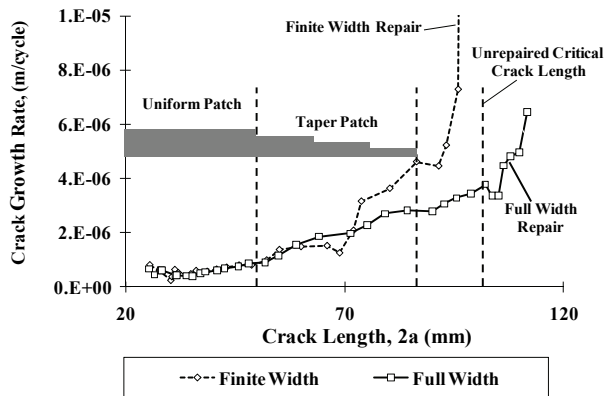


Figure 19: Crack growth retardation at unrepaired critical crack length and change of patch thickness

crack growth rate versus cycle data for repaired thick plate (6.350 mm) for patch length of 102 mm and stiffness ratio of 1.3 for finite width and full width patches. Here the crack growth rates for both patch widths are equal up to crack length equal to uniform width of the finite patch (50 mm). But once the crack propagates into the patch taper region, the crack growth rates for the finite width patch quickly increased and became more than those of the full width patch as expected. Exactly similar feature was seen with the thin panels (3.175 mm) as shown in Figure 17. Thus, there was no effect of the patch width on the crack growth rates up to crack length equal to the uniform width of patch, however wider patch would provide longer crack length which a repaired panel can sustain, and hence overall longer fatigue life.

4.4 Debond

The growth of debond was monitored during fatigue tests using infra-red (IR) thermography. Additionally, a limited number of ultra-sonic images (C-scans) were taken to validate the IR thermography results acquired during the fatigue tests. This validated the thermographic measurements since in-situ measurements from IR thermography did not require to stop the test and take out the specimen from the test machine for C-scan measurements. The details of these measurements and comparison are provided in a previous study [18]. Results of the thermographs and C-scans of the patched areas showed no detectable debond in the taper or edge areas of the patch in any specimens during testing, even at long crack lengths. Debond growth or delamination surrounding the crack remained near the crack and grew in a near self-similar fashion until the crack was either long (i.e. in the range of 90 to 100 mm) or the crack was outside the uniform thickness of the patch in the case of finite width patch. Similar debond behavior in the wake of the crack was also observed by Baker [3]. Figure 18 shows a typical debond growth during the test of 6.35 mm panels with finite width patch for the stiffness ratio of 1.0. Very little debond growth was observed until the crack reached the patch taper ($2a = 50$ mm) and did not grow appreciably until the crack grew beyond the patch edges ($2a = 86$ mm). As the crack grows beyond the patch edge, debond growth accelerated. Further after debond occurred, crack growth rates became erratic.

Examination of debond growth in all specimens tested in this study showed a similar growth pattern of debond (i.e. size and shape), regardless of patch length and width as well as stiffness ratio. Significant debond growth (away from the immediate area of the crack) occurred only either when change in patch thickness occurred (i.e. in its taper portion), or when the crack reached a length where it would have grown unstable in the unrepaired specimen. The unrepaired specimens failed catastrophically at crack length of approximately 90 ~ 100 mm during cycling as can be

seen in Figure 7. This means that at this crack length, the maximum applied load of 120 MPa on the repaired specimen created a condition where the stress intensity factor from the fatigue load at the crack tips exceeded the critical stress intensity factor, K_C of the unrepaired panel. This stress intensity factor caused the crack to grow unstably momentarily in the repaired panel. Similar condition also developed when there was a change in the patch width. This resulted in local plastic yielding, and consequently crack growth retardation similar to change in growth rate observed when a component experiences a stress overload. This behavior is shown in Figure 19. As can be seen in this figure, a momentary reduction in the crack growth rate occurred near crack length equal to 100 mm for the full width patch or near crack lengths equal to 50, 86 and 100 mm in the finite width patch, i.e. where its thickness changes. Thus once debond occurred, crack growth rates became erratic. Thereafter, crack growth rates were not only affected by the patch parameters but also on the amount and rate of debond, and thereafter the crack growth behavior became very complex. Hence, the characterization based on total fatigue life does not characterize accurately the effects of the patch parameters. So, present observations on the patch geometry effects, until debond growth occurred, have usefulness in the design of patch repair.

5 Conclusions

Fatigue crack growth behavior of thin and thick aluminum panels repaired with asymmetric bonded composite patch was investigated. Three patch lengths, two widths, and several patch-to-panel stiffness ratios were studied. Asymmetric repair introduced initial thermal curvature (or bending) from bonding of patch in the repaired panels. The initial curvature was affected by patch geometric factors, such as length, width, stiffness ratio as well as repaired panel's thickness. The radius of curvature decreased with increase of the patch length in the thicker plates (6.350 or 4.826 mm thickness) while the radius of curvature in the thin plate (i.e. 3.175 mm thickness) increased with increase in the patch length. The effects of stiffness ratio and patch width on the initial curvature of the asymmetrically repaired panel were dependent upon the length of the bonded patch, thickness of the repaired panel and stiffness ratio. Patch length affected total fatigue life in the following manner: (a) longer patch provided longer total fatigue life for the thin repaired panels, (b) practically no or small increase was observed in the total fatigue life of thick plates with increase of the patch length for stiffness ratio of 1.0, and (c) total fatigue life was reduced in the thick repaired panels with increase of patch length with higher stiffness ratio of 1.3. Overall, the effects of stiffness ratio and patch length on the fatigue life improvement of the repaired panel are complex which require further studies.

If there is no debond, the fatigue life would depend directly on the crack growth rate for a given set of patch parameters. However, debond occurred when there was a change in patch thickness, or when the crack reached a length where it would have grown unstable in the unrepaired specimen which was in the range of 90 to 100 mm in all specimens tested in this study. Before this, there was similar growth pattern of debond (i.e. only near the immediate area of the crack), regardless of patch length and width as well as stiffness ratio, and thereafter significant debond growth occurred. The crack growth rate in the thick repaired panels (6.350 or 4.826 mm thickness) up to crack length before any debond occurred was not affected by the patch length. On the other hand, the longer patch decreased in the crack growth rate relative to the shorter patch in the thin repaired panel (3.175 mm). The higher stiffness ratio provided the lower crack growth rate or longer fatigue life for both thin and thick repaired plate for a given patch length. Finally, there was no effect of the patch width on the crack growth rates up to crack length equal to the uniform width of patch.

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