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Fatigue life enhancement of defective structures by bonded repairs

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Abstract. Defective metallic components and structures are being repaired with bonded composite patches to improve overall mechanical and fatigue properties. In this study, fatigue crack growth tests were conducted on pre-cracked 7075/T6 Aluminum substrates with and without bonded Boron/epoxy patches. A considerable increase in the fatigue life and a decrease in the stress intensity factor (SIF) were observed as the number of patch plies increased. The experimental results demonstrate that the patch configurations and patch thickness can enhance fatigue life by order of magnitude. Quantitative comparisons between analytical and experimental data were made, and the analytical model based on a modified Rose's analytical solution appears to best estimate the fatigue life.

Key words: bonded repair; composite patch; fatigue life; crack growth rate; aluminum alloy; defective structure.

1. Introduction

Defective metallic components and structures are being repaired with bonded composite patches to improve overall mechanical and fatigue properties. Repairs using bonded composite patches have been reported to have various advantages over mechanical fastening or riveting, including improved fatigue behavior, restored stiffness and strength, and reduced corrosion (Wang 2002, Klug 1999, Seo 2002). The success of a bonding repair depends on the properties of the adhesive and the patch, and its affinity for the substrates. The quality of the bond also depends upon the bonding procedure and surface preparation. Most aircraft repairs involve or use bonded composite patching due to its high stiffness, high strength, low weight and cost effective. Boron-epoxy, carbon-epoxy and graphite-

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epoxy composites have been mostly used as repair patches. The thermal expansion coefficient of boron-epoxy makes it the best choice.

Although, the technology of repairing defective aircraft structures with composite patches has been gaining acceptance, the lack of standardized bonded repair methods and certification concepts impedes its wider application (Fredell 1999). Perhaps the most critical aspect of this technology is the long-term durability of the adhesive bond between the repair patch and the baseline structure. Stress analysis of patched structures, various processing conditions such as the quality of surface preparation, installation and curing conditions, and the optimized design of patches are the most challenging aspects in ensuring a reliable and durable bonded repair.

Fatigue characteristics of bonded composite repairs are a fundamental design aspect for determining the fatigue life extension. The fact that only one side of aircraft structures is, in practice, available for bonding repairs makes it important to design and analyze asymmetric patch configurations. Klug, Maley and Sun (1999) investigated analytically and experimentally, the fatigue response of pre-cracked 2024-T3 Aluminum plates bonded with carbon/epoxy patch. Single-sided repairs were found to provide about a 4-5 fold improvement in the fatigue life. Paul and Jones' (1994) experimental results revealed that the boned-boron/epoxy repaired aluminum alloy (7075-T6) specimens could greatly increase life expectancy. An experimental investigation was conducted by Schubbe and Mall (1999) to characterize the post-repair fatigue crack growth (FCG) behavior in 6.350 mm thick 2024-T 3 aluminum panels repaired with the asymmetrically bonded full width boron/epoxy composite patch. Improvement in the fatigue life was again found for repaired specimens as compared to the unrepaired baseline (cracked) specimens. In this study, fatigue crack growth (FCG) behavior of pre-cracked Al 7075/T6 substrates with bonded composite patches was investigated experimentally and analytically.

2. Materials and specimens

The substrate material, used in this study was 7075-T6 sheet aluminum. The composite patch was Textron's 5521 boron-epoxy prepreg tape. The 3M manufactured AF-163-2K adhesive was used to bond the patches to the substrate. Material properties are shown Table 1.

The substrates were machined to be 305 mm long and 51 mm wide from the 1.6 mm thick 7075-T6 aluminum sheets. A starter V-type notch was machined at the side of the specimen as shown in Fig. 1. Surface preparation of the substrate was done prior to the adhesive bonding of patches. Patched specimens were made by first cleaning the substrates with Scotch Brite abrasive, degreasing them using a 50/50 isopropyl alcohol/water mixture and then air drying. 3M (AF163-2K) scrim cloth structural adhesive tape was applied to the substrate in the middle section over the side crack. The boron/epoxy prepreg was then applied over the adhesive in successive layers. All the specimens bonded with 1-, 2-, and 4-ply patches were cured in an autoclave as follows,

Table 1 Material properties

	E (MPa)	σ_{ult} (MPa)	G (GPa)	τ_{ult} (MPa)	ρ (g/cm^3)
Al 7075-T6	72	520	28	210	2.8
Boron-epoxy	190	1550	7	70	2.0
Adhesive 3M	1.1	48	0.44	40	1.2

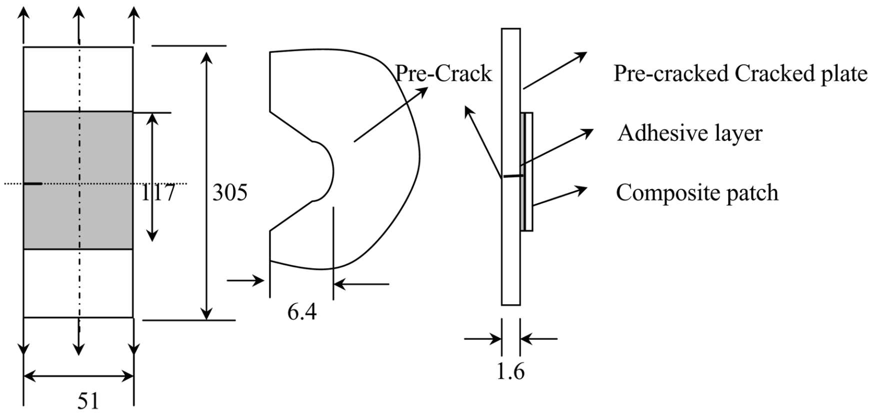

Fig. 1 The geometry of patched V-type side-cracked specimen

1) The repaired specimen is placed in the autoclave, and layered with Teflon sheets above and below; 2) A constant pressure of 50 Kpa is applied; 3) The temperature is ramped up to 121^{o}C and held steady at 121^{o}C for 90 min; 4) The specimen is cool-down to room temperature and then released from the pressure.

3. Experimental results

Fatigue tests were carried out on identical pre-cracked substrates with and without bonded boron/epoxy patches and the un-notched specimen using a servo-hydraulic machine. All fatigue testing was conducted at 3 Hz with a constant load amplitude, sinusoidal waveform and load ratio of 0.1. Crack length measurement was made optically using a micro-zoom lens to observe the polished surface of the specimen scribed with grid lines (spaced 0.25 mm apart). The crack length and the number of cycles were recorded periodically.

3.1 FCG behavior of the substrate

Tension/tension fatigue tests were conducted on aluminum substrates with a side V-crack to establish their fatigue behavior for comparison with the repaired specimen and to determine the material constants of Paris Law, C and m for analytical fatigue life prediction of repaired aluminum plates. Aluminum substrates having the same geometry were then repaired with boron/epoxy doublers with 1, 2 and 4 plies. The specimen geometry is shown in Fig. 1. The relationship between the crack growth rate and the SIF is shown in Fig. 2 for the Al substrate with a side pre-crack.

The initial SIF range for the substrate, ΔK_I, is expressed in equation (Anderson 1991),

$$\Delta K_I = \frac{\Delta P}{t\sqrt{W}} \frac{\sqrt{2\tan\frac{\pi a}{2W}}}{\cos\frac{\pi a}{2W}} \left[0.752 + 2.02\left(\frac{a}{W}\right) + 0.37\left(1 - \sin\frac{\pi a}{2W}\right)^3\right] \quad (1)$$

where, a is the crack length, W is the plate width, t is the plate thickness, and P is the applied load.

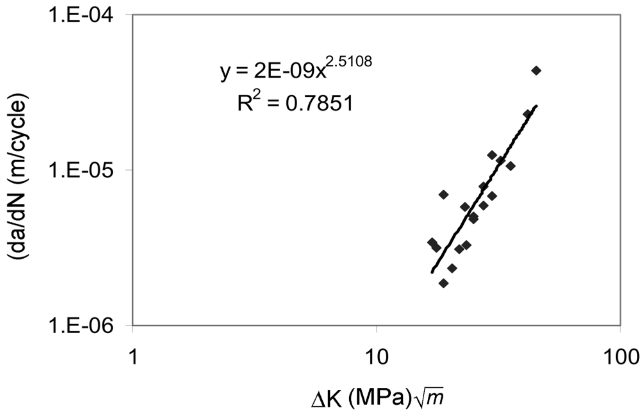

Fig. 2 FCG rate vs SIF range for the substrate

3.2 Effect of patch plies on fatigue life

As shown in Fig. 3, the pre-cracked specimen with 0-, 1-, 2-, 4-ply bonded patches failed at an average of 6000, 32000, 60500, and 82000 cycles, respectively. The crack initiated at the pre-cracked tip at about 3000, 12000, 13000 and 16000 cycles, respectively. The criterion for crack initiation was the observation of about a 0.5 mm crack as captured with the traveling optical microscope with a zoom lens. Considerable disbanding occurred only for the specimens with 1-ply bonded patch during fatigue crack growth. It was found that a life extension factor between 5 and 14 was obtained for the cracked specimens with different bonded patch plies. In general, the number of cycles to crack initiation had a major impact on the total number of cycles to failure. The crack growth life from baseline to failure was at 10-50% of the total fatigue life. As the number of plies increased, a considerable increase in both initiation and propagation lifetimes was noticed.

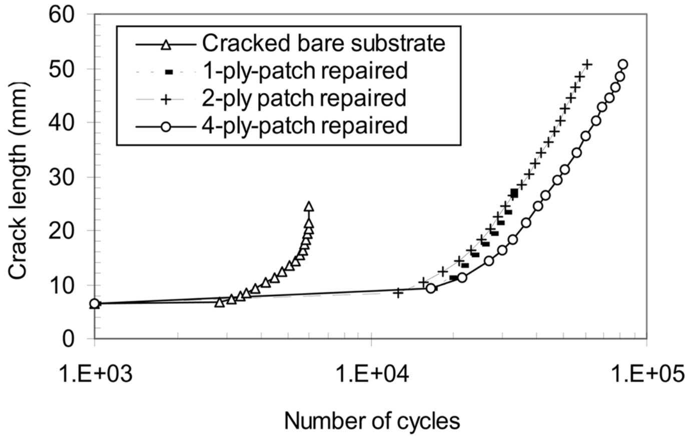

Fig. 3 FCG behavior of Al cracked substrate without and with bonded patches

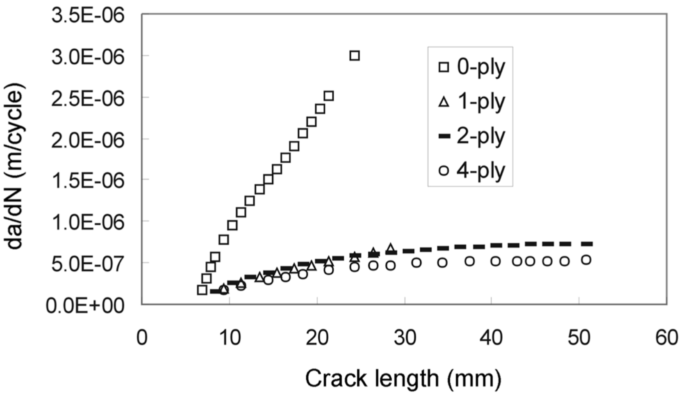

Fig. 4 Crack growth rate vs crack length

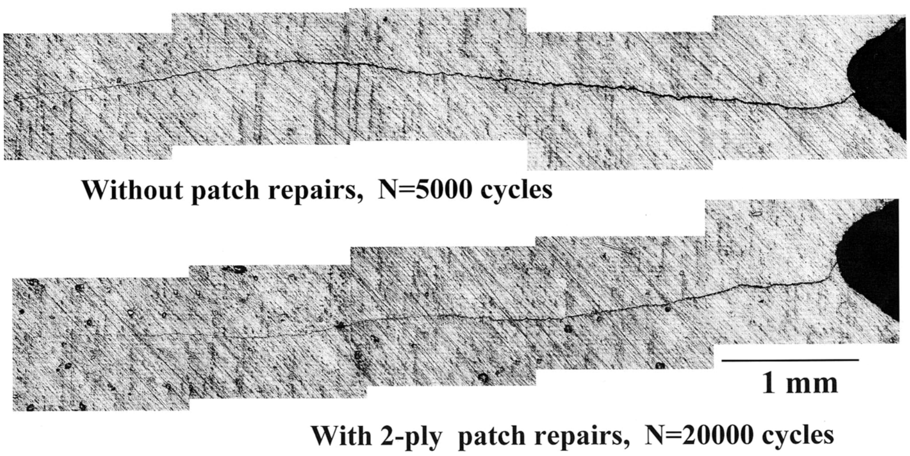

Fig. 5 Fatigue crack growth paths in aluminum substrate with and without patches

The crack growth rates for aluminum substrate with and without boron-epoxy patches are compared in Fig. 4. It is noticed that the all the patch repairs greatly slow down the crack growth rates. The crack growth rates for 2- and 4-ply patch repairs were relative slower compared to the baseline (?). Fatigue crack propagation paths are shown in Fig. 5. Fatigue tests were interrupted before fracture for the specimen without patch at 5000 cycles and for the specimen with 2-ply patch at 20000 cycles. The crack growth path for the repaired specimen is slightly more stable than that for the specimen without patch. Again patch repairs significantly extended the fatigue life by slowing crack growth. The fracture surfaces of tested specimens were investigated with a scanning electron microscope (SEM). Fig. 6 shows fatigue fracture surfaces of a 1-ply patch repaired specimen during fatigue crack growth. The boron fibers in the patch were fractured in a brittle mode. A disbond failure and a fatigue fracture were observed in the adhesive layer and in the substrate, respectively.

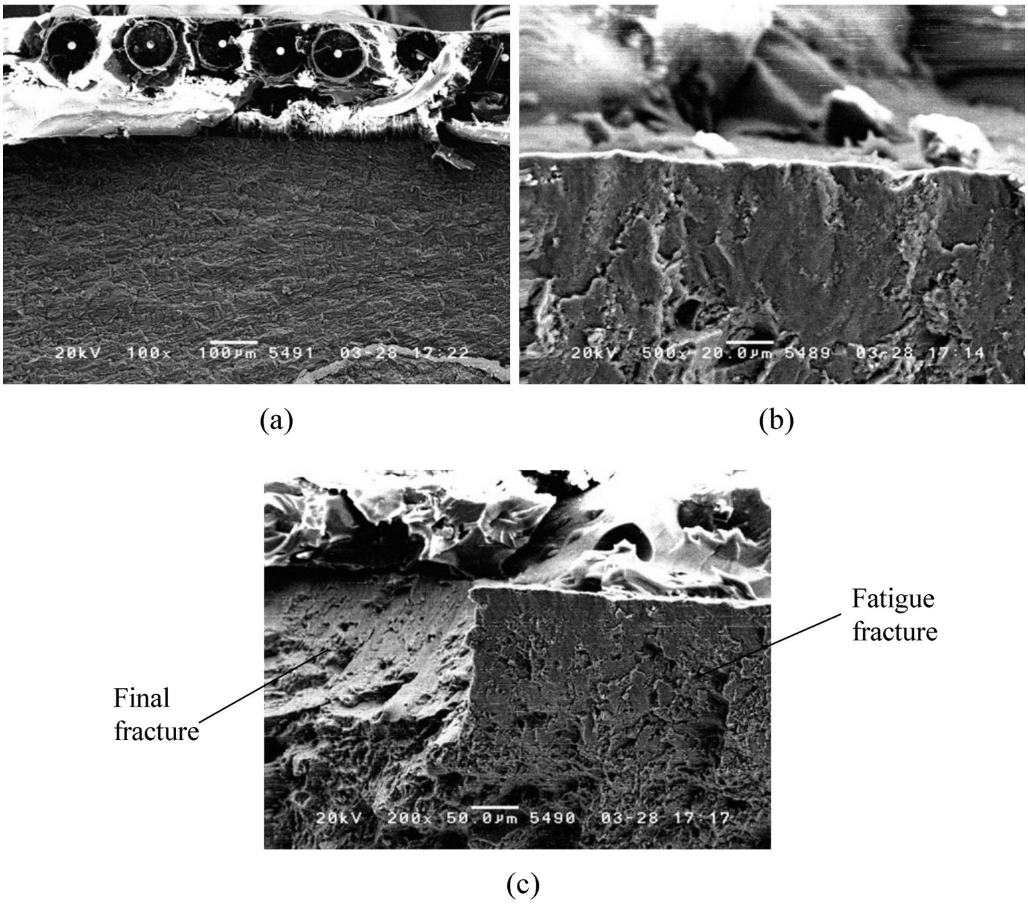

Fig. 6 SEM micrographs showing fatigue fracture of 1-ply patch repair (a) Overview of the fatigue fracture surface (b) Disbonding failure in the adhesive layer (c) Fatigue crack growth and final fracture

4. Model predictions and comparisons

In the current analysis, Rose's model (1982, 1981) to calculate stress intensity factor (SIF) in the patch repaired plate was used. This is an efficient and economical approach verified experimentally by Muller *et al.* (1999). The model uses Paris law of crack propagation to predict the fatigue life of cracked plates with and without repairs. In this analysis, the Paris law's material constants of the repaired plate, C and m, were assumed to be the same as the un-repaired substrate. The material constants were obtained from fatigue tests conducted on V-type cracked bare substrate.

4.1 SIF calculation

Rose's analytical model (Rose 1982, 1981) was used to compute the SIF for the repaired substrates.

$$K_R = \frac{K_I}{1+S}\left[\frac{\Lambda}{a+\Lambda}\right]^{\frac{1}{2}} \tag{2}$$

where the initial SIF for the Al substrate alone, K_I, can be obtained analytically, S is the stiffness ratio of the patch reinforcement to the substrate, and a is the crack length, Λ is the crack length at which the crack makes its transition from a short to a long crack and the crack opening displacement under the repair becomes more relevant (Rose 1982, 1981). The complete expressions for S and Λ are given

$$S = \frac{E_{patch}t_{patch}}{E_{plate}t_{plate}} \tag{3}$$

$$\Lambda = \left[\frac{t_{adhe}}{G_{adhe}}\left(\frac{E_{patch}t_{patch}E_{plate}t_{plate}}{E_{patch}t_{patch}+E_{plate}t_{plate}}\right)\right]^{\frac{1}{2}} \tag{4}$$

where E is the elastic modulus, t is the thickness, and G is the shear modulus.

Table 2 gives the stiffness ratios of the patch reinforcement to the substrate and the transition crack lengths for the specimen configurations. The stiffness ratio of 1.0 is generally recommended for the repair of aircraft structures (Schubbe 1999). Therefore, the 1-, 2-ply patch is referred to as the low stiffness ratio repair.

The various stress intensity factors computed from Eqs. (1)-(4) for repairs with different number of plies are shown in Fig. 7. The initial SIF range, ΔK, for the baseline test was 17.6 MPa$\sqrt{m}$ at a

Table 2 Number of patch plies, stiffness ratio and crack length at which the transition from a short to a long crack

Ply number	Siffness ratio, S
1	0.214
2	0.429
4	0.858

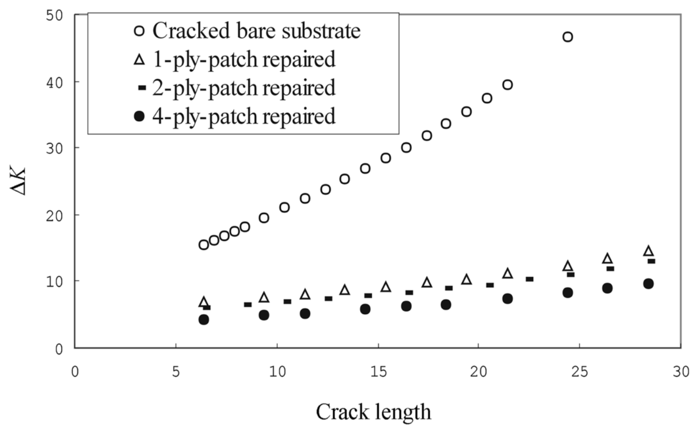

Fig. 7 SIF of the substrates without and with bonded patches

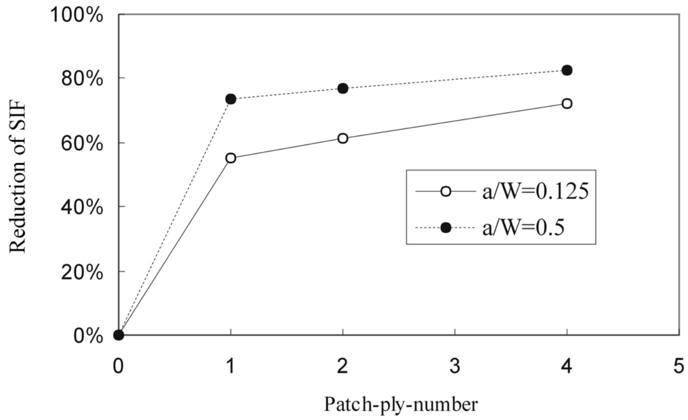

Fig. 8 Reduction of SIF of composite repairs with respect to Patch-ply-number

crack length, $a = 8$ mm, while the 1-, 2-, 4-ply repair SIF ranges, were about 7.9, 7.4, and 6.0 MPa$\sqrt{m}$, respectively, at the same crack length. The SIF for repaired substrates increased much slower than that of baseline with the increase in crack length. A two to four fold decrease in the SIF was achieved with increasing the number of plies.

As shown in Fig. 8, the composite patches reduce the stress intensity factor (SIF). The reduction of SIF, $1 - \Delta K_R/\Delta K_I$, increases with an increase in the number of patch plies. For example, an 80% reduction of SIF can be achieved for the 4-ply repaired substrate with a relative crack length, $a/W = 0.5$.

4.2 Fatigue life predictions and comparisons

Most fatigue-crack growth life prediction models employ the Paris power law due to its simplicity. In this investigation, Paris law is used to study the fatigue behaviors of cracked plates:

$$\frac{da}{dN} = C(\Delta K)^m \tag{5}$$

The material constants, C and m, for the 7075/T6 aluminum alloy, were obtained from experiments on cracked bare substrates as $C_{sc} = 6.0 \times 10^{-10}$, $m_{sc} = 2.51$ for the short crack ($\Delta a < t$, 1.6 mm), and $C_{lc} = 2.0 \times 10^{-9}$, $m_{lc} = 2.51$ for the long crack ($\Delta a \geq 1.6$ mm). The stress intensity factor range, ΔK, depends on the stress range, the geometry of the substrate and the patch characteristics. Based on the analytical stress intensity factors and experimental constants, predictions of the fatigue life of patched plates can be made by numerical integration of the Paris law:

$$N = \int_{a_0}^{a_{sc}} \frac{da}{C_{sc}(\Delta K)^{m_{sc}}} + \int_{a_{sc}}^{a_f} \frac{da}{C_{lc}(\Delta K)^{m_{lc}}} \tag{6}$$

where a_o, a_{sc}, and a_f are the initial, critical short, and final crack lengths, respectively.

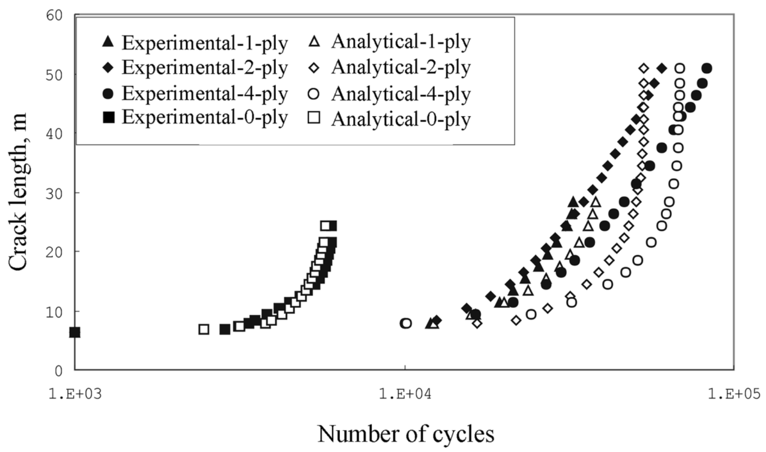

Fig. 9 Comparison of analytical result with experimental data for the fatigue life of patched and unpatched baseline

Comparisons of the fatigue lives between the experimental data and analytical results for all the patch configurations are presented in Fig. 9. As shown in Fig. 9, the predicted fatigue life was within 20% of the experimental results for substrates repaired with 1-, 2-, and 4-ply patches. This simple analytical model appears to estimate the fatigue life of repaired substrates accurately. It has shown experimentally and analytically that the fatigue life of the repaired substrates is increased as the number of patch plies is increased.

5. Conclusions

Fatigue crack growth behavior of pre-cracked aluminum substrate with and without boron-epoxy patches was investigated experimentally and analytically. Three composite patches with 1-, 2- and 4-ply were studied. About a ten fold increase in the fatigue life and a two to four fold decrease in the stress intensity factor were observed as the number of plies was increased. The 4-ply-patch repaired specimen demonstrated its effectiveness in increasing the fatigue life of the cracked substrates. An analytical model, based on Rose's analytical solution and Paris' law, was developed to predict the fatigue life of the bonded composite repairs. Quantitative comparisons between the analytical and experimental results were made. The analytical model appears to bet estimate the fatigue life of repaired substrates accurate. Thus, the present analytical procedure may be considered as a viable approach to assess the durability of bonded repair structures.

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