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Observation of static strength and fatigue life of repaired graphite/epoxy using a tensile coupon

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Abstract—The static strength and fatigue life of repaired graphite/epoxy laminates was observed using a tensile coupon. The lay-up of investigated laminates was $[0°/\pm45°/90°]_S$. Static strength was measured from the specimens prepared by various repair techniques such as cosmetic treatment, precured-single patch, precured-double patch and cure-in-place patch methods. The strength was recovered to the extent of 60–70% of unnotched case. Fatigue life was also measured from the laminates repaired with cure-in-place patch method. Hwang and Han's MFLPE 1 (modified fatigue life prediction equation (1)), which is based on the fatigue modulus degradation model and reference modulus, was chosen for fatigue life prediction of the repaired specimen and compared with the conventional fatigue life equations such as the S–N curve and Basquin's relation. The MFLPE 1 agrees more closely with experimental data than the S–N curve or Basquin's relation.

Keywords: Graphite/epoxy; repair; tensile coupon; strength; fatigue life; strength recovery; fatigue strength reduction factor; cure-in-place.

1. INTRODUCTION

The use of advanced composite materials, especially in aircraft, has been expanding in recent years because of their superior strength-to-weight and stiffness-to-weight ratios and better fatigue resistance compared to other materials previously used. But unfortunately, most composite materials tend to contain defects, such as cracks, voids and delaminations produced by fatigue, impact damage or poor design. These defects may have a deleterious influence on the various functional capabilities.

To restore a damaged part's structural integrity, attention has recently been focused on developing repair procedures [1, 2]. Considerable effort has been devoted to the development of generic repair technology for advanced composites with aircraft companies as the central figures, but the repair standards have not yet

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been established [3–5]. Some repair designs and application procedures have little chance of success, and in many cases service lives of components have been reduced by poor design.

To establish repair standards, the behavior of repaired composites must be observed not only under static but fatigue loading. In this study, the static and fatigue behavior of repaired composites is observed and analyzed.

2. THEORETICAL ANALYSIS

The fatigue modulus, F, proposed by Hwang and Han [6, 7] is defined as a function of loading cycle, n, and applied stress, q.

$$F(n, q) = \frac{\sigma_a}{\varepsilon(n)} = \sigma_u \frac{q}{\varepsilon(n)}, \tag{1}$$

where F is the fatigue modulus, σ_a is the applied stress, ε is the resultant strain, σ_u is the ultimate strength and q is the ratio of applied stress to ultimate strength. Initial and final conditions give the following relations:

$$\begin{aligned} F(0, q) &= F_0 = E_0, \\ F(N, q) &= F_f. \end{aligned} \tag{2}$$

The fatigue modulus at the zeroth cycle, F_0, is assumed to be the same as elastic modulus, E_0, and the fatigue modulus at fracture, F_f, is defined at the number of cycles to failure, N. It is reasonable to assume that applied stress has a linear relation with resultant strain at any arbitrary loading cycle if the specimen undergoes constant maximum loading. This assumption follows:

$$\sigma_a = F(n)\varepsilon(n). \tag{3}$$

The fatigue modulus degradation rate at any fatigue cycle can be assumed as a power function of the number of fatigue cycles and the fatigue modulus itself,

$$\frac{dF}{dn} = -A\frac{Cn^{C-1}}{BF^{B-1}}, \tag{4}$$

where A, B, and C are material constants. Integration of equation (4) by substituting the condition (2) gives

$$F_f^B - F_0^B = -AN^C. \tag{5}$$

The reference modulus, F_R, is assumed as follows:

$$\begin{aligned} F_0/F_R &= p, \\ F_f/F_R &= f(q) = q, \end{aligned} \tag{6}$$

where p and q are material constant and applied stress level, respectively. Substituting equation (6) into equation (5), one obtains

$$N = [M(p^B - q^B)]^{1/C}. \tag{7}$$

Using the above equation, the fatigue life of materials can be predicted as long as the material constants M, B, C, and p are known [8].

3. EXPERIMENTAL

The parent laminate was fabricated with a stacking sequence of $[0°/\pm45°/90°]_S$. The prepreg tape manufactured by Han Kuk Fiber Company was used. A circular hole was made at the center of each specimen using a drilling machine. Four different holes with radii of 1, 2, 3 and 4 mm were chosen for static tests and three different holes with radii of 1, 3 and 4 mm were chosen for fatigue tests. The width of the test laminate was 25 mm and thickness was 1mm. Static tests were conducted for the specimens repaired by the following repair methods.

3.1. Cosmetic treatment

The hole was filled with epoxy which was mixed with chopped graphite fiber and cured at room temperature.

3.2. Precured-single/double patch

The patch that had the same lay-up as the parent laminate was adhered to the damaged area with adhesive (2216B/A) manufactured by 3M Company. The width of patch was the same as for the parent laminate, and the length was 40 mm.

3.3. Cure-in-place patch

Prepreg was laid up in the order of 0°, −45°, 45° and 0° from the parent laminate, varying the length by 30, 40, 50 and 60 mm, respectively. To reduce the stress concentration at the end of the outer layer of reinforced patch, the outer patch was cut into a saw shape [9].

For the fatigue test, the cure-in-place patch specimens were chosen because these show the best results in the static test. The fatigue test specimen configuration is presented in Fig. 1. Fatigue tests were performed in load control mode using a sinusoidal wave form with frequency 3 Hz, which is considered to give a negligible temperature rise during tests.

4. RESULTS AND DISCUSSION

The tensile strength of the parent laminate was found to be 608 MPa. Table 1 lists the tensile strength of the notched specimen and the repaired specimen. The non-patch method (cosmetic treatment) does not show a reinforcing effect, while all patch methods show good results.

The strength recovery to the tensile strength of the parent laminate for various repair methods is presented in Figs 2 and 3. Figure 2 is the case when the flaw

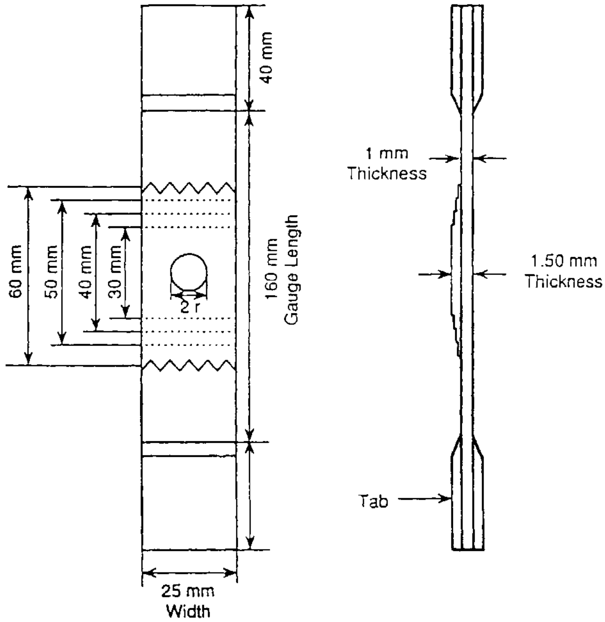

Figure 1. Fatigue test specimen configuration (cure-in-place).

Table 1.
Static test results (MPa)

Radius (mm)	1	2	3	4
Repair techniques				
Notched	445	373	335	298
Fill	—	369	—	303
Precured single patch (40 mm)	—	401	—	360
Precured double patch (40 mm)	—	464	—	393
Precured double patch (60 mm)	—	526	—	512
Cure-in-place double patch	—	—	—	451
Cure-in-place single patch	466	426	412	377

size was 2 mm and Fig. 3 is for a value of 4 mm. The failure mode of repaired specimens prepared by all types of repair technique in this study was the same as debonding of the patch material. Precured-double patch and cure-in-place patch methods show good results in the static test. In both cases, the tensile strength was recovered to the extent of about 60–70 % of the tensile strength of the parent laminate. However, sometimes it is difficult to apply the double patch method to real structures such as an aircraft wing when patching on the inside of the skin is unsuitable. To estimate repair efficiency, a strength recovery rate is defined by the ratio of the difference between repaired and notched strength to notched strength. As flaw size increases, strength recovery rate after repair increases. In other words, the repair is more effective for large damage than for small damage. As a whole, it

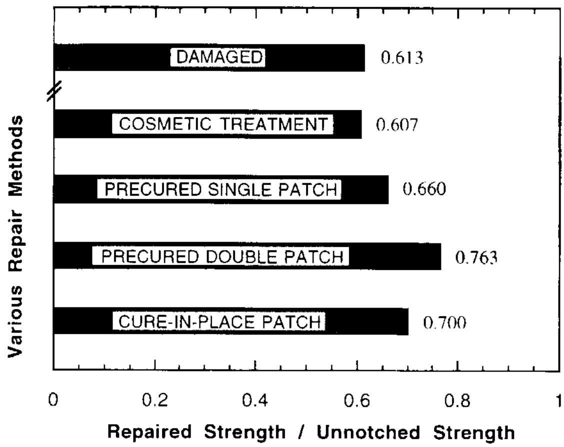

Figure 2. Strength recovery of various repair methods (r = 2 mm).

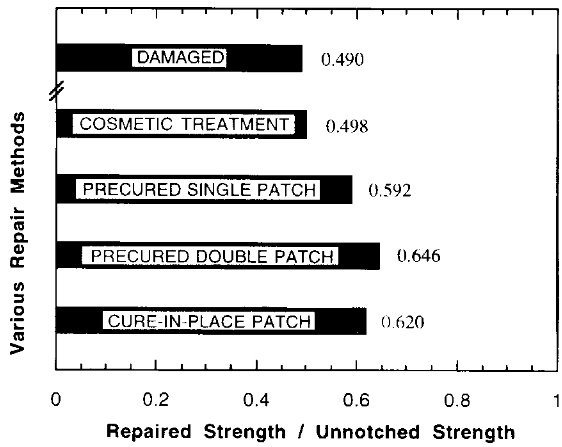

Figure 3. Strength recovery of various repair methods (r = 4 mm).

could be concluded that the cure-in-place patch method was the most effective one because it was good for strength recovery in the static test and for application to real structures and caused minimum weight increase.

For the fatigue test results of repaired specimens, fatigue life was predicted by the S–N curve, Basquin's relation and Hwang and Han's MFLPE 1. The S–N curve and Basquin's relation can be written as follows:

$$S\text{–}N \text{ curve} \qquad q = k \log N + d, \tag{8.a}$$

$$\text{Basquin's relation} \qquad \sigma_a = \sigma_f (2N)^b, \tag{8.b}$$

where N is the fatigue life, σ_a is the applied stress, q is the applied stress level, and k, d, σ_f and b are material constants.

Table 2.
Material constants and *SSR*

		$r = 1$ mm	$r = 3$ mm	$r = 4$ mm
MFLPE 1	p	0.974	1.091	1.005
	M	353.62	60.03	50.40
	B	2.672	0.158	0.993
	C	0.361	0.110	0.180
	SSR	0.1842	0.1943	0.1680
Basquin's relation	σ_f	518.18	409.09	413.22
	b	−0.017	−0.019	−0.022
	SSR	0.9784	0.3369	0.3416
S–N curve	k	−0.0324	−0.0370	−0.0440
	d	1.0386	0.9720	1.0594
	SSR	0.7827	0.3129	0.3011

To compare the accuracy of these prediction equations, the *SSR* (residual sum of squares) was defined as follows.

$$SSR = \frac{1}{n}\sum_{i=1}^{n}(\log N_{\mathrm{exp}} - \log N_{\mathrm{cal}})^2, \tag{9}$$

where N_{exp} is the experimental data, N_{cal} is the fatigue life predicted by life equations, and n is the number of data.

Table 2 presents material constants and *SSR* of life prediction equations. The value of *SSR* is smaller when predicted with MFLPE 1 than when predicted with other life prediction equations. The prediction results are compared with experimental data in Figs 4, 5 and 6 in the case of radii of 1, 3 and 4 mm, respectively. The comparison shows that fatigue life of repaired composite laminates could be predicted much better by MFLPE 1 than by the S–N curve or Basquin's relation.

The effect of flaw size on the repair was observed by comparing the fatigue life of unnotched, notched and repaired laminates. The comparison is presented in Figs 7, 8 and 9 which is the case of radius 1, 3, 4 mm, respectively. In all cases, repaired laminates exhibit higher fatigue strength. One possible explanation of this lies in the higher effective stiffness resulting from load distribution by the reinforcing patch. These figures indicate that as flaw size increases, the repair efficiency increases, which is same as for the static cases. This results from the fact that the decrease in notch effects are relatively greater in the larger flaw.

A fatigue strength reduction factor (*FSRF*) was defined to consider the fatigue strength degradation:

$$FSRF = \frac{\textit{Fatigue Strength of Notched/Repaired Composites at } N_i \textit{ Cycle}}{\textit{Fatigue Strength of Unnotched Composites at } N_i \textit{ Cycle}}. \tag{10}$$

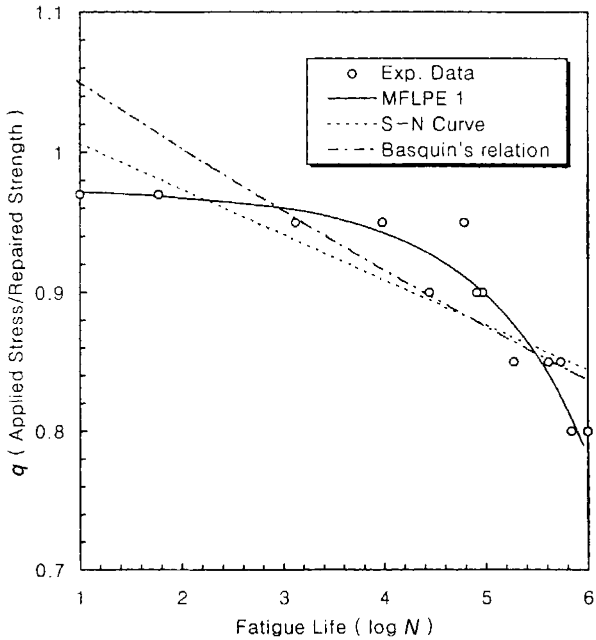

Figure 4. Comparison of MFLPE 1, S–N curve and Basquin's relation ($r = 1$ mm).

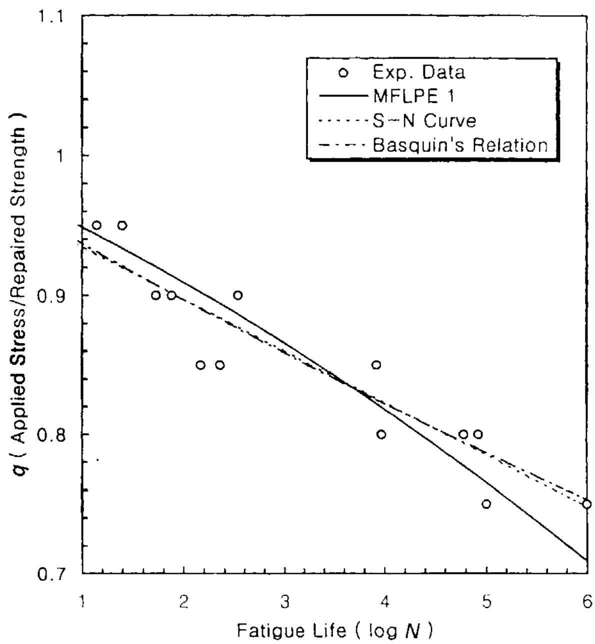

Figure 5. Comparison of MFLPE 1, S–N curve and Basquin's relation ($r = 3$ mm).

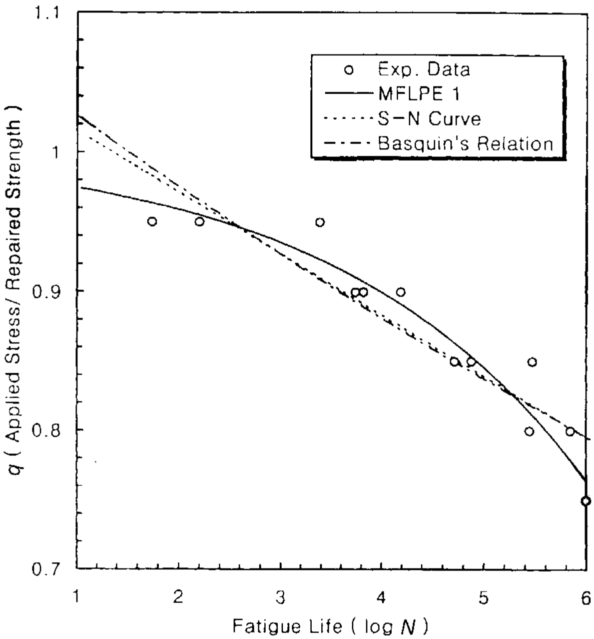

Figure 6. Comparison of MFLPE 1, S–N curve and Basquin's relation (r = 4 mm).

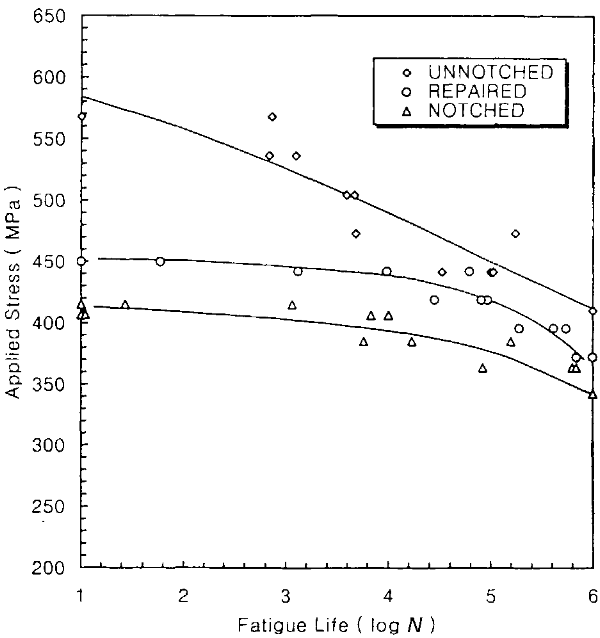

Figure 7. Comparison of fatigue life of unnotched, repaired and notched laminate (r = 1 mm).

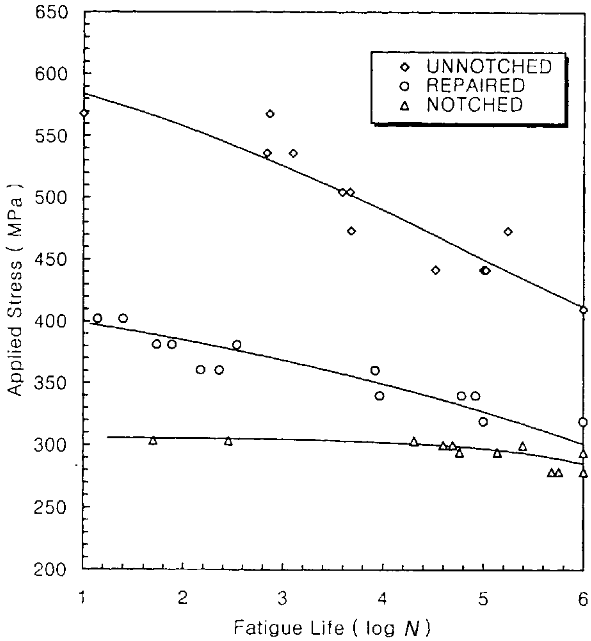

Figure 8. Comparison of fatigue life of unnotched, repaired and notched laminate (r = 3 mm).

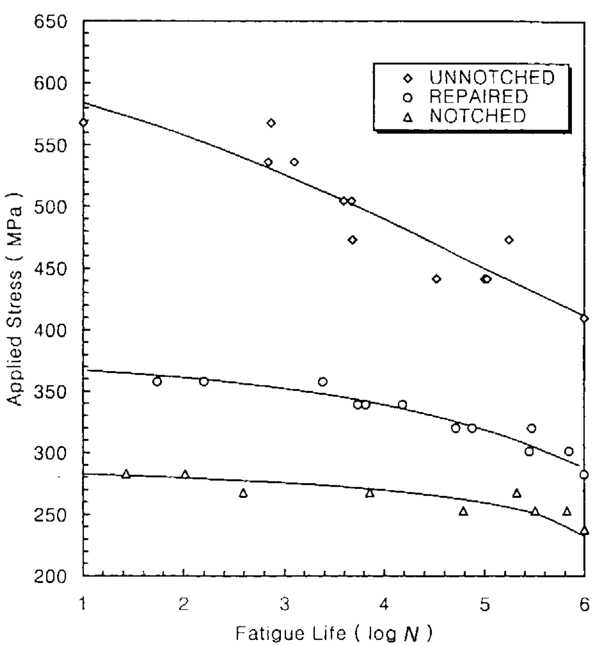

Figure 9. Comparison of fatigue life of unnotched, repaired and notched laminate (r = 4 mm).

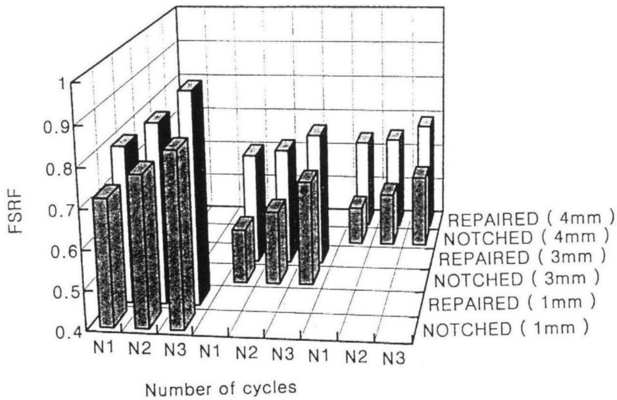

Figure 10. Fatigue strength reduction factor.

Arbitrary fatigue cycles ($N_1 = 50$ cycles, $N_2 = 2500$ cycles, $N_3 = 125\,000$ cycles) were chosen to observe the behavior of repaired composites. Figure 10 shows the comparison of *FSRF* at each arbitrary cycle. In the figure, *FSRF* of notched and repaired specimens increases with fatigue cycles, regardless of flaw size. As fatigue loading cycle progresses, the fatigue strength of notched and repaired specimens decrease, respectively. In the repaired specimens, the cure-in-place patches are debonded one by one gradually from the outer side, and finally are debonded entirely from the parent laminate about at the mid-cycle of fatigue life. Repaired laminates show a non-linear relationship between applied stress and fatigue life for these reasons. As a result, the fatigue strength degradation rate of a repaired specimen increases rapidly, so that the fatigue strength decreases in the high cycle region. However, *FSRF* of notched and repaired specimens increases with fatigue cycles because fatigue strength degradation in parent specimen is greater than in the case of notched and repaired specimens, which is caused by a stress redistribution effect [10] in notched specimen and by a reinforcing effect in a repaired specimen.

5. CONCLUSION

A cure-in-place patch method was found to be the most effective repair method among a variety of repair methods for relatively thin composite laminates. The static strength was recovered to the extent of 60–70% of that of the parent laminate. Static and fatigue strength was restored more as flaw size increased. Our own MFLPE 1 method showed better agreement with experimental data than conventional curves because the repaired laminate shows non-linear fatigue behavior. The non-linear behavior of a repaired laminate is caused by gradual debonding of the reinforcing patch from the parent laminate. A fatigue strength reduction factor (*FSRF*) can be used in evaluation of fatigue strength degradation of composite laminates. In this study, *FSRF* increased with fatigue cycles in both notched and repaired laminates by stress redistribution and by a reinforcing effect, respectively.

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