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STRUCTURAL FATIGUE TEST RESULTS FOR LARGE WIND TURBINE BLADE SECTIONS

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ABSTRACT

In order to provide quantitative information on the operating life capabilities of wind turbine rotor blade concepts for root-end load transfer, a series of cantilever beam fatigue tests was conducted. Fatigue tests were conducted on a laminated wood blade with bonded steel studs, a low-cost steel spar (utility pole) with a welded flange, a utility pole with additional root-end thickness provided by a swaged collar, fiberglass spars with both bonded and nonbonded fittings, and, finally, an aluminum blade with a bolted steel fitting (Lockheed Mod-O blade).

Photographs, data, and conclusions for each of these tests are presented. In addition, the aluminum blade test results are compared to field failure information; these results provide evidence that the cantilever beam type of fatigue test is a satisfactory method for obtaining qualitative data on blade life expectancy and for identifying structurally underdesigned areas (hot spots).

INTRODUCTION

NASA-Lewis Research Center is currently evaluating the operational performance of large wind turbines for the Department of Energy. The objective is to develop the technology base for large horizontal-axis wind turbines to produce electricity that is competitive with alternate energy sources.

One of the main components of wind turbines that requires technology development is the rotor. For large wind turbine systems, which have rotor diameters of from 125 to 300 feet, the rotor cost is generally in excess of 25% of the installed machine cost. In addition, the wind turbine rotor operates in a severe fatigue load environment, which may lead to high maintenance and/or replacement costs for blades with structural design deficiencies. Consequently, as part of the wind turbine program, a major effort is being expended on reducing rotor blade cost and qualifying the blades for a 30-year life.

One of the major areas of concern in the design of wind turbine generator (WTG) blades is the ability of the root end (the innermost section of the blade) to transfer the fatigue loads from the main spar section into the WTG hub. The root end is of particular concern because this is where bending moments reach their highest values: in many cases, this is also an area of transition between steel and some other material. Consequently, it is desirable to test new blade concepts in fatigue.

To accurately evaluate the design, testing would involve fabricating a full-scale root end section and subjecting that section to the load spectrum that would be experienced in the field. However, since the load spectrum occurs over a 30-year life and includes centrifugal, torsional, and bi-axial bending loads, all phased to one another, simulating the time phased load history is impractical. Testing to date has been done on the premise that loads other than the bending loads resulting from aerodynamic lift/drag and gravity forces produce negligible stresses and can thus be ignored. Further, the maximum flatwise and chordwise bending loads occur at approximately the same time and can be approximated (conservatively) as a single resultant moment. The load history would still involve as many as 4×10^8 cycles at the simplified design operating loads. At a test rate of 10 Hz, in excess of 1-1/4 years of continuous round-the-clock testing would be required to accumulate the required number of cycles. Thus, the testing is further simplified by applying higher loads for a smaller number of cycles and over a shorter period of time.

The resulting simplified test program (typical) uses a full-scale root end section of a WTG blade mounted as a cantilever beam to a very stiff test stand. The root moment is achieved by applying a single shear force at the outer end of the blade test section. The magnitude of the shear force is adjusted to approximate the desired resultant moment at the inboard section of the blade. One or two million load cycles are then applied under each of a number of load conditions that are representative of predicted blade operating conditions. The test procedure has been used on a series of Mod-OA blade sections, which include: (1) a prototype laminated wood blade, Ref. 1; (2) a steel spar blade with wood ribs and cloth skin; (3) a steel spar blade as in (2) but with a reinforced spar root end; (4) the final design configuration for the laminated wood blade, Ref. 2; (5) a 1/2 scale fiberglass composite spar with both a bonded and unbonded root end fitting; and (6) a spare aluminum blade from the Mod-0 program. A brief description of each of the blade concepts and the results of the test program are included in this report.

DESCRIPTION OF FACILITY

The U.S. Army Applied Research and Technology Laboratory has a helicopter fuselage structural test facility at Ft. Eustis, Virginia, which is being used as the wind turbine blade test facility. Three elements of the facility are used for the blade testing. One element is a "backstop" or structural support to which the blade sections are mounted in a cantilever fashion. The backstop consists of a 2" thick steel plate, 54" x 54" square, mounted to three vertical H beams. The H beams are structurally tied to additional H beams that run horizontally along the floor and are mounted on air cushions. The air cushions can be inflated or deflated to tune the natural frequency of the system. Figure 1 shows the backstop assembly with a typical blade mounted and ready for test.

The second element of the facility is the hydraulic loading system. This consists of a series of pumps supplying hydraulic fluid under pressure to a hydraulic cylinder(s). The hydraulic cylinder and plumbing can also be seen in Figure 1.

The third element of the facility is the control and data acquisition system. A closed loop analog controlled servovalve is used to proportion flow to the hydraulic cylinder in accordance with either stroke or load feedback signals. Data acquisition is controlled from the same computer network by measuring analog signals. Appropriate computer manipulation is applied to provide reduced output in a form such as maximum and minimum stress or cycle count.

LAMINATED WOOD BLADE TESTING

The testing of the laminated wood blade concept used two different specimens. The first was a prototype that simulated the early design of the laminated wood blade. The D spar, as shown in Figure 2, was made by laminating wood veneers to a male mold. A shear web was then bonded to complete the "D", and trailing edge panels were bonded onto the "D" to complete the airfoil. In subsequent wood blade development efforts, this method of construction was found to require too much hand labor in the fairing and finishing operation. Consequently, the concept shown in Figure 3 evolved and was used for fabrication of four blade sets (three of which are now operating on Mod-OA machines).

This current concept is to manufacture the blades in female blade-half-molds (an upper and lower half), and then to bond the two halves together. Structurally, the two concepts are identical, except for the details of the root end stud configuration. The first, or prototype specimen, initially used a stud as shown in Figure 4a. The embedded length was 15" of 1" x 7 Acme thread. External to the blade was a 5/8" NF threaded section that was designed to mate with the hub spindle on the Mod-0/OA machines. For the Ft. Eustis tests, the 5/8 studs were attached directly through the 2" thick backstop plate. This proved unsuccessful, as shown in Figure 5. Only 360,000 cycles at a root moment of 84,100 ft-lbs (maximum stud load of 10,000 lbs) were achieved prior to breaking 10 of the 24 studs. Examination of the failed studs and the test specimen indicated that failure had been caused not by the tensile force in the studs resulting from the blade bending moment but by bending stresses in the bolts induced by bending of the backstop plate. Consequently, it was decided to reinforce the backstop plate by adding an extra H beam and to provide a very stiff, flanged, spool piece between the blade and the backstop. This spool piece, Figure 6, would be needed not only for testing, but for machine application. A spool piece was required for machine application because the Mod-OA flange was designed to mate with a similar flange on the original aluminum blades and was not stiff enough to support the wood blade directly.

The blade section was returned to Gougeon Brothers, Inc., the manufacturer who replaced all 24 studs with the configuration shown in Figure 4b. The blade section and a boilerplate spool piece were then sent to Ft. Eustis to continue testing. One million cycles were run at maximum stud loads of approximately 10,000, 13,750, and 17,500 lbs (root moments of 84,000, 115,500, and 147,000 ft-lbs, respectively). No evidence of structural degradation could be found. At that point, the root moment was increased to 210,000 ft-lbs (maximum bolt load of 22,000 lbs) and an additional 670,000 cycles were accumulated. At that point, 7 studs were found to have failed. Failure was due to the sharp corner and consequent high stress riser at the transition from the 1" threaded shank to the 1-1/2" diameter collar (see Figure 4b). No evidence of any wood failure or significant epoxy fatigue could be found. Subsequent examination of the blade proved that the laminated wood construction had come through the test completely unaffected. A plot of the test points achieved and their relationship to operating loads and numbers of cycles is shown in Figure 7.

At that point, testing of individual studs had led to the development of a completely new stud design as shown in Figure 4c. (A complete description of the testing of individual studs is contained in Ref. 1.) In addition, a new blade manufacturing concept had evolved and NASA contracted with Gougeon Brothers, Inc. to manufacture a second fatigue test specimen utilizing the latest design concept (see Figure 3). This specimen was tested in a manner identical to that used for the first specimen with two exceptions. First, a spool piece identical to that used for Mod-OA operation was used instead of the boilerplate spool. The other difference was that a Linear Variable Differential Transducer (LVDT) was mounted on the spool piece to detect any change in spring constant across the interface. A photograph of a typical LVDT mounting is shown in Figure 8. However, the initial load of 12,500 lbs shear (269,000 ft-lbs) was selected to be high enough to insure failure in some element of the wood. This load was equivalent to that projected for the hurricane load case. Control of the blade loading was accomplished by controlling the blade test section tip deflection to a constant amplitude. As can be seen from the root bending moment curve in Figure 9, the wood blade did experience structural failure under this load condition. However, more than 20,000 load cycles were achieved before structurally significant damage occurred. And, the blade sustained more than 100,000 cycles to root moments in excess of 225,000 ft-lbs before significant drop-off of load carrying capability was experienced. The LVDT data plotted in Figure 10 indicate that some deterioration of the root end was occurring even at a low number of cycles, since the gap opening was steadily increasing. Relatively speaking, the change in gap opening was minor, changing only .014 inches in 43,000 cycles, or .0003" per thousand cycles. When compared to the initial value, this is a change of 2% per 1000 cycles. However, at about 90,000 cycles, the rate of change took a sudden increase, which indicates that major structural damage had occurred. It took another 25,000 cycles before this damage was serious enough to cause significant loss in load carrying capability (see Figure 9).

Consequently, the LVDT is felt to be a very sensitive tool for monitoring blade structural degradation and the concept is being used on all Mod-OA machines. Under normal operating conditions, the gap opening (or closing) is a constant value for a given set of operating loads. Any change would be reason to suspect potential blade problems. And, a limit switch could be used (and is installed on several Mod-OA machines) to effect an automatic shutdown. At the present time, however, there is no reason to suspect a problem with laminated wood blades on Mod-OA wind turbines. As is shown in Figure 7, the test data for both the prototype and the revised wood blade test section supports the design allowable curve selected for relating the maximum allowable bolt loads to an expected number of operating cycles. In addition, Figure 7 also shows that the design allowable curve lies substantially above the load/cycle data that is predicted by machine operating experience. Consequently, it is believed that the fatigue testing of sections at Ft. Eustis has proved that within the operating regimes of the field machines the blades should last for at least the design lifetime.

It should be pointed out that the fatigue testing of root sections does not simulate environmental effects that could accelerate structural degradation. Nor do the root end fatigue tests necessarily demonstrate fatigue strength of the blade material in the basic airfoil section. And, obviously, the fatigue tests do not demonstrate buckling capability. All of these items must be tested separately, the combination of tests then validating the blade capability. But in most cases, it is the blade root end that is of the greatest concern and is the most difficult to test. Additional data that support the effectiveness of the Ft. Eustis method of testing WTG blade sections are presented later in this report with the discussion of the aluminum blade testing.

STEEL SPAR BLADE

The concept of using a tapered steel spar (such as a utility pole) as the primary structural member of a wind turbine blade has existed for some time. In 1978 the requirement of a new set of blades for the

Mod-0 wind turbine resulted in the design and fabrication of two blades based on this concept. A description of these blades and their performance on Mod-0 is given in Reference 3. The details of the blade construction are shown in Figure 11 and a picture of the blades mounted on the Mod-0 WTG can be seen in Figure 12. A structural analysis of the steel spar blade design showed that the critical area in fatigue was the root end weld. This weld connects the spar to the flange required for bolting the blade to the hub.

Application of standard welding codes, such as the Structural Welding Code, to this weld resulted in the requirement of close interval (100 hour) inspections. To better ascertain inspection requirements of this weld, a root end specimen was tested in the Ft. Eustis facility. In addition, a prototype of a second root end design was also tested. This design consisted of a double wall at the root end. The outer tube was swaged over the inner tube. The purpose of the double wall was to reduce the stress in the critical spar-to-flange weld. Sketches of both the single wall and double wall specimens are shown in Figure 13. The results of these tests and the conclusions drawn from them follow.

Single Wall Steel Spar

The single wall steel spar consisted of a flange that was machined from rolled plate and a tapered tube of manufacture similar to that used for utility poles. Schedule requirements made it necessary to use available rolled plate for the flange rather than more desirable forged material. The tube was joined to the flange with a high quality weld. Weld soundness was established by radiographic inspection.

The spar was load cycled for 10^6 cycles at each step of increasing load until failure occurred. Failure occurred after 265,000 cycles at the fourth load level. This is shown graphically in Figure 14. The stress level indicated on the graph was calculated using simple beam theory. Failure occurred in the flange radius. Failure here rather than in the weld is attributed to the low strength of the plate material from which the flange was machined and the orientation of the grain structure with respect to the applied stress. Figure 15 compares the grain structure of the plate material with that of a forged material. The plate material was stressed transverse to the grain direction. Fatigue strength transverse to the grain direction has been shown to be significantly less than that parallel to the grain direction (Ref. 4). The forging process eliminates elongated grain structure and reduces fatigue strength sensitivity to stress direction. Subsequent flanges for spar blades have been machined from forgings.

Because failure occurred outside the weld area, the fatigue strength of the weld was not determined. However, certain conclusions can be drawn by comparing the test results to the fatigue stress levels allowed by the Structural Welding Code for turbular structures

(Ref. 5). In Figure 14 the single wall test results can be compared to three weld categories: Category A is plain, unwelded pipe; Category B is for butt splices with full joint penetration where the weld is ground flush and inspected by radiograph or ultrasound; and Category C is the same as B without the grinding and inspection requirements. The original inspection interval of 100 hours was set using Category B allowables. As the figure shows, the test data exceed Category A allowables. Therefore, a new inspection interval of 300 hours was set based on Category A allowables. It should be noted that in earlier versions of the Structural Welding Code, a high quality welded joint could be placed in Category A.

The Ft. Eustis test results verified that it was legitimate to apply the Structured Welding Code to a structure of this type. However, only a lower bound for fatigue strength was obtained. The actual strength will be obtained only with additional testing.

Double Wall Steel Spar

The purpose of the double wall steel spar was to reduce the stress in the critical flange weld by increasing the wall thickness. After cleaning mating surfaces, a short section of tapered tubing was hydraulically swaged over a longer piece of tapered tubing using commercial utility pole fabrication techniques. The end was trimmed and welded to a flange. The wall thickness at the weld was twice that of the single wall spar discussed above.

The double wall spar was tested in the same manner as the single wall spar. The initial load level was the highest load level that survived 10^6 cycles with the single wall spar. The spar survived this test and the load was increased to the level that caused failure in the single wall spar. After 380,000 cycles, the test was stopped because of severe circumferential cracking in the weld and adjacent metal, and longitudinal cracking in the tapered wall portion of the outer tube. A photograph of the crack in and near the weld is shown in Figure 16.

Analysis of the failure consisted of examining strain gage data and reviewing the Structural Welding Code in an attempt to categorize the double wall spar weld. In Figure 17, calculated strain is compared with measured strain on the outer tube. The calculated strain assumed the outer tube was fully effective in bending except in the tapered outboard section. The figure shows that the outer tube is much less than fully effective, which means the inner tube is picking up additional load. The high strain gradient near the weld indicates high shear stresses at the weld. The measured strain just inboard of the weld is very close to that calculated and about half that measured on the single wall spar for the same applied load.

The stress history for the double wall spar is shown in Figure 14. Examination of the Structural Welding Code showed there was no category that precisely matched the weld in question. It was clear, however, that there was a substantial reduction in allowable stress in structures where doublers were used and where shear in a weld was present. It was concluded that while the double wall reduced the nomimal stress in the weld, this was more than offset by the stress concentration inherent in this type of weld.

TFT FIBERGLASS BLADE

Details of the TFT Fiberglass blade were presented in the paper by Weingart. To provide a brief review, planform and cross sectional views of this blade are shown in Figure 18. The root end retention of the TFT fiberglass blade is shown in Figure 19. After applying a film adhesive, epoxy impregnated fiberglass was wound over the steel retention ring. Curing of this assembly provided an adhesive bond between the fiberglass and steel. To provide redundancy, the fiberglass was also mechanically locked into the retention ring. This was done by using hoop wraps to force the TFT into the depressions in the retention ring.

To reduce costs, half scale specimens were used for fatigue testing. A sketch of the specimen is shown in Figure 20. Two specimens were fabricated; the first specimen (bonded) was fabricated in the same manner planned for the full scale blade while a release agent was applied to the retention ring of the second specimen (unbonded) so that the retention capability of the mechanical lock could be tested.

Load Scaling

In subscale tests, the applied loads must be scaled down so that the applied stress is the same as in the full-size article. For an end loaded cantilever beam, the load scales according to the square of the scaling factor, if both cross section and length are scaled. For example, a half scale beam requires 1/4 the end load of a full-size beam to produce the same bending stress. To match the shear stress also requires 1/4 of the load. In some root end designs, the bending moment is the predominant failure-causing load. However, in a bonded joint such as that at the root of the fiberglass blade, the shear load is also important.

To provide both the desired shear and bending stress at the root end of a full size fiberglass blade would require a specimen 30 feet long. For a half scale test, the required length would be 15 feet. Because the half scale specimens were only 13 feet long, it was not possible to provide both the desired bending stress and the desired shear stress using a single shear load. Cost and schedule requirements did not allow the design and fabrication of a specimen where two or more shear loads could be introduced. The tests were conducted matching the desired bending stress. This resulted in the desired shear stress being exceeded by about 15 percent.

Test Parameters

The test load sequence and number of cycles for both specimens are tabulated in Table 1. After surviving the initial loading spectrum, the bonded specimen was rotated 90° about the pitch axis and the load cycling continued in an attempt to achieve 1×10^6 cycles at each load level. This specimen was rotated 90° so that the effect on the bond of the first set of load cycles would be preserved for later examination. The unbonded specimen was cycled in the same orientation throughout the entire test.

The bonded specimen was tested at a rate of 5 cycles per second (Hz). The initial rate used for the unbonded specimen was the same. However, when heat buildup was detected in the retention area, the rate was decreased to 3 Hz. No heat was detectable at the lower cycle rate.

Test Results and Conclusions

After 4×10^6 cycles at lower load levels, both specimens failed after about 350,000 cycles at the hurricane load level. (The hurricane load was defined as a pressure of 50 pounds per square foot applied flatwise to the blade.) In both cases, failure took place in a 1/16 inch flange fillet (Figure 20). Visual and tap test inspection of both specimens revealed no apparent damage in the retention area other than the flange failure. Definitive determination of damage will require sectioning of this area. This is planned for the near future.

During initial load cycling of the unbonded specimen motion was detected between the composite and steel retention. As the test progressed, this motion decreased even though the load was periodically increased. This behavior is shown graphically in Figure 21 where the compliance at the tip of the beam (deflection per unit of applied load) is plotted against number of cycles. The plot shows the compliance steadily decreasing for the first half million cycles. This behavior was probably caused by the composite being wedged on the tapered portions of the steel retention ring. If it had been possible to run the test with reversed bending, it is likely that high tip compliance and motion between composite and steel would have been observed during the entire test.

Compliance data for the bonded specimen after it had been cycled 2.22×10^6 times and rotated 90° is also shown in Figure 21. On average, the compliance of the bonded specimen is about 10 percent less than that of the unbonded one. Also, the data scatter for the bonded specimen is less. This kind of behavior would be expected. After about 4.5×10^6 cycles both specimens showed a very rapid increase in compliance. This is related to the failure in the flange fillet.

The results of these two tests gave high confidence in the ability of the fiberglass blade root end to successfully withstand the operating loads. After testing of the bonded specimen was complete, no damage to the bond was observed. The second test showed that if the bond failed, the mechanical retention was capable of withstanding operational loads.

ALUMINUM BLADE TEST

As mentioned earlier, fatigue testing of blade sections is not considered to be a quantitative test in that it will not predict the number of hours a blade will operate satisfactorily on a field machine. This type of testing is, however, very effective in highlighting design deficiencies or over-stressed areas (structural "hot spots") in specific blade locations (generally the root area). As a means of proving test effectiveness, one of the aluminum blades from the original three blades built for the Mod-0 (100kW) wind turbine was modified to be a fatigue test specimen. Details of the blade design and construction are contained in Reference 6. The modification consisted of cutting the 62.5 foot-long blade approximately 21 feet from the root end flange. The cut section was then reinforced for introduction of shear loads by slipping on a one-inch thick aluminum plate (with the airfoil section cut out of the middle) and rigidly fixing the skins, stringer, and trailing edge channel to the plate. Another one-inch thick aluminum plate (without airfoil cut out) was then bolted to the attached plate. This provided a flat surface, normal to the blade spanwise axis, on which the clevis for attaching the hydraulic cylinder could be mounted. A photo of the modified blade section mounted in the Ft. Eustis facility is shown in Figure 22.

To determine the loadings for the test series, the flatwise and edgewise moments at station 81.5 were combined vectorially as per predictions of the MOSTAB-HFW computer code for the Mod-0 blade in Mod-0A service. This established a relative direction and magnitude for a single shear load to be applied at the tip of the test specimen. The relative direction of the shear force line was 49° to the chord line of the Station 81.5 rib. The magnitude of the first shear force to be applied would be such as to produce a station 81.5 moment of 103,000 ft-lbs (maximum aluminum stress = 7340 psi). Subsequent load steps were to be such as to produce moments of 135,800 ft-lbs (9620 psi) and 164,800 ft-lbs (12,000 psi). The 7340 psi stress level represents what would be considered an infinite life fatigue stress (R-ratio = 0.01) while the 9620 psi figure was what would be expected as a maximum stress under the 40 MPH, 40 RPM operating conditions. The third stress level, 12,000 psi, was selected by arbitrarily placing a factor of 1.25 on the 40 mph, 40 RPM case. This turned out to be immaterial, however, since the testing never proceeded to that load level.

Testing was started with a shear load of 5900 pounds required to produce the Station 81.5 moment of 103,400 foot/pounds. This load level should have produced no problems in the aluminum blade based on design capabilities. However, as soon as testing started, it was evident that the root end load transfer from the innermost rib (Station 48) to the gunbarrel section (Figure 23), was inadequate. Considerable scraping and wear began immediately. This was directly comparable to what had already been experienced in the field and had resulted in the incorporation of a shim (or bearing surface) with high hardness and low coefficient of friction between the steel root end fitting and the aluminum rib at Station 48. Testing was allowed to continue at the 5900 pound shear level with the intention of shimming the Station 48 rib as soon as wear became excessive. A cyclic rate of 2 Hz was maintained; at about 500,000 cycles a loud popping noise was heard. A similar noise was heard again at about 900,000 cyles. One million cycles were completed without obvious external cracks, although it is probable that internal damage had occurred. Wear, as shown in Figure 23, had not progressed to the point where shims were required.

The shear load was increased to 7900 pounds, which represented the 40 MPH, 40 RPM case, and several more loud popping noises were heard immediately. After only a few hundred cycles, a skin crack was noticed in the trailing edge, extending 6 inches into the D spar skin. The extent of the crack is shown in Figure 24. The test was allowed to continue for another 55 minutes or until a total of 8778 cycles had been accomplished at 7900 pounds. At that point, the crack had grown further into the D spar skin and testing was terminated. The blade was removed from the test stand and returned to LeRC for inspection, which resulted in the following observations (refer to Figure 24):

1. The crack extended from the trailing edge through an internal splice plate at Station 88 all the way forward and 14 1/2 inches into the intermediate (D spar) skin.

2. The aft stringer was broken.

3. The middle stringer was broken.

4. The crack also extended up into the shear web for about half the blade thickness (10 inches).

5. The crack terminated in a rivet hole in the forward stringer.

6. The forward stringer was not broken.

This type of failure was typical of a particular mode of failure that was experienced on the Mod-OA machines. Dusting of rivets in the trailing edge skins was also typical of blades in the field. The test section, however, did not exhibit rivet dusting since the test blade section had a trailing edge skin that was much thinner than the

Mod-OA blade, and there were no trailing edge stringers. Therefore, not as much load was being transferred through the skin into the rivets and dusting did not occur. Also, the Ft. Eustis specimen did not experience Station 81.5 rib cracking as was seen in the field. The rib cracking of the blades in the field was caused by wear of the Station 48 rib, which in turn forced bending loads into the Station 81.5 rib. Thus, since wear did occur in the test secton, it is believed that had additional load cycles been applied to the blade, station 81.5 rib cracking would have been a certainty. To put additional cycles on the blade would, however, have required a major repair of the cracked skin and stringer and was not considered to be warranted.

Testing of the Mod-0 aluminum blade section was thus considered to have validated the fatigue testing concept being used at Ft. Eustis. Structural "hot spots" were identified; had this testing been conducted early in the aluminum blade fabrication effort, appropriate design modifications or structural fixes would have been made. It is probable that this type of testing would have prevented premature blade damage as was experienced in the field.

CONCLUSIONS

The following are general conclusions based on the blade testing experience at the Ft. Eustis facility and the correlation of the aluminum blade test data with operational experience in the field.

1. Fatigue testing of Mod-0/0A size root end sections in cantilever bending to $1X10^6$ cycles at a series of loads representative of the peak loads that wind turbines will see in service is an effective way to identify design deficiencies or structural "hot spots."

2. Cyclic test rates of 2 to 6 Hz on large blade sections can be achieved. This allows a root end concept to be structurally verified in a matter of 3 to 6 weeks of testing.

The following conclusions are specific to the different blade types listed.

1. The joining of laminated wood blades to the wind turbine hub through bonded studs provides a structurally sound system. Thousands of cycles at loads in excess of the hurricane load can be achieved without structurally significant damage. Use of LVDT's and/or limit switches is a very sensitive system for detecting failure of the bonded stud joint.

2. Should cracking and structural failure of the root end joint of a laminated wood blade occur, the failure mode is benign rather than catastrophic.

3. Test of a single wall steel spar showed that designing to the Structural Welding Code was conservative. To determine the actual fatigue strength of the critical spar weld requires additional testing.

4. Test of a double wall steel spar showed that, while the nominal stress in the weld was reduced, this was more than offset by the stress concentration inherent in this type of weld.

5. Half scale tests of the fiberglass blade root end showed that both the primary retention (bonding) and secondary retention (mechanical lock) are individually capable of withstanding the operational load spectrum without failure.

6. For the aluminum blade sections tested, the fatigue test damage correlated closely as to type and rate with the damage that was experienced in the field.

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Table 1. Fatigue Load History of Half-Scale Fiberglass Blade Retention Specimens

Significance of Load	Peak Applied Moment, lb-ft	Peak Applied Shear, lb	No. of Cycles	
			Bonded Specimen	Unbonded Specimen
Design	19,000	1440	10^6	10^6
High wind	22,000	1670	10^6	10^6
Normal Shutdown	24,500	1860	2×10^5	2×10^5
Emergency Shutdown	28,500	2165	2×10^4	2×10^4
Hurricane	42,000	3190	100	100
			(a)	
Normal Shutdown	24,500	1860	8×10^5	8×10^5
Emergency Shutdown	28,500	2165	9.8×10^5	9.8×10^5
Hurricane	42,000	3190	3.6×10^5(b)	3.8×10^5(b)

(a)Specimen rotated 90°
(b)Specimen failed

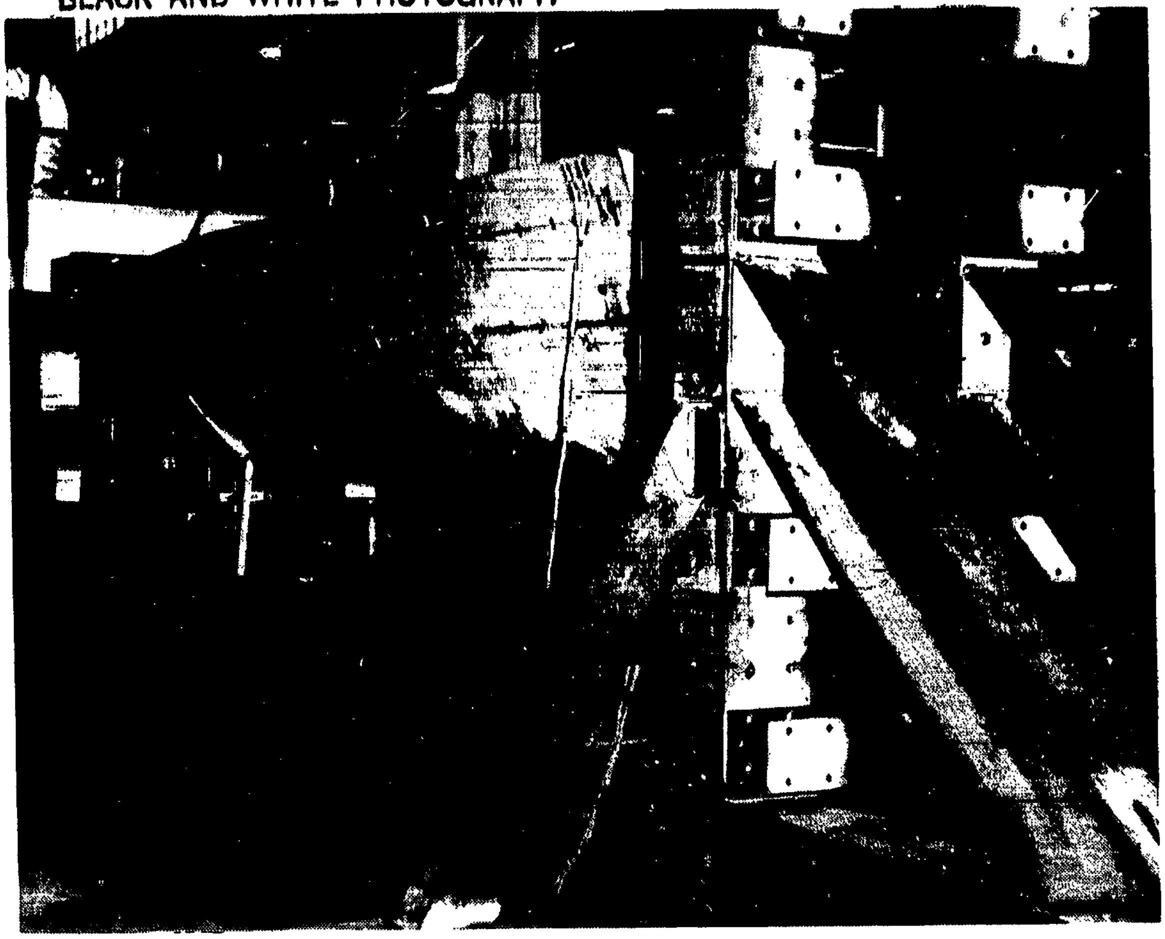


Figure 1. - Wind turbine blade test facility at Ft. Eustis, Virginia.

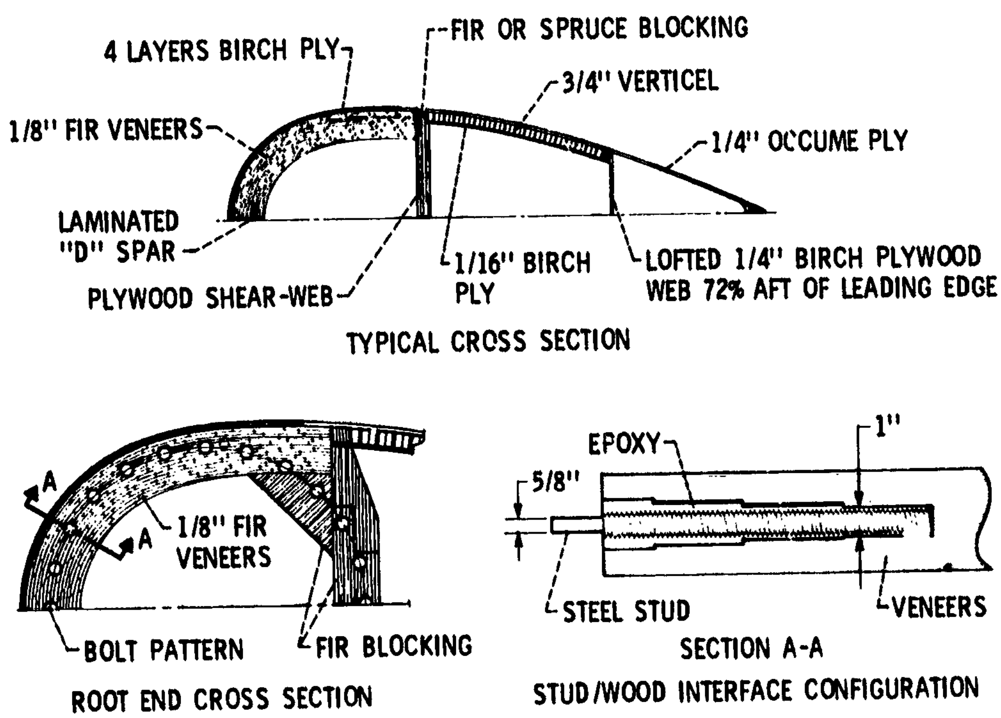


Figure 2. - Prototype wood blade concept.

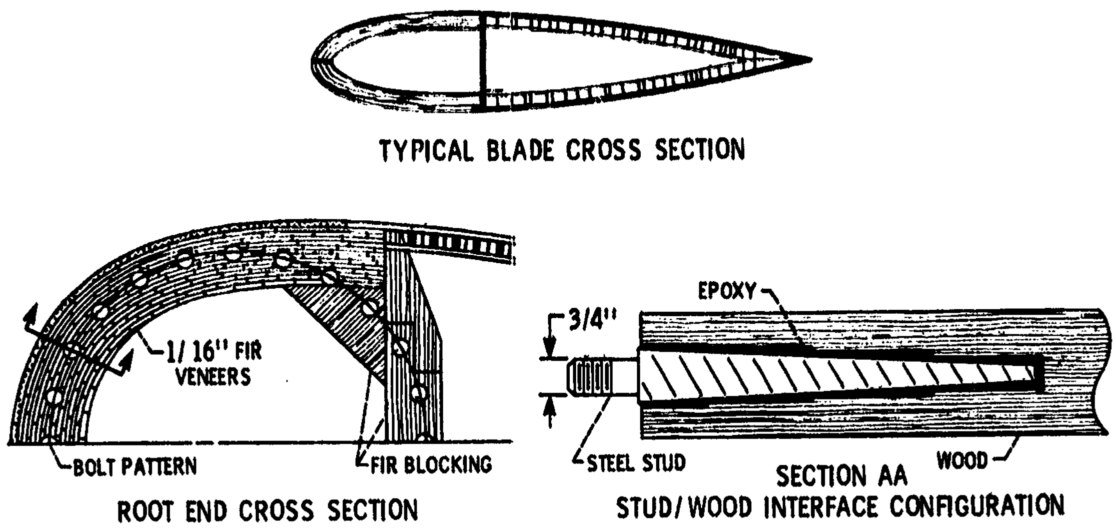
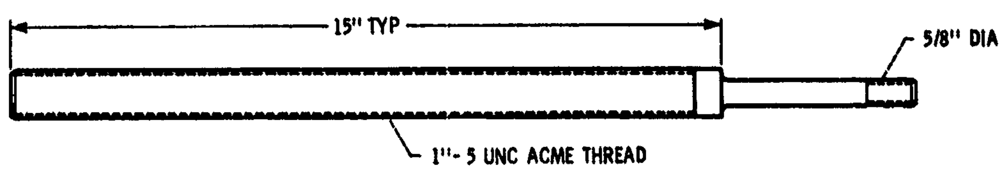
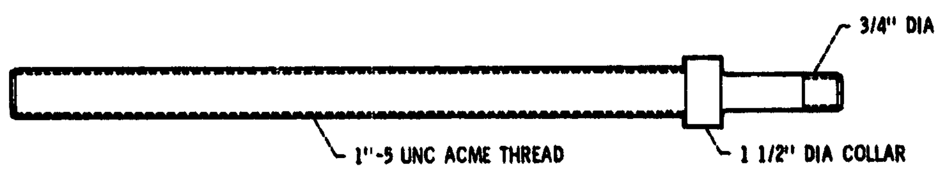


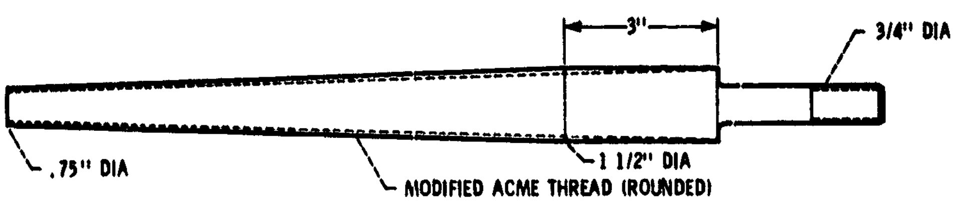
Figure 3. - Final design of laminated wood blade.



(a) Prototype blade stud design #1



(b) Prototype blade improved design stud



(c) Current stud design used for 2nd blade section and Mod-0A blades

Figure 4. - Stud design history.

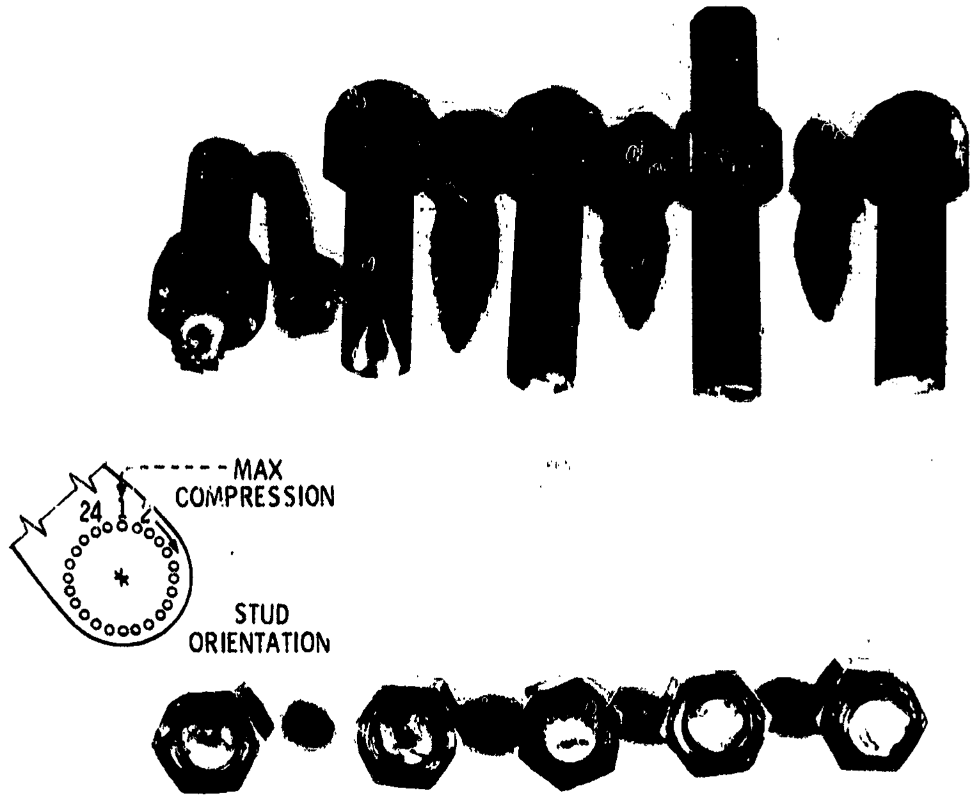


Figure 5. - Broken bolts from first test of prototype wood blade section.

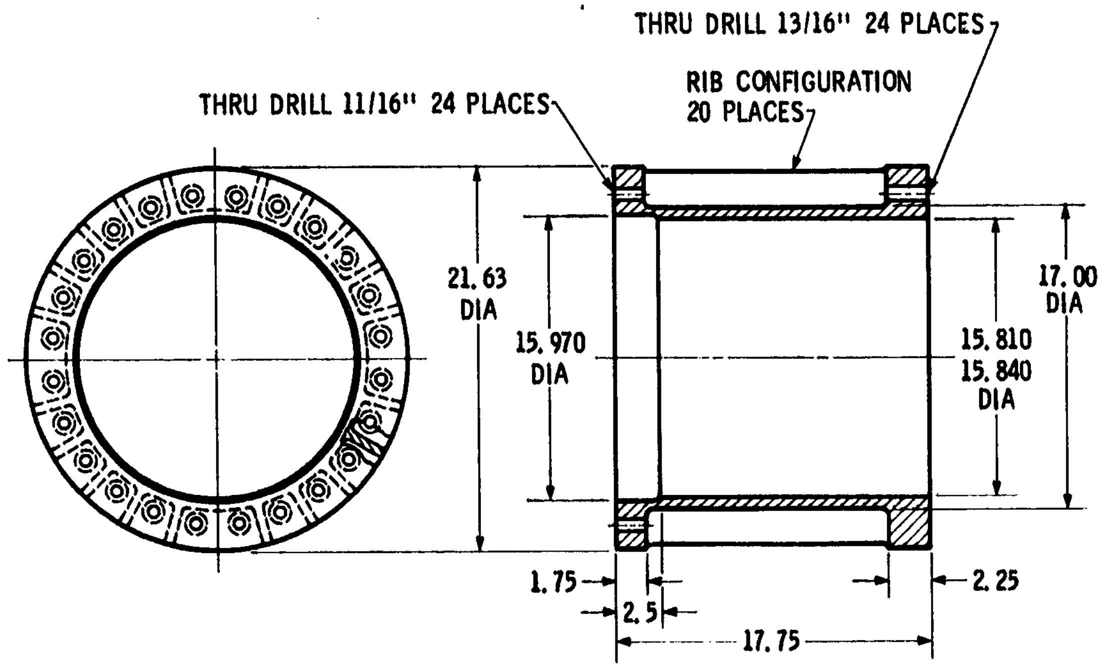


Figure 6. - Laminated wood blade root end adapter.

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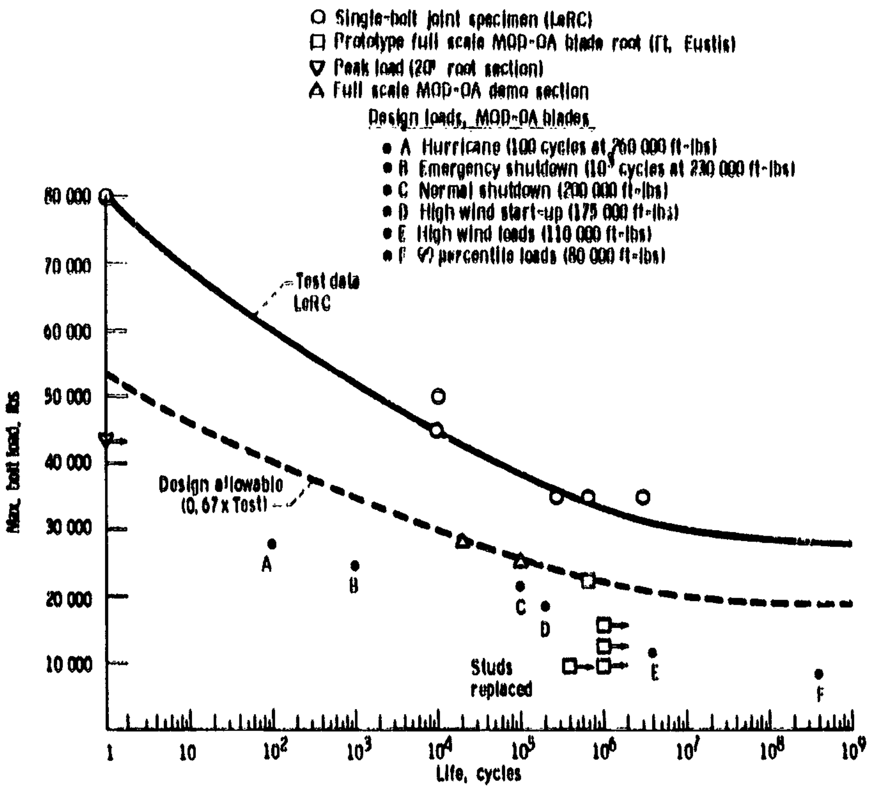

Figure 7. - Bolt-to-wood tension joint fatigue data.

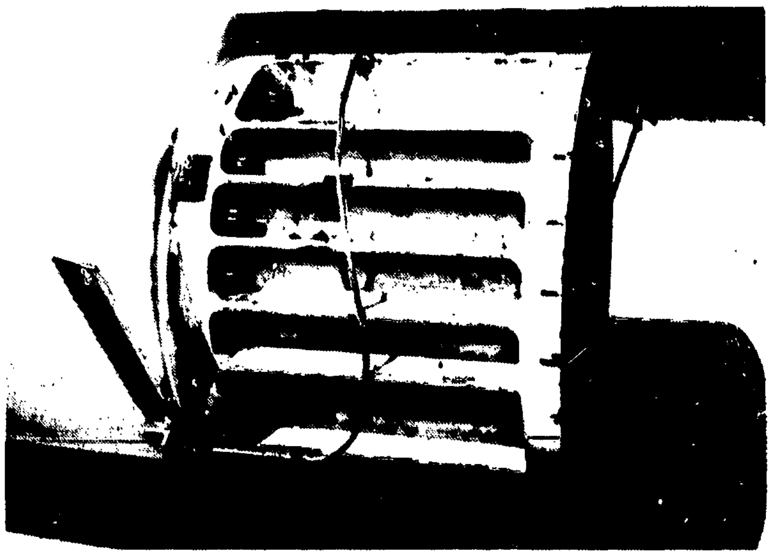

Figure 8. - LVDT mounting on wood blade root end.

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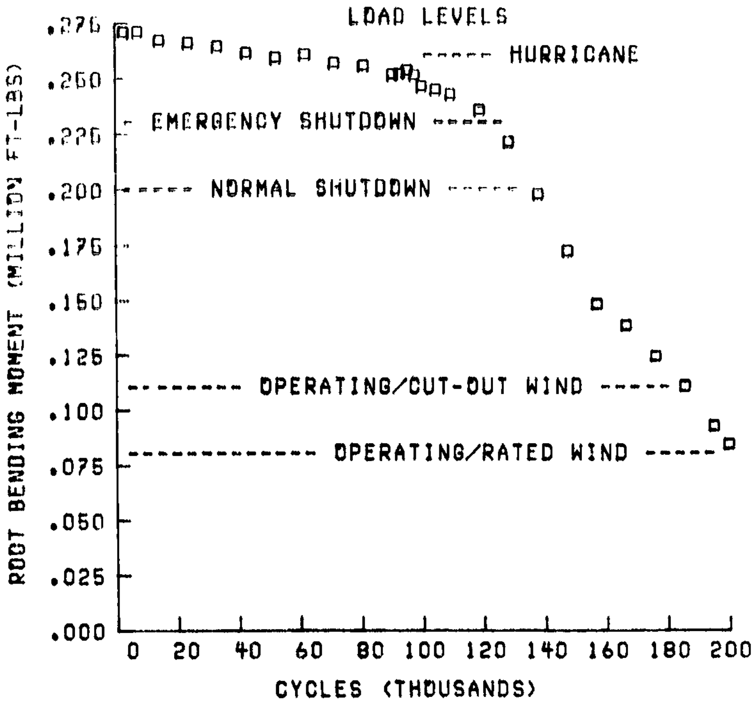

Figure 9. - Stiffness degradation during fatigue test of laminated wood blade.

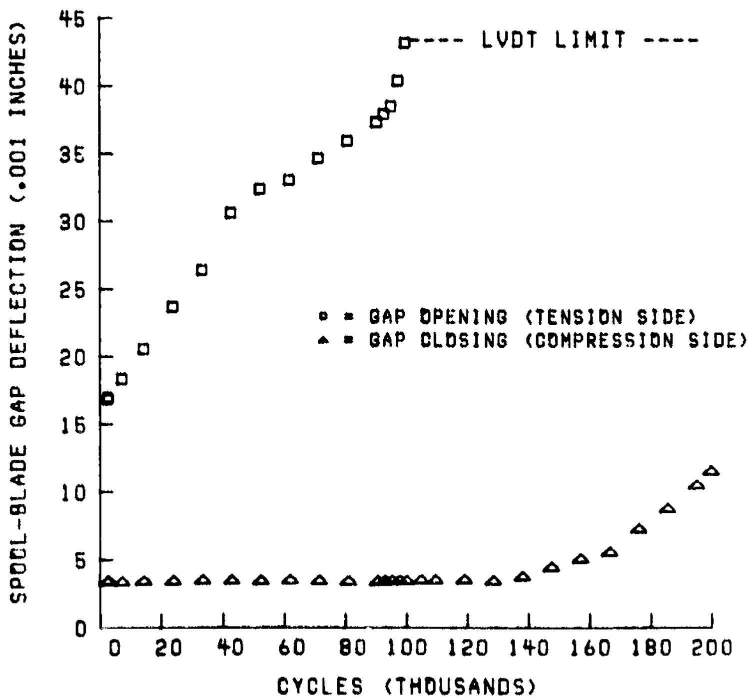

Figure 10. - Sensitivity of LVDT in measuring wood blade root end fatigue damage.

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Figure 11. - Fabrication procedure for steel spar (utility pole) blade.

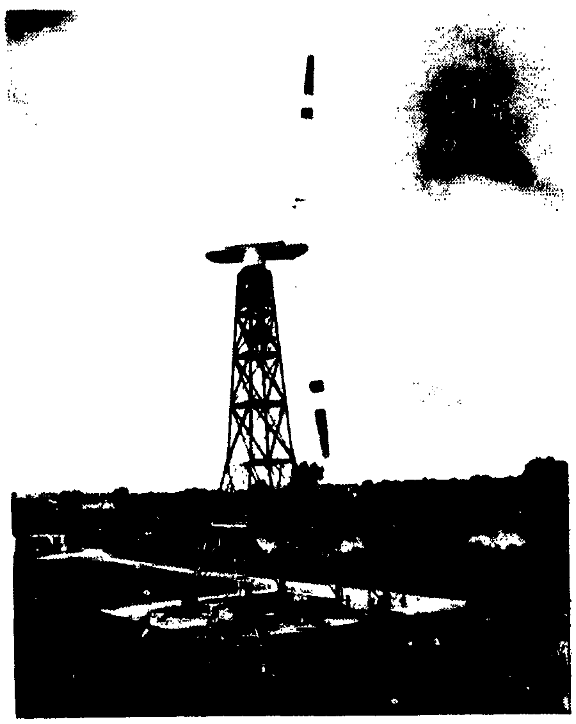


Figure 12. - Steel spare blades mounted on Mod-0 wind turbine.

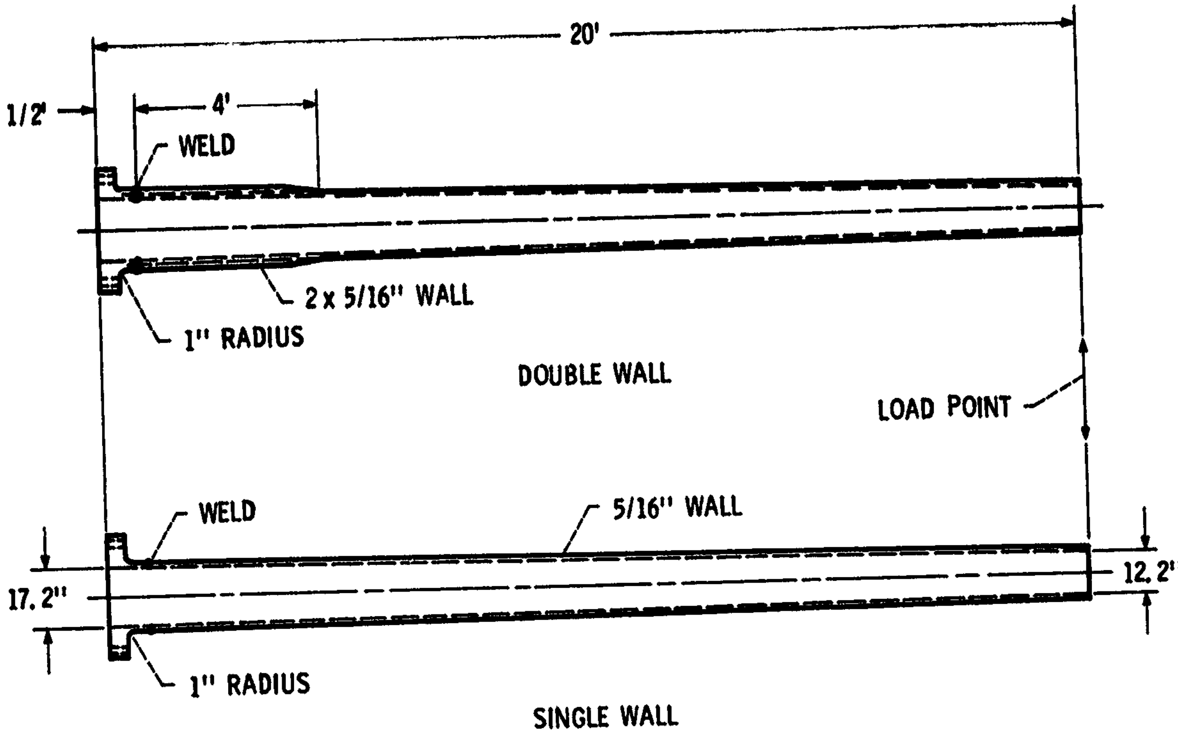


Figure 13. - Steel spar test specimens.

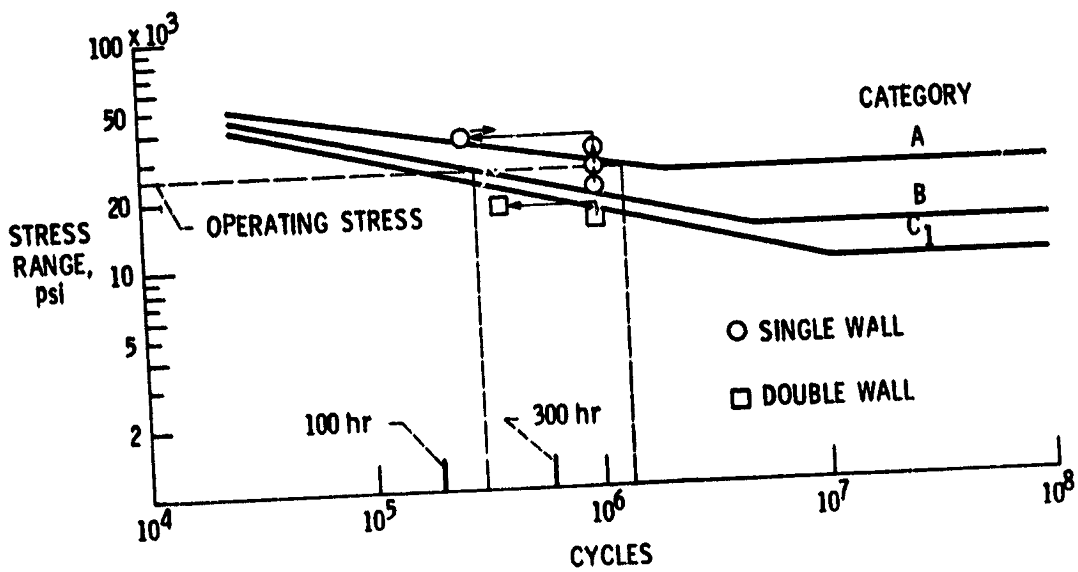


Figure 14. - Comparison of steel spar test results to Structural Welding Code allowables.

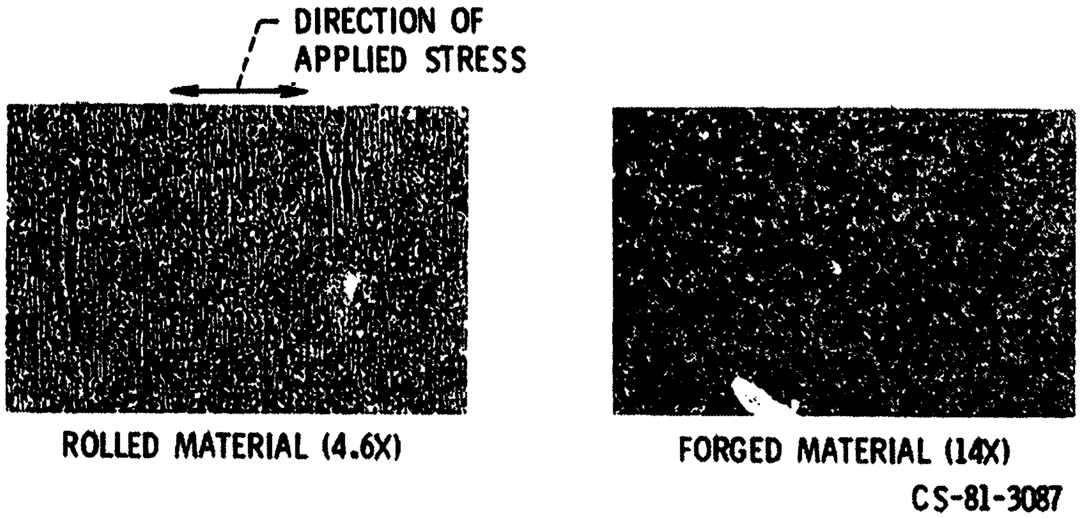


Figure 15. - Comparison of steel flange material grain structure used for steel spar blades.

Figure 16. - Weld crack resulting from fatigue test of double wall steel spar.

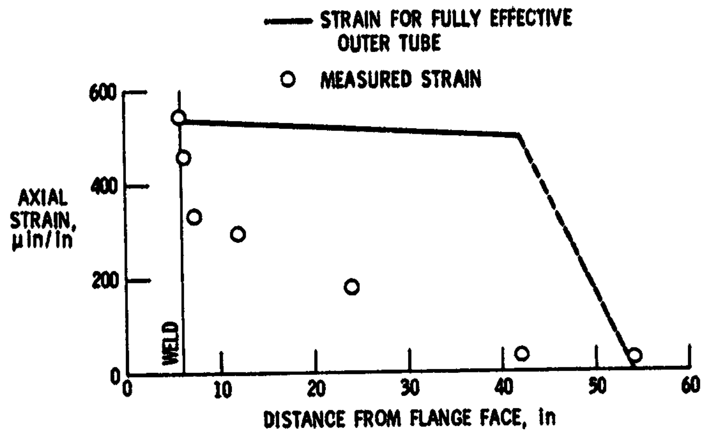
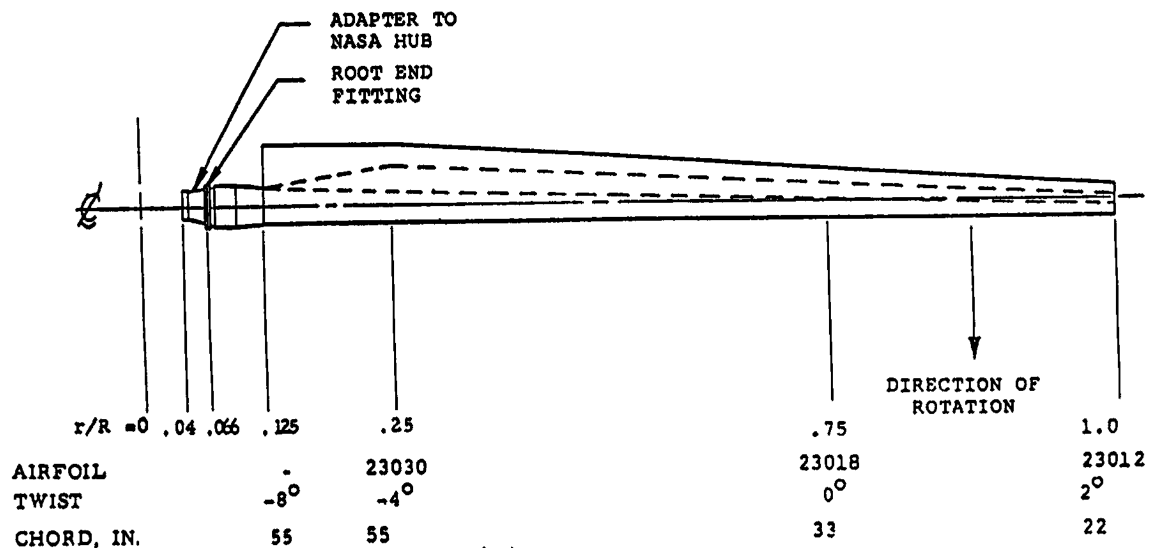
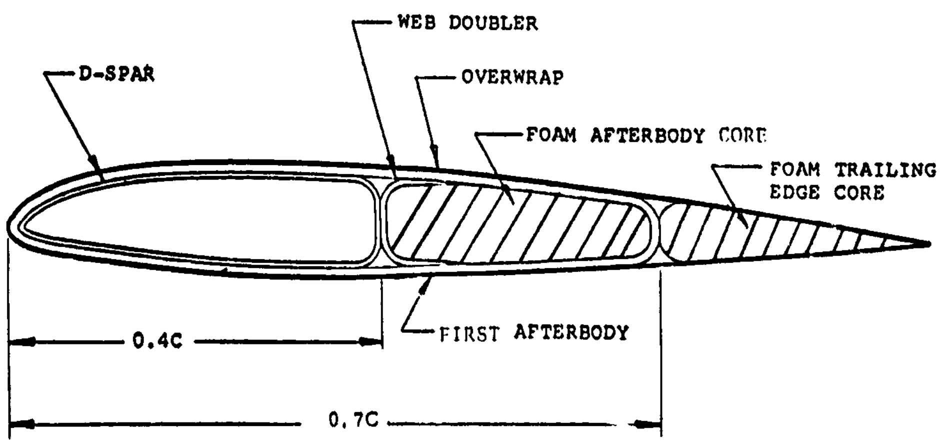


Figure 17. - Comparison of calculated and measured strain in double wall steel spar for an applied load of 10,000 lb.



(a) Planform



(b) Typical cross section

Figure 18. - Composite blade geometry definition.

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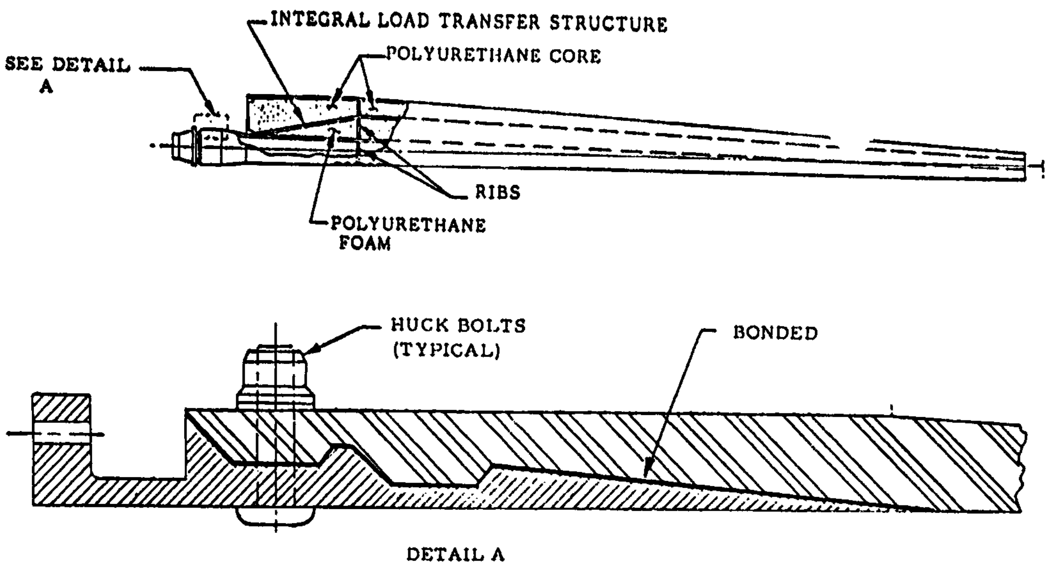

Figure 19. - Composite blade root end retention details.

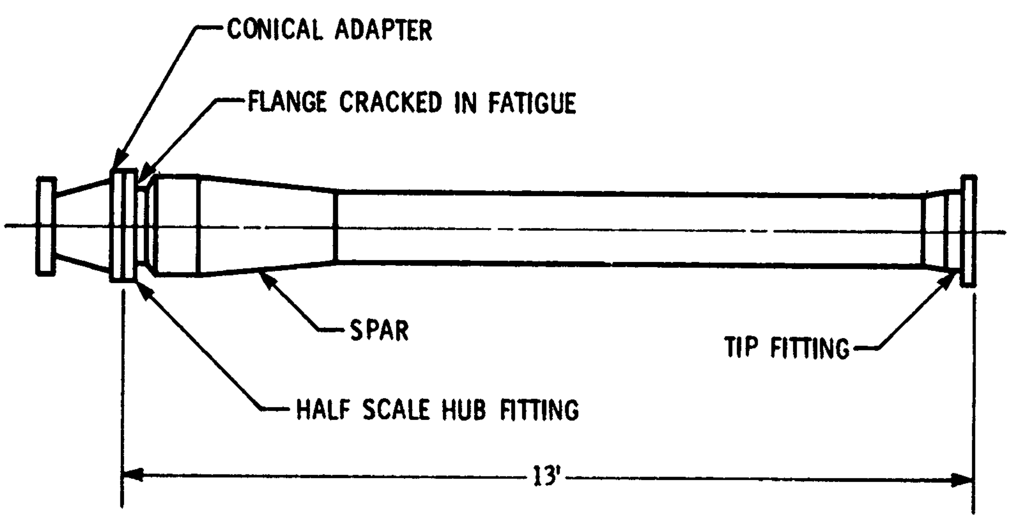

Figure 20. - Half scale composite blade hub joint fatigue test specimen.

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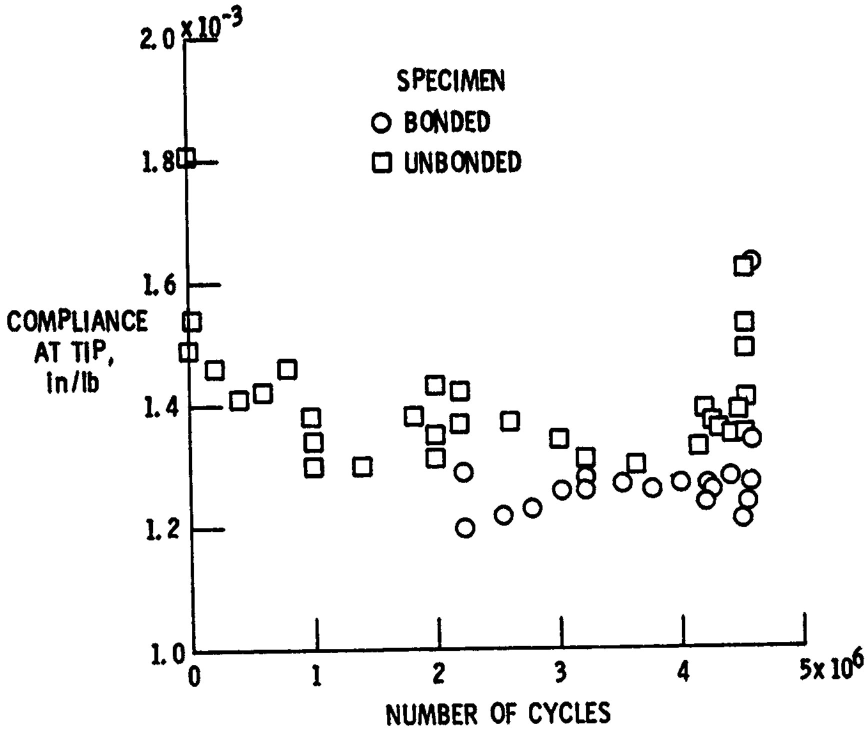

Figure 21. - Effect of load cycling on compliance of fiberglass fatigue specimens.

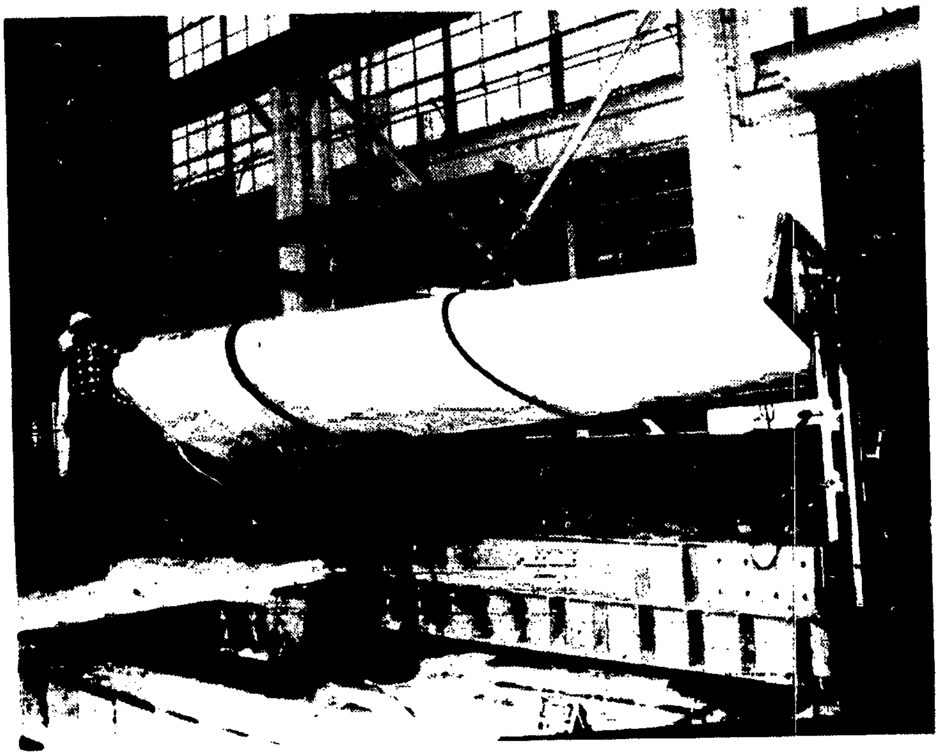

Figure 22. - Mod-0 aluminum blade mounted in the Ft. Eustis facility.

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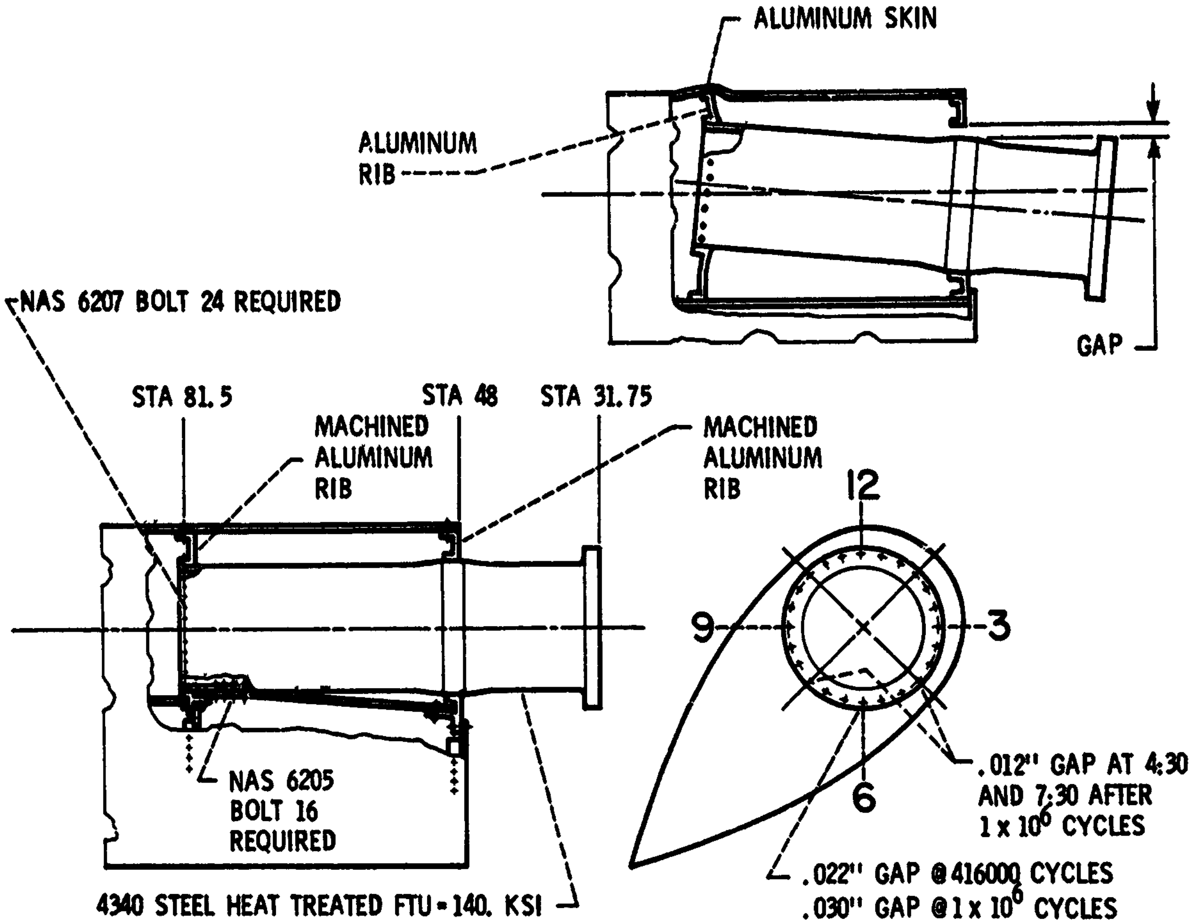

Figure 23. - Mod-0 aluminum blade root end details and wear pattern.

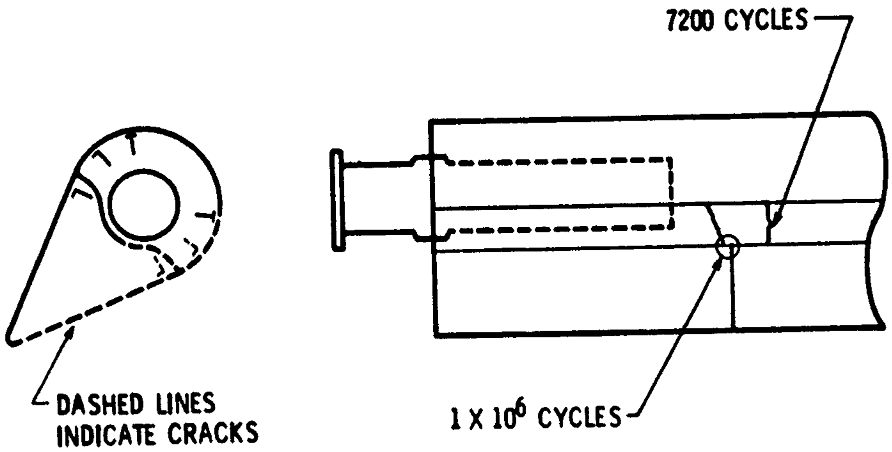

Figure 24. - Damage resulting from fatigue test of Mod-0 aluminum blade.