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Fatigue strength of adhesive bonded aluminum joints

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Fatigue strength of adhesive bonded aluminum joints

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San Jose State University, 1992

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**FATIGUE STRENGTH OF ADHESIVE BONDED
ALUMINUM JOINTS**

A Thesis

Presented to

The Faculty of the Department of Mechanical Engineering

San Jose State University

In Partial Fulfillment

of the Requirements for the Degree

Masters of Science

By

Weiming Li

December, 1992

**APPROVED FOR THE DEPARTMENT OF
MECHANICAL ENGINEERING**

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ABSTRACT

FATIGUE STRENGTH OF ADHESIVE BONDED ALUMINUM JOINTS

by Weiming Li

The present study involves the assessment of fatigue strength of the bonded joints. Patched coupon specimens made of aluminum alloy were tested under oscillating bending load. Sharp grooves were made on the surfaces of the coupon specimens beneath the patches to simulate the cracks in the turbine blades. Failures in form of patch delimitation were detected. Evidence concludes that patching has significantly increased the average fatigue life of specimen. Simultaneously, a computer analysis of stress was conducted. On the bases of experimental results and the stress analyses, an easy-to-use method for estimating the fatigue life of the adhesive bonded joints was developed. The application of the results of this research will assist field engineers to select appropriate patching scheme for large vertical wind turbine blades with an anticipated extension of the life span.

Acknowledgements

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1. Introduction

Wind power has been proven to be a viable energy source in certain regions in the world. This form of energy is renewable and can be produced without polluting the environment, or posing any threat to human health. Production of electricity using wind energy has been shown to be commercially viable by a leading industry-FloWind Co. in California, U.S.A.

There are two types of wind turbines used to produce electrical power: horizontal axis wind turbine (HAWT) and vertical axis wind turbine (VAWT). Photographs of VAWT operating at the Pleasanton site, in California are shown in Fig. 1.

The VAWT produces larger per unit output than that by the HAWT. The typical size of VAWT can be as high as 60 feet with a working diameter of 60 feet. The blades are made of aluminum alloy. All blades have airfoil cross-sections which have concave curvatures towards the center axis. These blades are subjected to enormous mechanical loading during spinning. Cracks and flaws were observed on the surfaces of some blades due to repeated mechanical loading [1]. Since initiation of new flaws is an unavoidable outcome of the operation, developing of existing cracks, however, must be retarded in these areas in order to prevent overall failure of the blade structure. One remedial solution was tried by the FloWind Corporation, which involved the patching of the flawed areas of the blades by attaching square pieces of aluminum plates bolted along the edges to the base blade material (Fig.2). A thorough study by Dr. Liniecki and his students in SJSU in 1990 found that such a solution actually made the situation worse as a significant amount of stress concentration was induced by the bolt holes in the

Fig. 1 Vertical axis wind turbine (VAWT)

Fig. 2 Bolted patch

patched sections. The many bolts needed to patch the cracked surface also increased the weight of the blades.

A new concept of patching the flawed sections was developed. It consists of attaching aluminum patches over the flawed blade surfaces by using adhesives such as epoxy resin. The advantages of bonding relative to the mechanical fastening of reinforcements, such as riveting and bolting, have been recognized [2, 3]. However, the reliability of adhesive bonded patches in the field application requires thorough studies of the mechanical behavior of the patched joints subject to all conceivable loadings.

Most of the previous studies on the strength behavior of adhesive joints have been conducted by using lap joints under static loading. Information is limited on their fatigue behavior, which is considered to be important for practical applications.

The objective of the present research is to evaluate the fatigue bending strength of adhesive bonded aluminum patches, and to develop an easy-to-use method for selecting adhesive and estimating the fatigue life of adhesive bonded patches for VAWT blades by field engineers with an anticipated extension of the life span.

This study is based on the fatigue strength of adhesively patched aluminum coupon under repeated bending moments following sinusoidal functions, and the stress distribution in the adhesive layer. Sharp notches were introduced on the surfaces of aluminum coupon specimens beneath the patches to simulate the cracks in the turbine blades. Experimental results confirmed that the patches did in fact significantly extend the life span of cracked blade. The effects of temperature and moisture on the fatigue strength of the patched specimens, however, were not included.

2. Fatigue Tests

2.1 Testing Facility

A Wiedeman (Baldwin) universal fatigue testing machine was used for the fatigue bending tests of aluminum specimens. This machine consists of a sturdy chassis and a suspended moving load train, or oscillator. Repeated mechanical loading on the specimens is provided by the vertical motion of the oscillator. The centrifugal force of this rotating mass causes the train to oscillate in the vertical direction (Fig. 3). The number of loading cycles is counted by a counting meter located at the upper right corner of the machine (Fig. 4a and Fig. 4b). When the specimen is broken, the machine will stop automatically, thus recording the number of failure cycles to failure for the specimen.

2.2 Specimens

All specimens were made of 6061-T6 aluminum alloy. The geometry and dimensions of the specimens are shown in Fig. 5. There were three types of specimens used in the tests:

- a. plain specimen
- b. specimen with notches cut at both surfaces
- c. notched specimen with thin aluminum patches.

The size of patch is 1" x 1", and the thickness of patch, t , is 0.020". The thickness of adherend, T , is 0.125".

The patch and the plate surfaces were subjected to finish abrading with silicon-carbide paper, and were cleaned carefully by using a degreaser prior to bonding. The adhesive resin is Hysol 9394 epoxy resin. A curing period of 5 days at room temperature was observed, as recommended by the manufacturer.

a) Testing system set-up

b) Specimen

Fig. 3 Schematic Diagram of Fatigue Bending Testing

a) The Universal Fatigue Testing Machine

b) Control Panel and Cycle Counter

Fig. 4 The Sonntag Universal Fatigue Testing Machine

Fig.5 Geometry and Dimensions of Patched Specimens

2.3 Peeling Detection

Since the maximum peeling stress and shear stress occur at the bonding edges [4-6], peeling of patches is expected to initiate at those edges. A unique scheme was thus developed to detect such peeling. As illustrated in Fig. 6, a closed circuit between the aluminum patches and the base plate (adherend) was constructed with the aid of metal paints which conduct electrical current through the circuit. The voltage u_0 is zero when the circuit is intact. However, when anyone of the edges of patches is debonded (i.e., disconnecting of any one of the silver paint joints), a surge of voltage, $E/6$ (Fig. 6), would be detected by the computer which is counting the cycles based on the signal from the accelerometer attached to the machine. This signal will make the computer stop counting and record the number of cycles at which the patch begins to peel off the specimen. Appendix A is the signal flow chart (computer program) for the data acquisition system. A low pass filter was used in the control circuit to improve the reliability of the system.

2.4 Fatigue Test

Three types of tests were conducted. These are:

- (1) fatigue strength of aluminum specimens without notch and without patch;
- (2) fatigue strength of notched aluminum specimens;
- (3) fatigue strength of notched aluminum specimens with aluminum patches.

The frequency of load was set at 30 Hz. During the test, the aluminum specimen was clamped to the bending rigs as illustrated in Fig. 3 and Fig. 7. The fatigue strength of the specimen was recorded by the counter of the fatigue testing machine, and the peeling strength of adhesive bond was recorded by the computer through signals from both the accelerometer attached to the top of the oscillator (counting signal) and the close circuit as mentioned above (control signal).

Four different thicknesses of adhesive bond, $t = 0.01"$, $t = 0.02"$, $t = 0.04"$ and $t = 0.06"$, were tested. It was observed that in the cases of $0.06"$ in thickness, one of the patches of specimen fell off at a very early stage of the fatigue test. In other words, the specimens were under testing with only one patch bonded on it. For $t = 0.06"$, debonding always occurred at the interface of adhesive bond and adherend. This is due to high stiffness of the thick adhesive bond. On the other hand, the fatigue strength for this thickness appeared to be the weakest among those four. Therefore, the thickness of $0.06"$ is not recommended for adhesive bonds.

Fig. 6 Schematic Arrangement for Detecting the Peeling Fatigue Strength of Bonded Patches

a) Fatigue Testing for Patched Specimen (wires are for detecting peeling of patches)

b) Circuit for Detecting Peeling of Patches

Fig. 7 Fatigue-Fracture Testing of Specimens with Patches

3. Results

More than 80 specimens were tested. Figure 8 shows applied bending moments (M) vs. number of cycles to failure (N) relationship of the patched joints under repeated bending load. As expected, the solid specimens had shown to be the strongest (the far right curve) and the unpatched specimens with notches were the weakest (the far left curve). Between these two extreme cases were those specimens with patches joined to the notched specimens by adhesive. All test data are presented in Appendix B. Evidence concludes that patching has significantly increased the average fatigue life of the specimen. Adhesive thickness varying from 0.01" to 0.04", however, showed little effect on the patch performance. This observation is in agreement with similar studies conducted by other researchers [3, 7]. No peeling was detected before the specimen failure in the cases of adhesive thickness of 0.01" and 0.02" under a loading above 75 in-lb, as P. Poole and D. Lock observed during their experiments [3]. However, peeling did occur prior to the overall failure of the specimen at lower loading . For an adhesive layer with 0.040" in thickness, the peeling failure consistently occurred before the specimen was broken. The difference between the peeling strength of adhesive bond and the fatigue strength of specimen became more evident as the load decreased (Fig. 8). Another interesting observation was that peeling started at the one end of the patch and propagated towards the other end until the patch fell off.

Fig. 8 Experimental Data

4. Stress Analysis

4.1 Finite Element Stress Analyses

In order to investigate the relationship between the fatigue strength of adhesive joints and the stress distribution of the adhesive layer, the stress analysis of the system was conducted using two-dimensional finite element method. A static plane strain analysis was applied. The computer program used in this research was called ANSYS. Figure 9 illustrates the finite element mesh for the joint under repeated bending loads. Figure 10 shows more detail at the center of the model where notches are located. The material properties used in this analysis

Fig. 9 Finite Element Mesh Used in Stress Analysis

are as follows:	Young's modulus:	400 kpsi	for adhesive
		11500 kpsi	for adherend
	Poisson's ratio:	0.42	for adhesive
		0.30	for adherend

The results of the analysis of the notched aluminum coupons without patches revealed that, due to the stress concentration at the tip of the notches, the computed resultant stress of 117 kpsi was found to be well above the yield strength of aluminum.

The results of the analyses of the notched aluminum coupon with patches showed a dramatic reduction of the stress. The resultant stress was computed to be 31.5 kpsi. However, there were significant stresses (shear and peel) in the epoxy bond at the ends of the patches. Figure 11 and Figure 12 show the stress distributions in the epoxy bond. The figures are plotted along the epoxy bond, covering from the center to the end of the path (along the length of the specimen). Table 1. illustrates the computed maximum shear stresses, $\tau_{\max}$, under various applied bending moments.

Table 1. Computed maximum shear stress under static bending moments

M \ t	0.010"	0.020"	0.040"
40	1565 psi	1191 psi	854.5 psi
50	1956 psi	1488 psi	1086 psi
60	2348 psi	1785 psi	1282 psi
75	2911 psi	2214 psi	1462 psi
90	3521 psi	2679 psi	1923 psi

t: thickness of adhesive bond (in)

M: Applied moment (in-lb)

4.2 Verification of the Results of Finite Element Analyses

The credibility of the finite element stress analysis was tested by the measurement of static strain on a patched specimen. The measured data was compared with the finite element result. The measurement was carried out by using a M-M ED-DY-031DE-350 strain gage at the center of top patch. Figure 13 shows the scheme of the measurement and the measured data. In the mean time, a finite element computation was conducted on the same structure under the same

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Fig. 10 Finite Element Mesh Model at Notched Location

Fig. 11 Shear Stress in 0.010 inch Thick Bond

Fig. 12 Peeling Stress in 0.010 inch Thick Bond

The thickness of aluminium patches: 0.020"

The thickness of adherend: 0.125"

Fig. 13 Measurement of Static Strain on Patched Specimen

applied loads in the measurement. The computed results and measured data are presented in Table 2.

Table 2 Comparison of computed results and measured data

Applied Moment	Computed Strain ($\mu\epsilon$)		Measured Strain ($\mu\epsilon$)	
	Adhesive thickness $t = 0.01"$	Adhesive thickness $t = 0.04"$	Adhesive thickness $t = 0.01"$	Adhesive thickness $t = 0.04"$
40 (in-lb)	760	471	858	808
60 (in-lb)	1,370	870	1,425	1,316

From Table 2 it can be seen that the computed results and measured data are very close when $t = 0.01"$. Noticeable differences in results are observed for $t = 0.04"$. These differences may be due to the uncertain properties of the adhesive used in the finite element model as these properties were supplied by the manufacturer. Thicker layer of adhesive had more effect on the analytical results. This effect became negligible when t is small. For the purpose of this study, the computed results were regarded as adequate.

5. Discussion

From the Fig. 8, it is obvious that the patches did serve the intended purpose of retarding the fatigue crack growth rate significantly. The same figure also indicates that the fatigue life of a patch was not strongly influenced by the thickness of adhesive bond. Observation on the experimental results showed that in most cases of patch failure, the patches were debonded at the interface of the patch and

adhesive when the thickness of adhesive bond is 0.010", whereas for the thickness of 0.040", most of the debonding occurred at the interface of adhesive and adherend. For the case of bond thickness of $t = 0.02$ ", debonding occurred either at the interface of the adhesive and the adherend, or at the interface of patch and adhesive. This observation suggests that the local shear stress dominates the patch failure when adhesive layer is thin. On the other hand, when the thickness of the layer is increased, the peeling stress becomes a strong contributing factor to the patch failure due to higher stiffness of adhesive bond.

Finite element analysis shows that the maximum shear stress in the adhesive is larger when $t = 0.010$ " than in the case in which $t = 0.040$ ". Therefore, when t is small, the relatively larger associated maximum shear stress cause a larger area of failure in adhesive. In contrast, at high t values, the load transfer efficiency is reduced due to the lower shear stress. This results in a reduction of fatigue life [7, 8]. This is one of the reasons why, for example, under 50 in-lb loading the $\tau_{\max}$ is 1956 psi for $t = 0.01$ ", and $\tau_{\max}$ was reduced to 1086 psi for $t = 0.04$ " under the same applied bending load, but this reduction resulted in little change of the fatigue life of the materials (Fig. 8).

6. Derivation of Fatigue Strength Equation

6.1 Derivation of Fatigue Strength Equation

To assist engineers in their design of adhesive bonded repair of aluminum plate, it is necessary to develop a mathematical description of those test results . Fig. 14 shows $M - N$ fatigue strength curves in logarithm scale with different thickness of adhesive bond (M is applied moment, and N is number of cycles to failure). There are some minor differences among those three curves due to varying adhesive thickness. All three curves have sharp knees, which occur at approximately 3.0×10^7 cycles. Since the shapes of the three curves are almost identical, one may look at the curve of $t = 0.010$ " first (Figure 14). It can be seen that the relationship between $\log M$ and $\log N$ is linear form 10^3 to about 3.0×10^7 cycles, whereas from about 3.0×10^7 and greater, M remains constant at a value M_e , i.e. the endurance limit.

It is an established fact that the maximum shear stress in an adhesive layer varies according to the size of patch [9], hence, the applied moment M can not be employed as a parameter to estimate the fatigue strength of the joint. Therefore, the maximum shear stress in the patched joints should be used as the parameter.

The functional relationship between the maximum share stress $\tau_{\max}$ (Table 1) and the number of cycles to failure, N can be established by using the *least squares* fit method. Here, the $\tau_{\max}$ is the computed maximum shear stress in the adhesive bond corresponding to an applied bending moment.

If we let:

$$Y = \log(\tau_{\max}) \qquad X = \log(N)$$

Fig. 14 M - N Diagram

and use the data presented in Table 1 and Appendix B, a new set of data is established as shown in Table 3.

Table 3. The computed data

$Y = \log(\tau_{\max})$	$X = \log(N)$	X^2	XY	Y^2
3.547	4.041	16.333	14.333	12.581
3.547	4.279	18.308	15.178	12.581
3.547	4.362	19.025	15.472	12.581
3.464	4.845	23.475	16.783	11.999
3.464	4.813	23.164	16.672	11.999
3.464	4.919	24.197	17.039	11.999
3.371	5.539	30.681	18.670	11.364
3.371	5.694	32.419	19.193	11.364
3.371	5.766	33.252	19.435	11.364
3.293	6.426	41.298	21.163	10.844
3.293	6.548	42.870	21.565	10.844
3.293	6.344	40.249	20.893	10.844
3.246	6.907	47.712	22.420	10.537
3.246	6.997	48.955	22.712	10.537
3.246	7.231	52.283	23.412	10.537
$\Sigma Y = 50.763$	$\Sigma X = 84.711$	$\Sigma X^2 = 494.221$	$\Sigma XY = 284.94$	$\Sigma Y^2 = 171.96$

Following the principle of the *least squares method* [10], we have a linear regression relationship between $\log(\tau_{\max})$ and $\log(N)$ for the range of $N = 10^3$ to $N = 3.0 \times 10^7$ as:

$$\log \tau_{\max} = a \log N + C \quad (1)$$

where

$$a = \frac{n \sum XY - \sum X \sum Y}{n \sum X^2 - (\sum X)^2}$$

$$C = \frac{\sum Y}{n} - a \frac{\sum X}{n}$$

$n = 15$

substitute the values given in Table 2 into the above equations we have:

$$a = -0.11$$

$$C = 4$$

Eq.(1) thus becomes:

$$\log \tau_{\max} = -0.11 \log N + 4 \quad (2)$$

or

$$\tau_{\max} = (N^{-0.11})10^4 \text{ (psi)} \quad (3)$$

Graphic representation of equation (2) is shown in Fig. 15.

Fig. 15 $\log(\tau_{\max})$ - $\log(N)$ Diagram

6.2 Analysis of Variance (F-Test)

The total variation in Y in terms of sum of the squares is $\sum (Y_i - Y_a)^2$, which can be partitioned into the unexplained variation and the variation attributable to X .

Here Y_i are the measured values and $Y_a = (\sum Y_i)/n$ [10, 11]. The purpose of the F-test is to verify that there is a linear relationship between Y and X . That is: actually in the relationship

$$Y = a X + C$$

a has a non-zero value.

Testing for $a = 0$ with a Type I risk of 0.05 by using an F-distribution with 1 and 13 ($15 - 2 = 13$) [10, 11] degrees of freedom requires:

if

$$F = \frac{\sum (Y - Y_a)^2}{\sum (Y_i - Y)^2} (n - 2) > 4.6672$$

then

$$a \neq 0$$

i.e., there is a linear relationship between Y and X [10, 11]. Otherwise, $a = 0$.

Since

$$\sum (Y - Y_a)^2 = a \left[\sum YX - \left(\frac{1}{n} \right) \sum X \sum Y \right] \quad (a = -0.11)$$

$$\sum (Y_i - Y)^2 = \left[\sum Y^2 - \left(\frac{1}{n} \right) (\sum Y)^2 \right] - a \left[\sum YX - \left(\frac{1}{n} \right) \sum X \sum Y \right]$$

substitute values from Table 3 into above equations, the result is:

$$F = \frac{0.191 \times 13}{0.0122} = 203.53 > 4.6672$$

A linear relationship between $\log(\tau_{\max})$ and $\log(N)$ has thus been established.

6.3 Standardization of Fatigue Strength Equation

Equation (3) is valid only for the case of $t = 0.010$ " as it does not include the effects of varying the thickness of the adhesive bonds. However, as we have already established the fact that the thickness of adhesive has an insignificant effect on the fatigue strength of the patched joints, Equation (3) can still be used as the basis for the cases involving other adhesive thickness. In order to apply this equation in the field application, the scope of its usage must be extended.

From Fig. 14 and Table 1, it can be seen that the $\tau_{\max}$ decreases as the adhesive thickness increases, but with only slight change in the fatigue life of the specimen. In order to consider these effects, two new parameters, α and β will be adopted to Eq.(3):

$$\tau_{\max} = \alpha^1 (\beta N)^{-0.11} 10^4 \quad (3)$$

where

$$\alpha = \frac{\text{Max. shear stress in adhesive for } t = 0.01"}{\text{Max. shear stress in adhesive at a different thickness}}$$

$$\beta = \frac{\text{Number of cycles to failure for } t = 0.01"}{\text{Number of cycles to failure at a different adhesive thickness}}$$

(1) The α -values:

The values of α can be derived on the basis of finite element stress analyses. From Table 1, take the values of $\tau_{\max}$ for $t = 0.010$ " and divide it by corresponding values of those for $t = 0.020$ " under the same loading conditions, such that:

$$\frac{1565}{1191} = 1.314; \quad \frac{1956}{1488} = 1.315; \quad \frac{2348}{1785} = 1.315; \quad \frac{2911}{2214} = 1.315; \quad \frac{3521}{2679} = 1.314$$

from which, we establish that

$$\alpha_{0.02} = 1.315$$

In the same way, we can find

$$\alpha_{0.04} = 1.857$$

(2) The β – values

The values of β can be found from the experimental results. Take the average N-values under all tested loading conditions for $t = 0.01''$, and divide them by the same values for those under the same conditions but for $t = 0.020''$. Then we will have:

$$\frac{17667}{15634} = 1.13; \quad \frac{72667}{36667} = 1.982; \quad \frac{474667}{359667} = 1.32; \quad \frac{2802000}{1725334} = 1.624; \quad \frac{11672376}{8967333} = 1.302$$

The arithmetic average of the above values is:

$$\frac{(1.13 + 1.982 + 1.32 + 1.624 + 1.302)}{5} = 1.472$$

So we have:

$$\beta_{0.02} = 1.472$$

In the same way, we can get:

$$\beta_{0.04} = 0.785$$

Both α and β values can be summarized as shown in Table 4.

Table 4. Values of α and β

	$t = 0.010''$	$t = 0.020''$	$t = 0.040''$
α	1.000	1.315	1.857
β	1.000	1.472	0.785

(3) Normalization of fatigue strength equation

Since the fatigue strength of patched blade also depends on the static shear strength of adhesive agent, the Eq.(3) should be normalized with τ_{st} , i.e.:

$$R = \alpha^{-1} (\beta N)^{-0.11} \times 10^4 \quad (3')$$

where:

$$R = \frac{\text{Calculated maximum shear stress in adhesive}(\tau_{\max})}{\text{Maximum static shear strength of adhesive supplied by manufacturer}(\tau_{st})}$$

$$= \frac{\tau_{\max}}{\tau_{st}}$$

is called *maximum shear stress ratio*.

In this study, the maximum static shear strength of Hysol 9394 epoxy resin is 4,200 psi at 77 F°. The graphic relationship between $\log(R)$ and $\log(N)$ shown in Fig. 16 is obtained by substituting this value into Eq.(3') .

7. Field Applications

7.1. Equivalent Stiffness Ratio

The results derived above can not be used for field application in present form as the geometry and dimensions of the VAWT blade structure in the field is

Fig. 16 Log(R) - Log(N) Diagram

substantially different from the coupon samples used to derive the above equations. The stress which would be transmitted by the patch at the location of the crack depends primarily on the *stiffness ratio* S [8, 12]; therefore, the equivalent stiffness ratio S_e can be used as a mechanistic correlation of these two types of structures.

The cross section of patched coupon specimen is illustrated in Fig. 16. It is a multimaterial laminated structure which has five layers of material. For this structure, the bending stress is given by [13]:

$$\sigma = \frac{Mc}{Z} \quad (4)$$

where

$$Z = \frac{EI}{E_c} \quad (5)$$

Z is the equivalent section stiffness, c is the distance from the neutral axis to the location where σ is to be calculated, E_c is the modulus of the material at distance c from the neutral axis, and $EI = E_1I_1 + 2E_2I_2 + 2E_3I_3$ is the overall flexural rigidity [13] (I_i represent properties for the components with respect to the neutral axis).

Fig. 17 Cross-Section of Patched Coupon Specimen

The adhesively bonded aluminum patch repair of the wind-turbine can also be treated as a laminated composites structure. It is known that, as illustrated in Fig. 17, the cross- section of patched wind-turbine blade (Fig. 17(a)) can be converted into an equivalent multimaterial laminated beam cross section (Fig. 17(b)). Also, this equivalent section has five layers of material (Fig. 17(b)).

Fig. 18 Cross-Section of Patched Wind-Turbine Blade

Assume the same magnitude of stress in adhesive bond causing fatigue damage in both the coupon specimen and the wind-turbine, that is:

$$\sigma_s = \frac{c_s M_s}{Z_s} = \frac{c_w M_w}{Z_w} = \sigma_w \quad (6)$$

The subscripts *s* and *w* in the Eq. (6) denote specimen and wind-turbine blade, respectively. For example, σ_s is the stress in the adhesive bond of specimen, and σ_w is the stress in the adhesive bond of VAWT-19 blade. Here, c_s and c_w are the distance from the neutral axis of the cross section to center line of the adhesive bond (Fig. 17).

Substitute Eq. (5) into Eq. (6), and rearrange the equation, we have:

$$\frac{M_s}{M_w} = \frac{c_w Z_s}{c_s Z_w} = \frac{c_w (E_s I_s / E_{cs})}{c_s (E_w I_w / E_{cw})} \quad (7)$$

where:

M_s is the moment applied on the specimen;

M_w is the moment applied on the blade in the field.

If the same type of bonding agent is used for both the coupon specimen and the blade, the values of E_{cs} and E_{cw} will be the same. So, Eq.(7) becomes:

$$\frac{M_s}{M_w} = \frac{c_w E_s I_s}{c_s E_w I_w} = \frac{c_w}{c_s} S_e \quad \text{or} \quad \frac{M_s}{M_w} = \frac{c_w}{c_s} S_e \quad (8)$$

where

$$S_e = \frac{E_s I_s}{E_w I_w} \quad (9)$$

is called *Equivalent Stiffness Ratio*.

7.2 Field Applications

When designing a real structure, engineers require prior knowledge of:

- maximum anticipated bending load;
- type of bonding agent;
- geometry of the cross section of the blade;

then:

- 1). choose patches over the crack surface, with: patch size, patch thickness t_{wp}

and adhesive thickness t_w , and determine c_w ; calculate $k = \frac{t_{wp}}{t_w}$;

- 2). evaluate the overall flexural rigidity, $E_s I_s$, of coupon specimen with a thickness of adhesive, t : for $k \geq 2.0$, choose $t = 0.01$ "; for $2 > k > 0.5$,

- choose $t = 0.02"$; for $k < 0.5$, choose $t = 0.04"$; and determine c_s [13];
- 3). determine the anticipated fatigue life for the wind turbine, and conduct a finite element stress analysis of the patched blade structure to find the maximum shear stress in adhesive bond;
 - 4). calculate the value of R , and use Eq.(3') to check if this value meets the desired fatigue life; if not, change the patch size and do the calculations again;
 - 5). with the maximum shear stress found above, use Table 1 to find the corresponding moment for the coupon specimen;
 - 6). use Eq.8 to find required value of equivalent stiffness ratio S'_e ;
 - 7). calculate equivalent stiffness of wind-turbine cross section so that (Fig. 18) :

$$I'_{w1} = I'_{we1}$$

- 8). evaluate the overall flexural rigidity, $E_w I_w$, of patched section of blade ($E_w I_w = E_{w1} I'_{we1} + 2E_{w2} I'_{we2} + 2E_{w3} I'_{we3}$), and use Eq. (8) to calculate the value of equivalent stiffness ratio S_e ;
- 9). if: $S_e = S'_e$, then the design is satisfied; otherwise, modify the structure by changing the parameters, and repeat some of the calculations mentioned above till the results are satisfactory.

Appendix C illustrates a numerical example of designing a patched wind turbine blade.

8. Conclusions

1. Adhesively bonded aluminum patches dramatically increased the fatigue life of 0.125" thick aluminum alloy plate specimen containing sharp notches.
2. Varying adhesive thickness had a minor effect on patch performance. When adhesive thickness is small, the shear stress is the key factor for failure of the joint. But when adhesive thickness increases, the peeling stress will contribute more to the failure of the structure.
3. An easy-to-use mathematical description of the relationship between the maximum shear stress, τ_{max} and cycles to failure, N is derived by using the *least squares method*. This description is very close to the real world because it is based on both experimental results and finite element stress analyses. It is proposed to use this description in field applications to estimate fatigue life of the adhesively bonded aluminum patch repair of wind turbine blade, and to assist engineers to select an appropriate patching scheme for large vertical wind turbine blades with an anticipated extension of the life span.

9. Recommendation

It is recommended that the research be continued since many studies have revealed that the environmental conditions, such as temperature and moisture, influence the performance of adhesively bonded patches [1, 7, 14], so that the effects of those factors could be included in the Eq. (3), which will extend the scope of using this equation.

References

1. P. S. Veers, " Simplified Fatigue Damage and Crack Growth Calculations For Wind Turbines ", Proceeding of The Eighth ASME Wind Energy Symposium, SED-Vol. 7, ASME, January 1989.
2. A. A. Baker, R. Jones, " Bonded Repair of Aircraft Structures ", Martinus Nijhoff Publishers, 1988.
3. P. Poole, D. Lock, A. Young, " Composite Patch Repair of Thick Aluminium Alloy Sections ", Proceedings of International Conf. on Aircraft Damage and Repair, Melbourne, August 1991, pp 85-91.
4. R. W. Cornell, Windsor Locks, " Determination of Stresses in Cemented Lap Joints ", Journal of Applied Mechanics, September 1953, pp 355-364.
5. Toshio Hattori, " A Stress-Singularity-Parameter Approach for Evaluating the Adhesive Strength of Single-Lap Joints ", JSME International Journal, Series I, Vol. 34, No. 3, 1991, pp 326-331.
6. E. D. Reedy, Jr., and T. R. Guess, " Tubular Lap Joints For Turbine Applications: Test And Analysis ", 10th ASME Wind Energy Symposium, SED-Vol. 11, ASME 1991, pp 355-364.
7. Poole P., Stone M.H. and Sutton G.R. " Effect of Adhesive Bonding Variables on the Performance of Bonded CFRP Patch Repairs of Metallic Structures ". AGARD Conference Proceedings No.402, 1986, pp 9.1-9.21.
8. L. R. F. Rose, "Basic Concepts in Assessing the Efficiency of Bonded Repairs ", Proceedings of International Conf. on Aircraft Damage and Repair, Melbourne, August 1991, pp 202-208.
9. M. Imanaka, W. Kishimoto, K. Okita, H. Nakayama and H. Nagai, " Fatigue Life Estimation of Adhesive Bonded Shaft Joints ", International Journal of Fracture, Vol. 41, 1989, pp. 223-234.
10. E. P. Hickman and J. G. Hilton, " Probability and Statistical Analysis ", Intext Educational Publishers, USA, 1971, pp 257-275.
11. J. D. Chen, W. Liu and K. R. Wang, " Statistical Analysis ", People's Publishers, PRC, 1980.

12. Rose, L.R.F., Int J. Solids Structures, Vol. 17, 1981, pp 827-838.
13. J. H. Faupel, " Engineering Design ", John Wiley and Sons Inc., New York, 1964.
14. J. D. Venables, D. K. Mcnamara, J. M. Chen, B. M. Ditchek, and T. I. Morgenthaler, " Effect of Moisture on Adhesively Bonded Aluminium Structure ", 12th National Tech. Conf., Oct 1980, 909-23, Society for the Advancement of Material and Process Engineering.

APPENDIX A

Signal Flow Diagram of Data Acquisition System

APPENDIX B
Experiment Data

Specimen No.	Applied Moment (lb-in)	Broken Cycles N	Peeling Cycles N _p	Average Peeling/Broken Cycles
38	90	11,000	10,807	17,063/17,667
48	90	19,000	18,167	
49	90	23,000	22,214	
32	75	70,000	69,662	71,460/72,667
33	75	65,000	62,587	
34	75	83,000	82,132	
30	60	346,000	208,283	427,945/474,667
29	60	494,000	492,000	
31	60	584,000	583,551	
35	50	2,669,000	1,619,229	1,975,372/2,802,000
36	50	3,528,000	2,104,109	
37	50	2,209,000	2,202,777	
47	45	8,080,000	8,078,714	9,809,945/11,672,376
50	45	9,926,900	5,446,249	
51	45	17,010,228	115,904,873	
51A	40			Not Broken at 19,000,000 Cycles
51B	40			

1). Specimens: patched coupon specimens with epoxy layers of 0.01" in thickness.

APPENDIX B (2)
Experiment Data

Specimen No.	Applied Moment (lb-in)	Broken Cycles N	Peeling Cycles N _p	Average Peeling/Broken Cycles
52	90	16,900	16,101	15,234/15,634
55	90	10,000	9,600	
57	90	20,000	20,000	
53	75	48,000	47,563	36,116/36,667
59	75	26,000	25,172	
60	75	36,000	35,612	
65	60	310,000	233,893	303,474/359,667
66	60	401,000	366,530	
67	60	368,000	310,000	
61	50	1,317,000	1,071,281	1,479,396/1,725,334
63	50	1,545,000	1,053,113	
64	50	2,314,000	2,313,793	
54	45	5,447,000	4,089,885	4,960,516/8,967,333
56	45	7,505,000	7,502,421	
62	45	13,950,000	3,289,241	
62A	40	Not broken at 18,994,000 cycles		

2). Specimen: patched coupon specimens with epoxy layers of 0.02" in thickness.

APPENDIX B (3)
Experiment Data

Specimen No.	Applied Moment (lb-in)	Broken Cycles N	Peeling Cycles N _p	Average Peeling/Broken Cycles
73	90	29,000	27,000	20,088/22,300
79	90	23,900	23,516	
80	90	14,000	10,107	
68	75	76,000	43,962	69,016/93,000
72	75	112,000	103,123	
81	75	91,000	60,962	
77	60	422,000	380,192	392,438/465,000
78	60	590,000	421,109	
82	60	383,000	376,013	
74	50	1,985,000	11,107,000	1,160,028/5,303,667
75	50	7,713,000	481,416	
76	50	6,213,000	1,891,667	
69	45	17,161,000	2,813,192	3,002,462/14,527,000
70	45	16,325,000	3,121,102	
71	45	10,095,000	3,073,091	

3). Specimen: patched coupon specimens with epoxy layers of 0.04" in thickness.

APPENDIX C

A Numerical Example of Designing a Patched Wind Turbine Blade

This is an example of designing adhesively bonded patches over the VAWT-19 wind turbine blade.

Figure 18 illustrates the cross-section of VAWT-19 blades manufactured by FloWind Corporation in California. From their air foil design data (19m VAWT), the stiffness of equivalent cross-section, I'_{we1} is 34.3 in^4 (Fig. 18).

Fig. 19 Cross-Section of VAWT-19 Blade & Its Equivalent Section

Suppose: $M_w = 290,000 \text{ (in-lb)}$ $E_{w1} = E_{w3} = E_1 = E_3 = 11.5 \times 10^6$

- 1). Select Hysol 9394 epoxy resin as adhesive agent for the structure,

i.e. $E_{w2} = E_2 = 0.40 \times 10^6$

From the information supplied by the manufacturer, the shear strength of 9394 epoxy resin at room temperature is: $\tau_{st} = 4,200$ psi.

- 2). Choose patch thickness t_{wp} , and adhesive thickness t_w , for the wind turbine:

$$t_{wp} = 0.25"; \quad t_w = 0.09".$$

- 3). Since: $k = \frac{t_{wp}}{t_p} = \frac{0.25}{0.09} = 2.8 > 2$

select the coupon specimen with a thickness of 0.010 in. Then, its overall rigidity:

$$E_s I_s = E_1 \frac{1 \times 0.125^3}{12} + 2E_2 (1 \times 0.01 \times 0.0675^2 + \frac{0.01^3}{12}) + 2E_3 (1 \times 0.02 \times 0.0825^2 + \frac{0.02^3}{12}) = 5833.43$$

$$c_s = 0.0675$$

and from Table 4, for $t = 0.01"$, we get: $\alpha = 1.0, \beta = 1.0$.

- 4). Determine the anticipated fatigue life of patched wind turbine blade:

$$N_f = 2.7 \times 10^6$$

- 5). Choose patch size (Fig. 20).

$$I'_{we1} = 34.3 \text{ in}^4$$

Fig. 20 Equivalent Cross-Section of VAWT-19 Blade and Patch Size

From Fig. 20 we have: $c_w = 1.8475 + 0.045 = 1.8925$.

- 6). Conduct a FEA on patched wind turbine blade structure. Suppose in this example the computed maximum shear stress in adhesive bond is:

$$\tau_{\max} = 1965 \text{ psi ; then, } R_f = \frac{\tau_{\max}}{\tau_{st}} = \frac{1965}{4200} = 0.468.$$

- 7). From Eq. (3'), for $R_f = 0.468$, $N_f \approx 2.7 \times 10^6$. This is the anticipated fatigue life of the blade.
- 8). With the maximum shear stress in adhesive bond found above, $\tau_{\max} = 1965 \text{ psi}$, the corresponding moment, $M_s \approx 50 \text{ lb-in}$, can be found from Table 1 for the specimen.
- 9). Use Eq.(8) to find required equivalent stiffness ratio S'_e :

$$\frac{c_w}{c_s} = \frac{1.8925}{0.0675} = 28.04$$

$$\frac{M_s}{M_w} = \frac{c_w}{c_s} \times S_e = 28.04 \times S_e = \frac{50}{290000} = 0.0001724$$

$$S'_e = \frac{0.0001724}{28.04} = 0.0615 \times 10^{-4}$$

Since we have had the value of $E_s I_s$ and have chosen the patch size, now, we can check our design by verifying if : $S_e = S'_e$.

- 10). Calculate the overall rigidity of patched equivalent wind turbine section:

$$\begin{aligned} E_w I'_{we} &= 34.3E_1 + 2E_2 \left(\frac{22}{12} \times 0.09^3 + 0.09 \times 22 \times 1.8925^2 \right) + 2E_3 \left(\frac{22 \times 0.25^3}{12} + 0.25 \times 22 \times 2.0625^2 \right) \\ &= 34.3 \times E_1 + 5.67 \times 10^6 + 2 \times E_3 \times 23.42 = 9.4 \times 10^8 \end{aligned}$$

$$11). \quad S_e = \frac{E_s I_s}{E_w I'_{we}} = \frac{5833.43}{94000} \times 10^{-4} = 0.062 \times 10^{-4} \approx 0.0615 \times 10^{-4}$$

Conclusion: the design is satisfactory, and the fatigue life of this patched structure is about 2.7×10^6 cycles.

If one does not satisfy with the results, he or she can repeat some of the procedures mentioned above until the results are satisfactory.