DOE/NASA/20320-30
NASA TM-81719

Test Evaluation of a Laminated-Wood Wind-Turbine-Blade Concept

James R. Faddoul
National Aeronautics and Space Administration
Lewis Research Center

DOE/NASA/20320--30

May 1981

DE81 024946

Prepared for
U.S. DEPARTMENT OF ENERGY
Conservation and Solar Energy
Division of Wind Energy Systems

DOE/NASA/20320-30
NASA TM-81719

Test Evaluation of a Laminated-Wood Wind-Turbine-Blade Concept

James R. Faddoul
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

May 1981

Work performed for
U.S. DEPARTMENT OF ENERGY
Conservation and Solar Energy
Division of Wind Energy Systems
Washington, D.C. 20545
Under Interagency Agreement DE-AI01-76ET20320

TEST EVALUATION OF A LAMINATED WOOD WIND TURBINE BLADE CONCEPT

James R. Faddoul

SUMMARY

Because of the high stiffness and fatigue strength of wood (as compared to density) along with the low cost manufacturing techniques available, a laminated wood wind turbine blade application has been studied. This report presents the results of the testing performed on elements of the wood blade-to-hub transition section which uses steel studs cast into a laminated wood spar with a filled epoxy. Individual stud samples were tested for both ultimate load carrying capability and fatigue strength. A one-time pull-out load of 78,000 lb was achieved for a 15 in. long stud with a diameter of 1 in. Tension-tension fatigue indicated that peak loads on the order of 40% of ultimate could be maintained as an endurance limit (mean load = 20,000 lb, cyclic load = $\pm$15,000 lb). Following the individual stud testing, a full-scale inboard blade section (20 ft in length) was tested. One million load cycles were imposed on the test section at each of three load levels; representing the rated wind condition (4×10^8 cycles over 30 yr), the cut-out wind condition ($\approx 10^7$ cycles), and 25% above the cut out wind condition. This was followed by 670,000 load cycles to a peak moment of 210,000 ft-lb which represents the emergency shutdown load condition (≈ 1000 cycles); at which point fatigue failure occurred at a stress con- centration in the stud. No evidence of distress to the wood, the epoxy, or the epoxy-to-steel bond was found. Based upon the results of this testing, two sets of wind turbine blades have been built and are operating on MOD-OA (200 kW 125 ft diam rotor) wind turbines at Kahuka, Hawaii and Block Island, Rhode Island. In addition, a set of 40 ft long inner blade sections have been fabricated for a tip controlled wind turbine, MOD-O (100 kW, 125 ft diam rotor), at Sandusky, Ohio.

1.0 Introduction

NASA Lewis Research Center is currently evaluating the operational characteristics 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 the large wind turbine systems, which have rotor diameters from 125 to 300 ft, 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 leads to high maintenance and/or replacement costs. Consequently, as part of the wind turbine program, a major effort is being expanded on reducing rotor blade cost and qualifying the blades for a 30-yr life. Five blade concepts are currently being evaluated. These concepts can be characterized by their primary materials of construction, namely, aluminum, fiberglass Transverse Filament Tape (TFT), fiberglass continuous filament, spot welded stainless steel, welded steel, and wood. The status of this technology development is described in References 1-3. Blade sizes being developed under the NASA LeRC effort are 60, 100, and 150 ft long.

For all of the blade programs, the blade-to-hub transition (blade root) appears to be the major area of concern. The blade root is subjected to a normal operating bending moment in excess of 1.5×10^5 ft-lb for the 60 ft blade and in excess of 1.4×10^6 ft-lb for the 150 ft blade. Methods for transferring moments of these magnitudes require careful design consideration in order to provide the proper balance between structural redundancy, weight, and cost. Consequently, the blade-to-hub transition area in each of the blade concepts is being thoroughly analyzed and the resulting designs are being evaluated experimentally.

This report presents the results of a series of tests which were conducted to demonstrate the structural capability of the wood blade-to-hub transition. Both component testing and full scale testing were performed and are discussed.

2.0 Wood Blade Structrural Features and Loads

Because of the unique combination of high stiffness-to-density, high fatigue strength-to-density and potential for low fabricated cost per part, wood has gained considerable interest as an engineering material for large (62 to 200 ft radius) wind turbine (WT) rotor blades. To this end, NASA LeRC awarded a study contract in 1977 to evaluate the structural, aerodynamic, and cost potential of a laminated wood WT blade. Several different configuration and construction methods were evaluated and the concept shown in Figure 1 was selected for structural evaluation. The primary elements of the concept are a laminated epoxy impregnated "D" spar which would be fabricated in a female mold. To this D spar would be bonded a plywood main shear web which, except for the root end area, would extend the full length of the blade. In the root area of the blade, the shear web would be tapered out and replaced with fir blocking. The root thickness of the D spar and the fir blocking would be such that oversize holes could be drilled into which steel studs would be bonded (Fig. 2). The blade would be finished by adding trailing edge panels stiffened with a honeycomb (Virtacel) core and an aft plywood shear web. Figure 3 shows a planform of the blade and cross sections at different locations along the span. As can be seen, in the inboard part of the blade, a diagonal brace is added to transfer the loads from the trailing edge panels into the main D spar.

2.1 Development Philosophy

With this design there were two main areas of concern. The first, and most critical, was the ability of a bonded stud to carry both the high, one-time, hurricane load and the 30-yr fatigue loads introduced through WT operation. The second was the validity of the proposed manufacturing concept and its resulting low cost potential. Accordingly, to evaluate the stud loading concept, a number of test specimens (see Fig. 4) were fabricated and tested to establish a capability for carrying both one-time pull out loads and high cyclic life fatigue loads. In addition, a full scale section of the inboard (root end) 20 ft of the blade was fabricated (see Fig. 5) and tested to verify both the manufacturing process and the structural performance capability of the root end of the blade.

Results of these tests were encouraging and led to a second contract with the Gougeon Brothers to build two 40-ft sections for the MOD-0 WT (125 ft diam rotor, 100 kW) at NASA LeRC, Plum Brook, to refine the low cost wood blade concept, and to deliver two 62.5-ft blades for use on the MOD-0A at Kahuku, Hawaii (125 ft diam rotor, 200 kW) (Ref. 4). As part of this second contract effort, additional stud test specimens were fabricated and tested to optimize the stud/epoxy/wood interface configuration.

2.2 Root End Design and Test Conditions

Because of the constraints imposed by the MOD-0/0A WT configuration, operational wood blades of the MOD-0/0A size are required to transfer the blade loads to the rotor shaft through 24 bolts on an 18.625 in. bolt circle. And, while it would be possible to build the wood blade root to a much larger diameter and use a greater number of studs, to do so would require an adapter which would be heavy and costly and therefore undesirable. Consequently, it was decided early in the program that an 18.625 in. bolt circle with 24 studs that would mate directly to the existing MOD-0/0A hub flange would be a design goal.

2.2.1 Stud Load Analysis. - Having fixed the bolt circle and the number of studs, the maximum individual stud loadings could be quickly approximated. For fatigue loads, the maximum predicted flatwise and chordwise bending moments as predicted by MOSTAB (Ref. 5) computer analysis, and modified by MOD-0A operational experience, were combined vectorially to give a maximum root bending moment. This condition is conservative; since under normal operating conditions the flatwise and chordwise moments do tend to peak within the same 15^o of azimuth angle, but the maximum loads, which are experienced during high wind start-up and emergency shutdown do not peak simultaneously. For static loadings (hurricane), conservatism is built into the loads by using a 50 lb/ft^2 loading over the entire surface of the blade. The following table lists the loads which were used for design of the laminated wood blade and the test specimens.

Load condition	Root bending moment (ft-lb)			Bolt load (lb)	
	Flatwise	Edgewise	Combined	Mean	Cycle
Hurricane (includes 1.25 FS for buckling)	362,000	50,000	365,000	39,000	42,000
Fatigue (cut out wind condition 10^7 cycles)	10,000 $\pm$80,000	20,000 $\pm$50,000	22,000 $\pm$94,000	2,400	10,100

It should be noted that the "design" loads have not been fixed throughout this program. As additional data was made available from operational wind turbines and as computer codes were updated, the design loads changed. The loads shown in the table, therefore, represent typical design loads in a time frame near completion of the work effort being discussed in this report.

2.2.2 Test Conducted. - In all, approximately 100 stud specimens were tested. The 20-ft blade and root section was tested statically in flatwise, edgewise, and combined bending and also in torsion. In addition, fatigue tests at five different levels of combined flatwise and edgewise bending moment were conducted. The results of these studies have been applied in the blade fabrication contract efforts and the effectiveness of the test program will be determined by the operating experience on both the 40 ft and 62-1/2 ft blades which will be reported in the near future. The following sections of this report discuss the results, conclusions, and recommendations of the test program.

3.0 Stud Specimen Test Program

3.1 Test Specimen Design

Rather than test an entire set of studs on a simulated root end, it was decided that single, full-size, stud specimens would be used to evaluate the bonding concept and configuration. Each specimen (see Fig. 4) consisted of a laminated wood block, approximately 4 in. square and 24 in. long. Each of these blocks was drilled with an oversize hole on one end to accept a hardened 4140 steel stud which was cast in place using a filled epoxy resin. The other end of the block was fitted with 1/2 in. thick steel doubler plates which were bolted by using six 1/2 in. bolts and bonded with epoxy and glass scrim cloth. Variables evaluated in the test program were the wood block materials of construction, the epoxy/filler system used to cast the stud in place, the stud configuration (length, diameter, imbedded thread), and the hole configuration in the block (straight, tapered, step tapered, etc.).

3.2 Test Equipment

All stud specimens were tested using a Gilmore multiaxial test machine capable of 100,000 lb axial test force. In addition, the Gilmore machine could provide cyclic loading at rates up to 25 Hz. Control of the fatigue testing was achieved by a closed loop servo valve system with both upper and lower limits to prevent accidental or machine induced overload or underload conditions.

3.3 Initial Test Conditions and Results

The initial two variables investigated were the materials of construction of the wood block and the imbedded length of the stud. Approximately 50 specimens were tested in this series. However, during the initial testing effort, several test and specimen conditions which resulted in premature failures were discovered and resolved through appropriate specimen/test modifications. The two most significant items in this category are described below:

First, because the stud transfers load to the wood through shear in the epoxy resin, high shear stresses develop at the point of entry of the stud into the wood block. These shear stresses cause significant cross grain tensile stresses to develop at the end of the wood block. Since the cross-grain tensile capacity of the wood is less than 500 lb/in.^{2}, the result is a splitting failure of the wood with a premature pull out of the stud (see Fig. 6). It was found that bonding a thin layer of birch plywood to the end of the specimens would alleviate this problem. Plates clamped to the top of the specimen and fiberglass wrapping of the top were also tried but with less success. The effect of the birch ply can be seen in Figure 7 where comparative tensile load capacities are presented. As a result, birch ply was added to all subsequent stud test specimens and was also used to cap the end of the 20 ft blade test section.

The second item was more specifically related to the stud test configuration rather than to a stud/wood interface problem. During both the fatigue tests and the tensile ultimate tests, failures in the steel doubler plate area would frequently occur prior to any damage to the stud-epoxy-wood area. This problem was virtually eliminated by clamping flat steel plates on the two sides of the block that did not have the doubler plates. The plates extended from the bottom of the wood block to the top of the steel doubler plates and were clamped in place with four heavy "C" clamps. This effectively put a high compressive force on the entire bottom end of the block when the C clamps were tightened and the six bolts that held the doubler plates were torqued to about 100 ft-lb. Using this technique, doubler plate failures were reduced to about one specimen in five for tensile testing and almost no failures for fatigue testing. Having resolved the problems with the test specimen and test procedures, the initial phase of tensile ultimate and fatigue testing was completed and the results are plotted in Figures 7 through 10.

3.3.1 Test Variables. - The initial group of about 50 specimens included a number of variables which are noted on the plots and are summarized as follows:

(1) Wood type:

(a) Fir block; pieces of Douglas fir laminated from 3/4 in. to 1 in. thick

(b) Fir block specimens with a 1/2 in. thick plywood core in the approximate center simulating the shear web at the back of the built up spar

(c) Laminated 1/8 in. thick Douglas fir specimens

(d) Ash block specimens (similar in construction to the fir block)

(2) Imbedded stud length - Three different stud lengths; 9 in., 12 in., and 15 in. were evaluated. All studs were 4340 steel, heat treated to an ultimate strength of about 180,000 psi. The studs were 1 in. diameter and the imbedded length was threaded with a 1 in.x5 Acme thread. The length of stud protruding from the block was 2-1/2 in. long and had a 1 in.x13 thread which was screwed directly into the test machine.

(3) Hole configuration - Straight 1-1/4 in. diameter holes and tapered holes were evaluated.

3.3.2. <u>Discussion of Initial Results.</u> - Results of the tests are listed in Table 1 and are summarized as follows:

(1) Laminated fir veneer specimens show the greatest fatigue life in cyclic tests and can resist stud "pull-out" at tensile loads in excess of 70,000 lb.

(2) 15 in. stud depths increase both the tensile load and cyclic fatigue life of all specimens when compared with 12 in. and 9 in. stud depths (see Figs. 7 through 10).

(3) A step-tapered hole is a method that can be used to increase the load carrying ability of the wood/stud bond. As can be seen in Figure 7, fir veneer specimens with 15 in. stud depths increased in tensile load capacity from about 67,000 lb load to 75,000 lb load when the hole was step tapered (load values are an average of two specimens in both cases). The step-tapered hole causes more tearing to occur during failure (see Fig. 11) than does the continuous diameter hole which generally fails by splitting or shearing the wood.

(4) After reinforcing the specimen end with birch ply or fiberglass, the mean pull-out load for all 15 in. stud depth, laminated fir (veneer) specimens was 69,000 lb. This is well in excess of the 35,000 lb maximum load expected on the blade.

(5) One 12 in. stud depth specimen experienced over 10^6 load cycles at 10,000 lb $\pm$ 10,000 lb without failure of the bond. Based on all the specimen cyclic data, 15 in. stud depth laminated fir specimens are projected to have fatigue capability in excess of 10^6 cycles at 35,000 lb $\pm$ 10,000 lb as shown in Figure 10. (Plots of other cyclic fatigue tests with different stud depths are shown in Figs. 8 and 9.) This capability compares favorably with the requirement of 2400 lb $\pm$ 10,100 lb for 10^7 cycles.

(6) Fir block specimens are comparable with fir laminated specimens in stud pull-out capacity (see Fig. 7) but are inferior to the laminated specimens when loaded in a cyclic manner (see Figs. 8 & 9).

(7) With reference to the tensile ultimate capability as shown in Figure 7, fir block with plywood core specimens are inferior to fir block or laminated fir in load carrying capacity. The specimens have a tendency to split within the plywood, as shown in Figure 12, resulting in a premature failure of the specimen. Because of this problem, the blade design was modified to eliminate the plywood shear web in the area of the stud bolt-circle blocking.

(8) Results of the ash block specimen tests are inconclusive. Two of the specimens were of poor quality. The third was assembled differently from other block specimens but gave the highest tensile load value recorded (89,565 lb load). More testing of ash specimens is not recommended, however, since the capability of the fir appears to be more than adequate and fir is more readily available at a lower cost.

3.4 <u>Revised Specimen Testing</u>

As a result of the test program on the first 50 specimens a baseline stud configuration was developed. The key features were as follows:

Imbedded length - 15 in.
Block material - laminated Douglas fir (1/16 in. thick veneers)
Hole configuration - 5 step tapered - 1-3/4 in. diameter top to 1-1/8 in. diameter bottom
Stud material - 4340 (4140) heat treated steel

In addition, the stud design outside of the block was changed. Since the most frequent fatigue failures had been in the 1 in. threaded stud which screwed into a collar in the test machine, the studs for the second phase program were turned from 2-1/4 in. bar stock so as to leave a 2 in. threaded section which could be screwed into the test machine directly (without the collar). A picture of one of the studs can be seen in Figure 13. An additional 44 of these specimens were tested at various load levels and with appropriate modifications in the hole configuration and epoxy bonding material in an attempt to optimize the stud/wood bond configuration.

3.4.1 <u>Variables Investigated</u>. - This second series of stud test specimens also investigated a new set of variables which included:

(1) Fiberglass wrap around stud thread (vs. no wrap)
(2) Epoxy fillers of asbestos, carbon fiber, microspheres, silica, or CAB-O-SIL (vs. no filler)
(3) Release agent on imbedded threads (vs. bond prepared surface)
(4) 2 in. step tapered holes vs. 1-3/4 in. step tapered holes
(5) Auxiliary holes in the end of the wood block to alter and match the stiffness of the end of the specimen to the stiffness of the stud at the point of entry (see Fig. 14)
(6) Imbedded stud shape and thread configuration (see Fig. 15).

For each of the 44 specimens made for this phase of testing, the type of test run, and results are listed in Table 2 and are summarized below:

3.4.2 <u>Discussion of Results.</u> - Results of the second series of stud tests are summarized as follows:

(1) Static test data on a number of specimens was not obtained due to premature failure of the doubler plate bond/bolt joint. The valid failures that were obtained did, however, demonstrate that an average pull out strength on the order of 78,000 lb could be achieved. This value seems to be dictated by the maximum shear strength of the wood since failure is through shear of the wood very close to the epoxy/wood interface. This is not surprising since the shear area is on the order of 70 $in.^2$ and the resulting shear stress is in excess of 1100 psi. And, from the table of properties for Douglas fir, the maximum shear stress varies from 900 to 1400 psi with the material being used for the blade being estimated to be at the 1100 psi value. Consequently, if additional pull out resistance is needed, simply increasing the hole diameter and/or length will help. However, at 78,000 lb maximum stud load capability, a moment in excess of 700,000 ft-lb could be sustained on a typical MOD-0/0A type of blade (18.625 in. bolt circle - 24 bolts). This provides a factor of safety of 1.85 against the maximum design moment which is the hurricane wind loading. A similar condition will exist for larger blades because, even though the moment will increase by an order of magnitude, the bolt loading is inversely proportional to

the factor, nr, where n = number of bolts and r = bolt circle radius, which also increases by an order of magnitude.
(2) Fatigue data does not provide as concise a picture as does the static data. Initially, the fatigue failures were in the first thread of the stud where it entered the wood. All cyclic tests were run at 20,000 lb $\pm$ 15,000 lb load and stud failure occurred over a wide range--23,000 cycles to 1.1×10^6 cycles. This was not entirely surprising since the rate at which the first thread tapered from zero depth to full depth was quite variable (1/2 turn to 3 turns). Unfortunately, there were also several failures of the epoxy/stud interface. The first occurred at only 7000 cycles. This poor result was thought to be the result of a poor stud to epoxy bond (it was found that release agent had been applied to the stud). However, subsequent testing tends to cast doubt on this conclusion, and this result remains as an anomoly in the test program. But, when all the fatigue data for 15 in. long specimens is plotted as in Figure 16, it is apparent that except for three specimens, all of the fatigue failures are in excess of 100,000 cycles. Although one of these failures occurred at a stud load of 20,000 lb $\pm$ 15,000 lb, there appeared to be an anomoly in that particular specimen since all other specimens tested at that level went more than 100,000 cycles. If the 20,000 lb $\pm$ 15,000 lb load level is used for an upper bound fatigue limit, this translates to a maximum root moment of more than 325,000 ft-lb. (The equation $P = 2M/NR$ relates the stud load, P, to the bending moment, M. This equation assumes an equally spaced bolt pattern of N bolts on a circle of radius R. For the MOD-OA blade, $N = 24$ and $R = 18.625/2$. Thus for MOD-OA, $P = M/111.75$ for M expressed in units of in-lb or $P = M/9.3125$ for M expressed in ft-lb.) Using the lower bound line estimated on Figure 16, the infinite life fatigue case would be about 15,000 $\pm$ 15,000 lb, which translates to a root moment of 279,000 ft-lb. For comparison, the current measured fatigue data from MOD-OA operations shows that the blades will experience a maximum root moment of only 230,000 ft-lb; and this will occur less than 1×10^4 times. The MOD-OA machine will more normally be operating at a root moment of 120,000 ft-lb which is a maximum bolt load of only 13,000 lb. Consequently there is a minimum of 21% margin on fatigue, even if the extreme fatigue moment condition is assumed to accumulate not 1×10^4, but an infinite number of cycles. And, while additional stud testing is required to further refine the lower failure bound in fatigue and to resolve the few anomolies in this data, there appears to be adequate margins in both fatigue and ultimate capability to warrant use of the design concept for fabrication of demonstration blade hardware.

3.5 Single Stud Test Conclusions

As a result of the two stud test series; the following conclusions were drawn:

1. Stud configuration (imbedded portion) should be tapered similar to that shown in Figure 15(a). Thread type and taper ratio appear to be rather insignificant to overall performance.
2. The hole in the wood should be step tapered.

3. Asbestos filler in the epoxy appears to be a good choice although a carbon-fiber filler (or other fillers which would tend to increase modulus) may eventually prove to be better from a fatigue standpoint.
4. For 15 in. long stud designs, pull out loads in excess of 78,000 lb per stud can be achieved.
5. For the 15 in. long, tapered stud design, an infinite life fatigue load of 15,000 lb $\pm$ 15,000 lb was indicated by test data and 10,000 lb $\pm$ 10,000 lb could be used as a design value.

4.0 20 Ft Root End Section Testing

A 20 ft section of a laminated wood wind turbine blade was fabricated for use as a test specimen. This test specimen duplicated the inboard 20 ft of the proposed 62-1/2 ft MOD-0 blade except that the outboard 3 ft were reinforced in the area of the D-spar to provide for input of shear loads during the test program. Also, since it was decided to test the blade for trailing edge buckling stability, the test specimen did not have the trailing edge panels slotted as specified by the design of the MOD-0 blades. If it was determined during the test program that slotting was necessary, the slots could be provided at that time. (Subsequent designs have eliminated the need for slotting of the trailing edge.) The blade root was fitted with 24 studs (Fig. 17) on an 18.625 in. bolt circle. An aluminum load block (Fig. 18) was then screwed and glued to the outboard end of the blade and the blade section was instrumented with 43 strain gauges (Fig. 19).

The instrumented blade section was subjected to three test phases. The initial phase, at NASA LeRC, included load/deflection tests in flatwise, edgewise, and combined cantilever bending. The blade section was then sent to Ft. Eustis, Va. (US ARTL Applied Technology Lab) for Phase II which was cantilever bending fatigue testing. Upon completion of the fatigue tests, the section was returned to LeRC for Phase III which included tests to evaluate the effect of pretorque and moment on stud stress and the final failure load/deflection test in flatwise cantilever bending. The discussion of the testing and results from each phase is as follows:

4.1 Phase I Tests

The instrumented 20 ft blade section was installed in the flatwise position as a cantilever beam on a strongback as shown in Figure 20. Hydraulic jacks mounted on the load frame and controlled by hand operated hydraulic pressure regulators were used to load the blade through a chain connection. Initially, the blade was pulled upward from the forward hole in the load block and then from the aft hole (see Fig. 18 for hole locations). The applied load, deflection, and rotation were recorded and used to determine the shear center of the blade section. A hole was then drilled in the load block so that the hydraulic jacks would pull through the shear center. Further tests indicated that this empirical method was accurate since even at loads in excess of the hurricane moment, only minimal twist could be detected (as described in following paragraph).

4.1.1 Test Procedure. - Once the shear center was located, flatwise, edgewise, and combined bending tests were conducted. Maximum root moments achieved were 224,000 ft-lb for both flatwise and chordwise bending, and 231,000 ft-lb for combined bending. In each case, the load was introduced in discrete steps and the strain gauge readings were recorded after the load had stabilized at each step. Blade deflection was measured by measuring change in displacement of pointers attached to both ends and the center of a 10 ft bar which in turn was attached to the end of the blade (see Fig. 21). This technique confirmed the position of the empirically determined shear center since less than 3° twist could be detected under the maximum loads.

4.1.2 Discussion of Results. - The maximum deflections measured were somewhat misleading at first. In the flatwise test, a deflection of about 6 3/8 in. was measured. This compared with the predicted deflection of 3 1/4 in. However, subsequent measurement of plate bending for the backstop indicated that a deflection of 3 1/8 in. could be accounted for through rotation of the fixture. Hence, the actual measured deflection was adjusted to 3 1/4 in. which agreed with the predicted value.

Response of all strain gauges was repeatable and linear with respect to applied load. EI curves and complete strain gauge locations are shown in Figures 22 and 23. The strain gauges placed over one stud and between two studs (see Fig. 23(c)) showed almost identical response to loading (see Fig. 24) indicating that the studs were transferring the bending load efficiently and without high peak stresses in the wood. The maximum stress recorded occurred during flatwise loading to 224,000 ft-lb and was less than 3400 psi (compression). When the applied moment is ratioed to the 116,000 ft-lb cut-out wind condition moment (10^7 cycles) the stress drops to 1760 psi which is well below the 2200 psi infinite life design allowable stress. Once again, when a high level, limited cycle, load condition is considered an infinite life case, a significant, 25%, positive margin of safety is shown. Figures 25 and 26 show some of the measured maximum strain data for flatwise bending and comparisons with predicted data. As can be seen, the predicted data is conservative (greater than or equal to the measured data). The occasional large discrepancies between measured and predicted values for certain gauges are attributed to the fact that the predicted values were based on the assumption that the trailing edge panels were slotted and contributed little to the load carrying capability. In the actual case, the panels were not slotted and therefore shifted the chordwise neutral axis and the load sharing within the structure. Table 3 presents the predicted versus the measured values for selected strain gauges in the three loading cases.

Edgewise, and combined bending all showed similar trends but lower stresses. No permanent set, cracking, buckling, or warping was detected. For edgewise bending, with the trailing edge in compression, the trailing edge panels showed no evidence of buckling. Consequently, it was determined that the trailing edge panels would not require slotting to preclude buckling.

4.2 Phase II Tests

Following completion of the Phase I load/deflection tests, the instrumented blade was shipped to the U.S. Army Research and Technology Laboratories at Ft. Eustis, Va. for fatigue testing. At Ft. Eustis, the blade was mounted as a cantilever beam to a 2 in. thick steel plate (54 in.^{2}) which was backed up with 12 in. "H" beams having reinforced webs. Figures 27 and 28 show the blade as mounted. The free end of the blade was attached to a hydraulic actuator through a load cell and an LVDT. Load was calibrated as a function of actuator stroke and the test was then controlled by the stroke measurement. Periodic checks were made to determine if changes in load/stroke relationships had occurred. To closely approximate the combined flatwise and edgewise design loads, which reach similar peak values at approximately the same time, the blade chord line was set at a 45^{o} angle to the applied load. The innermost 3 ft of the test section then was subjected to loadings which closely approximated those expected in the field. This had little influence on the outboard portion of the test specimen since the applied moment was well below the peak seen by that part of the blade during actual service. Figure 29 shows a plot of the moment on the blade as induced by wind turbine operations and a comparison of the test moment. Eighteen strain gauges were active for this phase of the testing. Using the data obtained in the Phase I testing, strain/moment values were predicted and found to correlate for most of the active gauges during the initial load deflection tests in the Ft. Eustis facility.

4.2.1 <u>Problem Definition and Resolution.</u> - After running a load/deflection/strain test, the fatigue testing was started by applying a cyclic force between 500 and 4000 lb at the free end of the blade. A cyclic frequency of 4 Hz was used throughout the testing (except for some limited attempts at 6 and 8 Hz operations). This load was equivalent to the rated wind condition on an actual blade. After 370,000 cycles it was found that 10 of the studs had failed in the 5/8 in. diameter threaded length outside of the wood. All but 4 of the failed bolts were on the compression side of the bolt circle and subsequent examination (Fig. 30) indicated that failure of the studs was due to bending and not tensile stresses. Visual observations of the framework during testing corroborated this analysis since the 2 in. thick steel plate could be seen to deflect significantly under load. There was no evidence of any damage to the wood portion of the test specimen.

Rather than abandon the test, the specimen was sent back to the contractor, Gougeon Bros., Inc., for replacement of the studs. This became an ordeal as it was quickly learned that removal was not easy. A number of staples had been used in the construction of this blade section (a practice which is no longer used) and the staples made the use of a deep hole saw difficult. An attempt was then made to simply unscrew the studs from the epoxy. This resulted in breaking the stud. The unscrewing technique was then tried in combination with application of a high amperage current to heat the stud and soften the epoxy. This was equally unsuccessful. Finally, the hole saw technique was made to work by "brute force" with the result that a rather large and uneven hole was left in the blade as each stud was removed. These holes were subsequently smoothed and tapered by a large boring cutter and were then filled by matching tapered wood plugs made from laminated fir. When all studs had been removed and the holes filled, the root of the test section was redrilled and fitted with 24 new studs having a slightly modified configuration (Fig. 31) featuring a 3/4 in. diameter threaded shank rather than the previously used 5/8 in. diameter. This modification was based on the decision that mating with a hub spindle on the wind turbine would require a very stiff flange which could quite easily accomodate a 3/4 in. stud. Consequently, prior to sending the test section back to Ft. Eustis, a 10 in. long spool piece was machined (Fig. 32).

4.2.2 Fatigue Test Load Level. - After the repair of the studs was completed and the concept by which wood blades would be mated to a wind turbine spindle was revised, the test specimen and spool piece were shipped back to Ft. Eustis to continue the test program. Mounting and set up was identical to that used before, except that the 2 in. steel plate was reinforced with an additional H beam and the 10 in. spool was inserted between the root end of the blade and the plate.

Testing was then resumed at Ft. Eustis at the 4000 lb load level. One million cycles were completed without incident. The peak load was then increased to 5500 lb and another $1x10^6$ cycles were run without incident. This represented the 40 mph wind, 40 rpm rotor speed condition. Once again, the load was increased by 1500 lb and another $1x10^6$ cycles were run with no damage to the blade or studs. Finally, the load was increased to a 10,000 lb peak which represented the MOD-0 emergency shutdown condition. This load would be expected to occur less than 10^4 times for either MOD-0 or MOD-0A operations. After 670,000+ cycles at this condition, four studs on the tension side of the blade were found to have failed in the 3/4 in. threaded section. The testing was then terminated and the blade section was returned to LeRC for examination and additional testing.

4.2.3 Summary of Fatigue Test Results. - Throughout the entire test program at Ft. Eustis, the strain gauges operated linearly and effectively. This was most evident when attempts were made to increase the cyclic rate. At about 6 Hz a definite flatwise resonance was detected which resulted in increased strains for gauges on the upper and lower blade surface. Again, at 8 Hz, an edgewise resonance was detected through increased strain in leading and trailing edge gauges. A somewhat crude analysis was then made, with estimated load block and actuator weights, and the natural frequency of the test specimen was found to correspond closely to the resonant modes found in the test program; calculated flatwise = 5.4 Hz and calculated edgewise = 7.2 Hz.

To complete the Phase II testing, the blade section was examined at LeRC. The spool was removed and it was found that, not four, but seven studs had failed. The three studs carrying the highest tensile load had failed at the transition from the 1 3/8 in. collar to the 1 in. acme threaded stud which was imbedded in the wood. Due to an oversight, there was an extremely sharp corner at this point (estimated to have a radius less that 0.002) (see Fig. 31). It was surmised that these three studs had failed due to the stress concentration at that point and had then dumped the additional load into the studs on either side. The two studs on each side had then failed in the 3/4 in. threaded section (and were the ones noticed to have failed at Ft. Eustis), probably due to the increased load the studs were required to carry along with bending load in the 3/4 in. section from the deflection of the spool piece flange face.

Figure 33 is a summary of the test conditions at Ft. Eustis as compared to both the blade operating requirements and the individual stud test data. It should be noted that Figure 33 has converted the actual test moments to a maximum bolt load based on the number of studs and the bolt circle diameter. To convert back to moment, multiply the bolt load by 9 (approximate) to obtain the moment in ft-lb. The most significant point to be extracted from Figure 33 is, however, that while the actual testing of the blade section was far in excess of the MOD-OA design points there was no failure of the wind or bend joints. In addition, 670,000 cycles were required to fail studs even though there was a severe stress concentration built into the stud and $3x10^6$ cycles at lower loads had been previously applied.

Based on the fatigue testing the following conclusions were reached:

1. The concept of a laminated wood blade was practical.
2. Bonded studs could be designed to adequately transfer the spectrum of cyclic bending moments which would be experienced during the operational life of a wind turbine blade.
3. The physical properties of the wood, and the wood construction methods were more than adequate to survive the severe fatigue loads of wind turbine service.
4. Additional design optimization of the studs could provide for increased operating loads or margins of safety in the wind turbine blade application. However, future MOD-OA size machines should provide a larger diameter bolt-circle which will allow lower cost and less complex bolt concepts to be considered as design alternatives.

4.3 Phase III Testing

Phase III testing consisted of 3 elements. First, in order to evaluate the effectiveness of pretorquing the 3/4 in. studs in reducing fatigue stresses, three studs were each instrumented with four strain gauges. Plots of stud stress were developed as a function of both the pretorque value and the applied bending moment on the blade section. Then, with the broken studs oriented to be on the compression side of the bolt-circle, the blade section was loaded in cantilever bending to failure. Finally, the 20 ft long blade was cut up for examination. A discussion of each of these elements is provided below:

4.3.1. Stud Pretorque Tests. - For this test, three adjacent studs were each instrumented with four strain gauges. The gauges were applied by grinding flats on the unthreaded portion of the 3/4 in. stud. Orientation of the gauges and the studs was as shown in Figure 34. Very fine lead wires (36 gauge) were used and grooves were ground in the face of the stud shoulder to preclude crushing of the wire when the spool was put on and the nuts were torqued. The spool piece was then slipped into position and all the studs but the three having strain gauges (and those broken) were torqued to 150 ft-lb. The blade was then mounted on the test stand as a cantilever beam and the strain gauges on the instrumented studs were zeroed.

Nuts were then placed on each of the three instrumented studs and pretorque was applied. Then, a bending moment was imposed on the blade in discreet steps and the change in stud strain for each step (including the pretorque step) was measured. The strain data from the four gauges on each stud was then used to determine the centerline stress and a maximum perifial stress for each load level and each stud. Plots of the most highly stressed stud are shown in Figure 35. As can be seen, pretorque of the stud-through-flange configuration of the wood blade does not eliminate the cyclic stresses in the shank of the bolt. This finding is in contrast to the typical flange-to-flange joint where the bolts can be pretorqued to produce a stress that will hold the flange faces together under the highest load to be expected. Normally in a bolted joint with sufficient pretorque in the bolts, subsequent changes in stress in the bolt are very small or non-existent as long as the load does not exceed that for which the pretorque was established. For 3/4 in. bolts, the pretorque can be as high as 400 ft-lb. However, for the stud-to-flange connection of the wood wind turbine blade, pretorque above 250 ft-lb would probably tend to decrease cyclic capability. Additional test data will be developed and reported at a later date. However, it appears that there is a rather broad range of torque values (50 - 200 ft-lb) that will produce satisfactory fatigue results. And, even at 350 ft-lb, the value selected for the fatigue testing at Ft. Eustis, a properly designed stud provides a positive margin of safety on fatigue.

4.3.2 Failure Load Test. - Upon completion of the last pretorque test, the test section was loaded to failure. Two 11 kip hydraulic actuators were used to load the blade tip. A total force of 19,200 lb was applied. At that point, all the nuts on the studs on the tension side of the bolt circle stripped off. No damage was done to the blade but at this point the studs were past the point of salvage (threads stripped and some bending) and the test was terminated. No further attempt was made to break the blade. The applied load represented a root moment in excess of 390,000 ft-lb which is about 1/3 greater than the hurricane loading. Once again, the wood demonstrated structural capability in excess of the design requirements.

4.3.3. Visual Examination. - After all testing was complete the blade was sectioned for examination. Pertinent photographs are shown in Figures 36 through 43. Only one area of wood cracking was found and can be seen quite clearly in Figure 39. It is not known what caused this crack but it could have come from the work of replacing the studs or from the sectioning operation itself. Due to its location, it is not considered to be a result of the fatigue or ultimate loads.

Several studs were removed from the blade and an attempt was made to examine the cast epoxy area. By slicing through wood and epoxy on either side of the stud and then prying the two halves apart, it was possible to visually evaluate the result of the testing on the stud bond. In general, the studs were still well bonded. In local areas, the epoxy was cleanly separated from the stud and in some areas there was evidence of fatigue cracks in the epoxy. None of the damage was as severe as that seen in the individual stud tests discussed in Section III. It is therefore believed that the stud-to-wood bond was not close to fatigue failure. A picture of one of the studs with the wood and epoxy broken away is shown in Figure 43.

5.0 Conclusions

As a result of the test effort described above, the following conclusions have been drawn.

1 A properly designed, epoxy impregnated, laminated wood blade with bonded-in studs can withstand the wind turbine load spectrum with a positive margin of safety.
2. Laminated wood impregnated with epoxy can be fabricated into a stable engineering material with dependable performance characteristics.
3. A stiff flange is required to accept the studs without causing excessive bending stresses and subsequent premature failure of the studs.
4. Bonded studs can be replaced without affecting the capability of the blade.
5. The root end design resulting from this test effort meets or exceeds the current requirements of the MOD-0/0A wind turbines. However, if increased moment capability should be required in the future, there are several techniques available. A larger diameter bolt circle with more studs would be the most straight forward solution. Another solution would be the further refinement of the stud design to achieve a higher allowable load for each stud.
6. Environmental effects of temperature, moisture, and sunlight should be more thoroughly evaluated. While the testing discussed in this report took place over a period of 15 months and included outdoor tests in both winter and summer, no detailed evaluation of environmental effects has been conducted. In addition, long term exposure has not been evaluated at all. It should be stated that a problem is not expected since this type of construction has been used for boats for a number of years without incident, but, the performance of blades in the field should be monitored for potential environmental effects.

6.0 References

1. Sullivan, T. L.; et al.: Wind Turbine Generator Rotor Blade Concepts With Low Cost Potential. NASA TM-73835, DOE/NASA/1028-77/13, 1977.
2. Griffee, D. G., Jr.; Gustafson, R. E.; and More, E. R.: Design, Fabrication and Test of a Composite Natural Wind Turbine Rotor Blade. (HSER-7383 Hamilton Standard Div., United Technologies Corp.; NASA Contract NAS3-19773.) NASA CR-135389, 1977.
3. Large Wind Turbine Design Characteristics and R and D Requirements. NASA CP-2106, CONF-7904111, 1979.
4. Gougeon M.; and Zutech, M.: Use of Wood for Wind Turbine Blade Construction, Large Wind Turbine Design Characteristics and R&D Requirements. NASA CP-2106, CONF-7904111, 1979, pp. 298-308.
5. Spera, D. A.: Comparison of Computer Codes for Calculating Dynamic Loads in Wind Turbines. NASA TM-73773, 1977.

TABLE I
INITIAL BONDED STUD TEST RESULTS
(a) Tensile Ultimate Results

SPECIMEN #	STUD DEPTH (IN.)	MATERIAL[1)]	MAX. LOAD (LBS)	FAILURE[2)] TYPE	NOTES
1A	15	LF	75,350	Tear out of wood	Tapered hole, fiberglass wrap on stud
2A	12	AB	50,725	Wood Core	Birch Ply Top
3A	12	PB/PC	48,485	"	"
4A	12	AB	41,265	"	"
MS	15	LF	67,560	"	"
3	9	LF	42,000	"	"
9	9	LF	38,000	End Split	No top reinforcing
10	12	LF	53,350	Wood Core	Birch Ply Top
12	12	LF	50,000	Plate Loose	"
13	12	LF	63,460	Wood Core	"
17	12"	LF	44,900	End Split	No top reinforcing
20	15"	LF	61,345	Wood Core	Fiberglass top
21	15"	LF	44,000	End Split	No top reinforcing
24	15"	LF	65,800	Wood Core	Birch Ply Top
27	15"	LF	47,190	End Split	Plates Clamped at top
28	9"	FB	34,000	Wood Core	Birch Ply Top
30	9"	FB	44,900	"	"
31	12"	FB	57,560	Plates Loose	"
32	12"	FB	47,890	Wood Core	"
34	15"	FB	44,565	Plates Loose	"
35	15"	FB	55,840	"	Plates clamped at top
36	15"	FB	54,140	"	" " "
39	9"	FB/PC	32,600	Ply Core Split	No top reinforcing
40	12"	FB/PC	43,640	"	" "
41	12"	FB/PC	35,790	"	" "
43	15"	FB/PC	45,325	"	" "
44	15"	FB/PC	58,145	"	Birch Ply Top
45	15"	FB/PC	58,365	"	Plates clamped at top
47	15"	AB	89,565	Wood Tensile	Birch Ply Top
48	15"	LF	74,775	Tear out of wood	Same as 1A

(b) Fatigue Test Results

SPECIMEN #	STUD DEPTH	MATERIAL[1)]	MEAN LOAD (LBS)	CYCLIC LOAD ± LBS	CYCLES	FAILURE[2)] TYPE	NOTES*
5A	9"	AB/PC	20,000	10,000	51,900	Pull out	Wood split at 5400 cycles
2	9"	LF	15,000	20,000	128,109	Stud	
4	9"	LF	25,000	10,000	50,010	Pull out	
5	9"	LF	30,000	10,000	3	"	Cyclic speed (manual)
6	9"	LF	10,000	10,000	630,804	Stud	
7	9"	LF	30,000	10,000	1,222	Pull out	
8	9"	LF	20,000	10,000	61,973	"	
11	12"	LF	20,000	20,000	4,783	"	
14	12"	LF	10,000	10,000	1,307,140	Stud	
15	12"	LF	20,000	10,000	399,890	"	
16	12"	LF	30,000	10,000	210,021	"	
18	12"	LF	30,000	10,000	121,296	"	
19	15"	LF	40,000	10,000	10,639	Pull out	
22	15"	LF	20,000	20,000	36,800	Stud	
25	15"	LF	40,000	10,000	99,152	Stud	
29	9"	FB	20,000	10,000	50,812	Pull out	
33	12"	FB	30,000	10,000	51,577	Pull out	
46	15"	FB	20,000	10,00	124,582	Stud	Tapered hole, fiberglass

1) Material Designations:
LF - Laminated Fir (1/8" thick veneers of fir)
AB - Ash block (1/2" to 1" thick dimensional lumber bonded to make specimen)
PB - Pine block (1/2" to 1" thick dimensional lumber)
/PC - Plywood Core bonded into center of test specimen
FB - Fir block (1/2" to 1" thick dimensional lumber)

2) Failure Type:
Tear out of wood - Failure of wood in combined tension and shear with splintering and very rough edges.
Wood core - Shearing of a core of wood, adjacent to the epoxy, leaving a clean straight-sided hole slightly larger in diameter than that originally drilled and equal in length to the imbedded depth of the stud.
End Split - Opening of the stud end of the block due to cross grain tensile forces and resulting in expansion of the hole size to the point where the stud comes out cleanly.
Plate Loose - Failure of the doubler plate bonded/bolted joint.
Ply Core Split - Identical to end split except that these specimens had a 1/2" thick plywood layer in the center in which the splitting started.
Wood Tensile - One specimen appeared to have failed due to a straight tensile stress in the wood block in the area where the bolt holes for the doubler plate had been drilled.

*All fatigue specimens had birch ply bonded at top and were cycled at about 10Hz except as noted.

TABLE II

TEST RESULTS FROM SECOND SERIES OF STUD SPECIMENS

SPEC. #	TEST TYPE	STUD TYPE	MAX[1] HOLE DIA. (IN.)	EPOXY FILLER	STUD TREATMENT	MAX. LOAD (LBS.)	MIN. LOAD (LBS.)	CYCLES	FAILURE TYPE
1	Static	1" ACME	1 3/4	Asbestos	None	54,000	--	--	Doubler Plate
2	Fatigue	"	"	"	"	45,000	5,000	9,635	"
3	F	"	"	"	"	45,000	5,000	3,821	"
4	S	"	"	"	"	50,000	--	--	"
5	F	"	"	"	Release Agent	45,000	5,000	6,857	Pull Out
6	F	"	"	"	None	45,000	5,000	9,533	Doubler Plate
7	S	"	"	"	"	65,860	--	--	"
8	F	"	"	"	"	45,000	5,000	23,086	Stud
9	F	"	"	" (2)	"	45,000	5,000	12,540	Doubler Plate
10	F	"	"	CAB-O-S/L	"	35,000	5,000	280,383	Epoxy Fatigue
11	F	"	"	Asbestos[2]	"	35,000	5,000	64,000	Stud
12	F	"	"	Carbon Wool	"	35,000	5,000	172,000	"
13	F	"	"	"	"	35,000	5,000	1,112,840	"
14	F	"	"	"	"	35,000	5,000	64,880	"
15	S	"	"	"	"	79,000	--	--	Wood/Epoxy Interface
16	F	"	"	"	"	35,000	5,000	71,450	Stud
17	F	"	2"	Asbestos	Sanded	35,000	5,000	608,450	Epoxy Fatigue
18	F	"	"	"	"	35,000	5,000	43,660	Stud
19	F	"	"	"	"	35,000	5,000	36,110	"
20	F	"	" (3)	"	"	35,000	5,000	90,040	"
21	S	"	" (3)	"	"	71,800	--	--	Doubler Plate
22	S	"	" (4)	"	"	76,300	--	--	"
23	F	"	" (4)	"	"	35,000	5,000	207,340	Epoxy Fatigue
24	Fatigue	"	1 3/4	Microspheres	Grit Blast	35,000	5,000	12,800	"
25	"	"	"	"	Sanded (6)	35,000	5,000	220,500	Stud
26	"	"	"	Silica	" (6)	35,000	5,000	28,610	"
27	"	"	"	"	" (6)	35,000	5,000	138,450	"
28	"	"	3.14	(5)	Grit Blast	35,000	5,000	5,930	Accidental Overload
29	"	"	1 3/4	Asbestos[2]	Sanded[6]	35,000	5,000	167,600	Epoxy Fatigue

30	Static	Tapered(7)	1 3/4	Asbestos(2)	Grit Blast	80,000	--	--	Doubler Plate
31	"	" (8)	"	Asbestos	"	88,700	--	--	"
32	"	" (9)	"	"	"	82,500	--	--	"
33	"	" (10)	"	"	"	77,900	--	--	Wood/Epoxy Interface
34	Fatigue	" (8)	"	"	Grit Blast & Mold Release	35,000	5,000	2,906,470	Epoxy Fatigue
35	"	" (7)	"	"	"	35,000	5,000	807,000	"
36	"	" (9)	"	"	"	35,000	5,000	3,005,290	Doubler Plate
37	"	" (10)	"	"	"	35,000	5,000	3,024,110	Epoxy Fatigue
38	"	" (11)	"	"	"	Data Lost			
39	"	" (8)	"	"	Grit Blast	35,000	5,000	1,040,100	Epoxy Fatigue
40	"	" (7)	"	"	"	35,000	5,000	722,870	"
41	"	" (9)	"	"	"	35,000	5,000	125,480	Doubler Plate
42	"	" (10)	"	"	"	35,000	5,000	511,810	Epoxy Fatigue
43	"	" (10)	"	"	Wire Brush/ Mold Release	35,000	5,000	1,484,550	Doubler Plate
44	"	" (10)	"	"	Wire Brush/ Mold Release	35,000	5,000	240,820	Epoxy (Stud Misaligned)

(1) All holes for this test series were step tapered. Hole diameter listed is the maximum hole size.

(2) Also included in the filler was a fiberglass-tape which was wrapped around the screw threads.

(3) Auxiliary holes in each of four corners filled with resin and silica. Hole configuration step tapered: 3/4" to 6" deep, 1" to 4" deep, 1 3/4" to 2" deep.

(4) Same holes and filler as (3) with four additional step tapered holes 7/16" to 6" deep, 5/8" to 4" deep and 3/4" to 2" deep.

(5) Asbestos filled Jeffamine resin used instead of WEST epoxy.

(6) Reused studs (sanded).

(7) Stud as per Figure 15b.

(8) Stud as per Figure 15a.

(9) Stud as per Figure 15c.

(10) Stud as per Figure 15d.

(11) Stud as per Figure 15e.

TABLE III

BLADE PROPERTIES AND STRAINS

							Strain (in)			Strain (in)			Strain (in)	
GAGE	EIx*	EIy	EI45o	X(IN)	Y(IN)	Mx (IN-LB)	PRE-DICTED	MEA-SURED	My (IN-LB)	PRE-DICTED	MEA-SURED	Mc (IN-LB)	PRE-DICTED	MEA-SURED
1	19	17.5	18.25	-12	0	2.62×10^6	0	0	2.385×10^6	1506	562	2.698×10^6	836	468
2	19	17.5	18.25	3	10.6	1.98×10^6	1587	365	2.385×10^6	375	---	2.698×10^6	-1830	-198
3	19	17.5	18.25	12	9.96	1.98×10^6	1491	168	2.385×10^6	1506	---	2.698×10^6	-2714	-134
4	19	17.5	18.25	24	7.14	1.98×10^6	1069	36	2.385×10^6	3013	---	2.698×10^6	-3673	-4
5	19	17.5	18.25	36	2.93	1.98×10^6	439	121	2.385×10^6	4518	-124	2.698×10^6	-4488	-150
12	44.5	13.8	29.15	-14	0	1.98×10^6	0	0	1.845×10^6	581	980	2.087×10^6	405	750
13	44.5	13.8	29.15	1	10.02	1.98×10^6	1438	1385	1.845×10^6	-41	-312	2.087×10^6	-862	-1042
14	44.5	13.8	29.15	16	8.26	1.98×10^6	1185	719	1.845×10^6	-663	-440	2.087×10^6	-1532	-786
15	44.5	13.8	29.15	34	2.76	1.98×10^6	396	260	1.845×10^6	-1409	-1162	2.087×10^6	-2165	-1156
20	37.5	10.8	24.15	16	7.93	1.55×10^6	1138	1126	1.485×10^6	-633	-976	1.680×10^6	-1472	-1396
21	28	16.3	22.2	16	8.72	2.41×10^6	1289	392	2.205×10^6	-1260	-228	1.495×10^6	-2241	-452
28	19	17.5	18.25	7	-10.6	2.62×10^6	-1587	-326	2.385×10^6	125	---	2.698×10^6	376	114
29	19	17.5	18.25	22	-7.14	2.62×10^6	-1069	-17	2.385×10^6	2761	---	2.698×10^6	-2180	-18
34	50.5	13	31.75	7	-9.82	1.83×10^6	-1382	-1236	1.725×10^6	34	-188	1.952×10^6	123	598
35	50.5	13	31.75	16	-8.10	1.83×10^6	-1140	-500	1.725×10^6	546	-762	1.952×10^6	-604	-282

*Corrected for trailing edge panel contribution

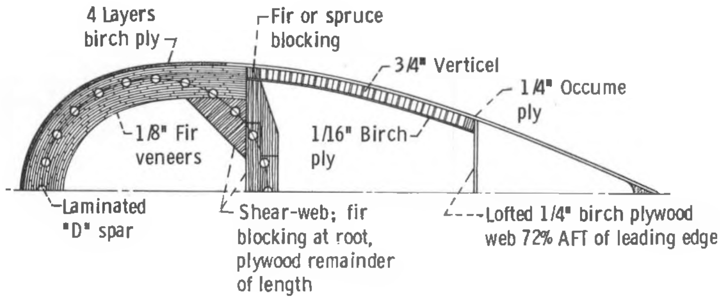


Figure 1. - Laminated wood blade design concept.

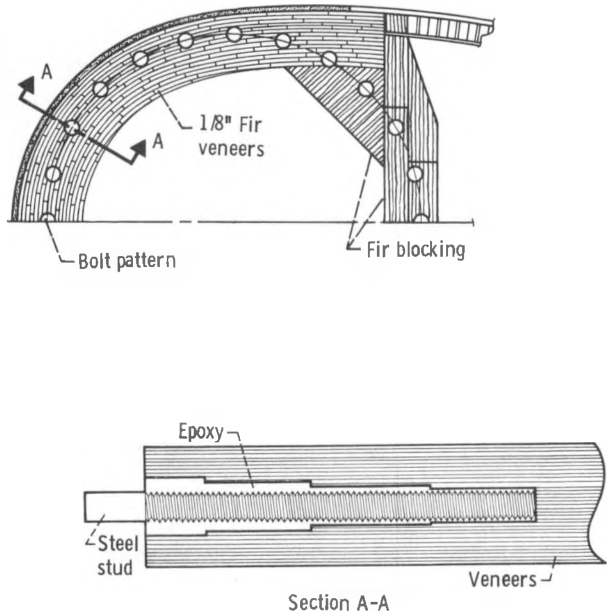


Figure 2. - Wood blade root-to-hub attachment concept.

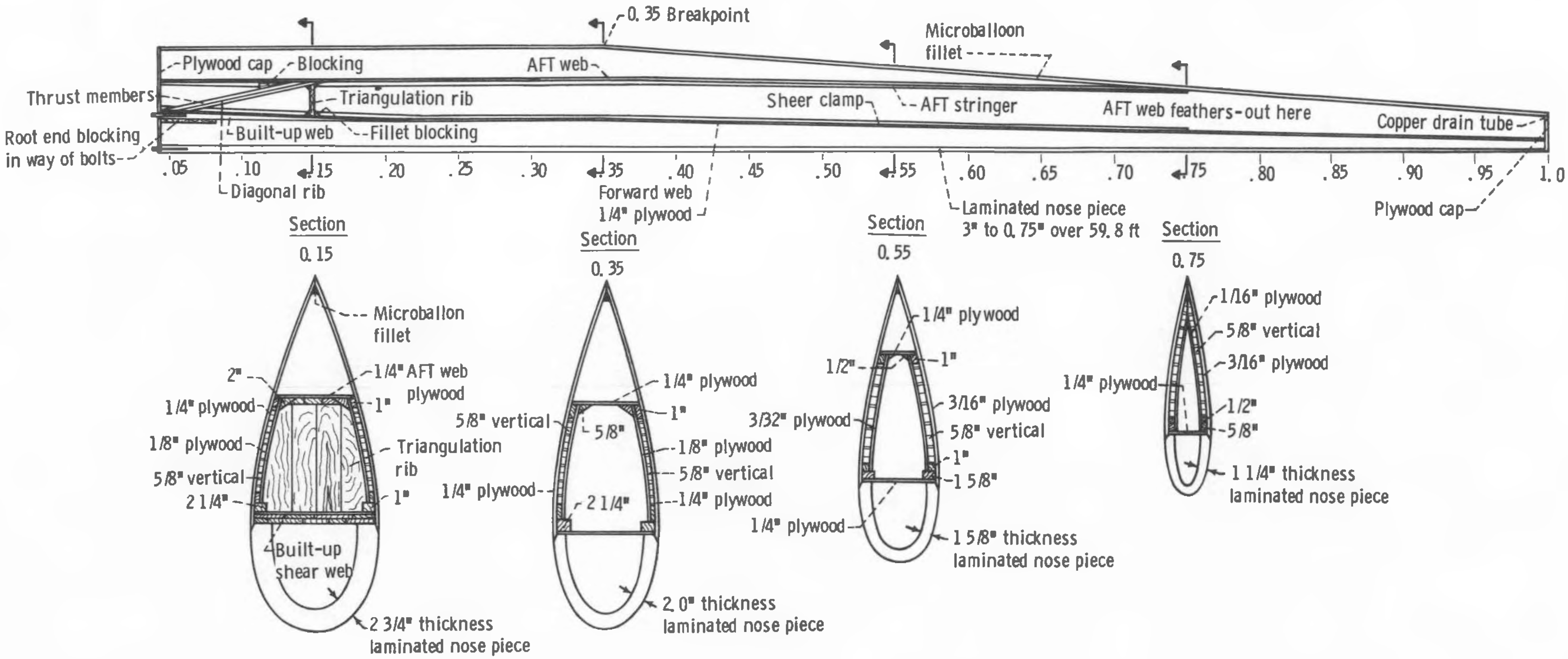


Figure 3. - Detailed planform of Mod O laminated wood wind turbine blade design.

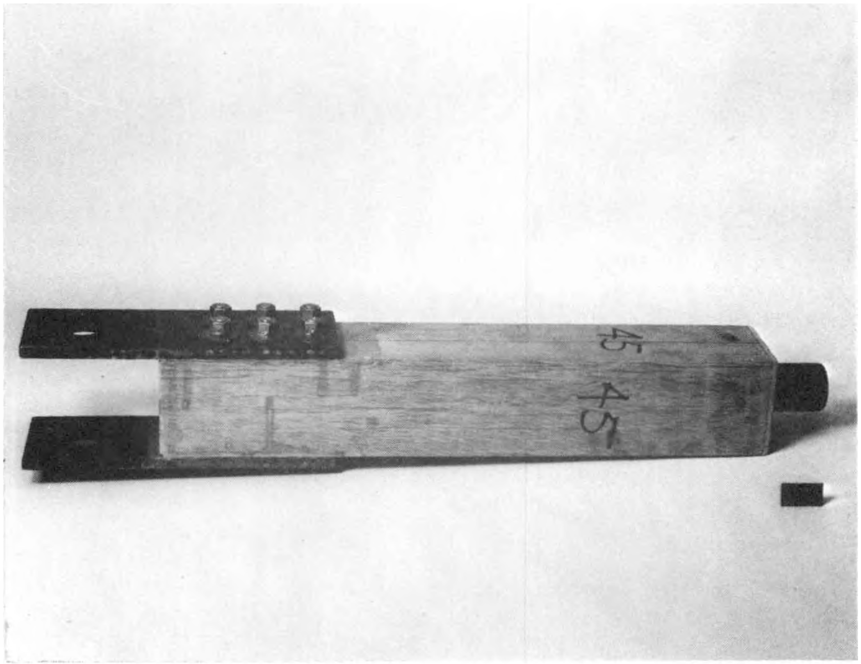


Figure 4. - Typical stud bond test specimen.

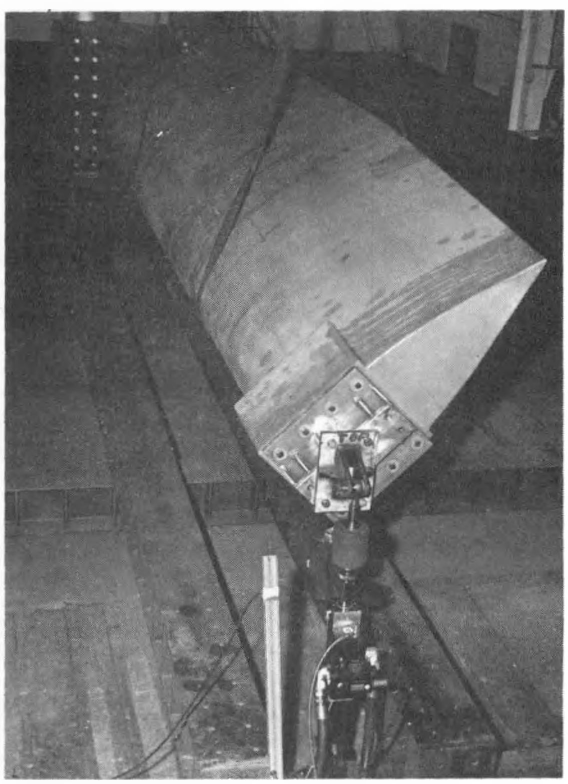


Figure 5. - Twenty foot long laminated wood wind turbine blade test specimen.

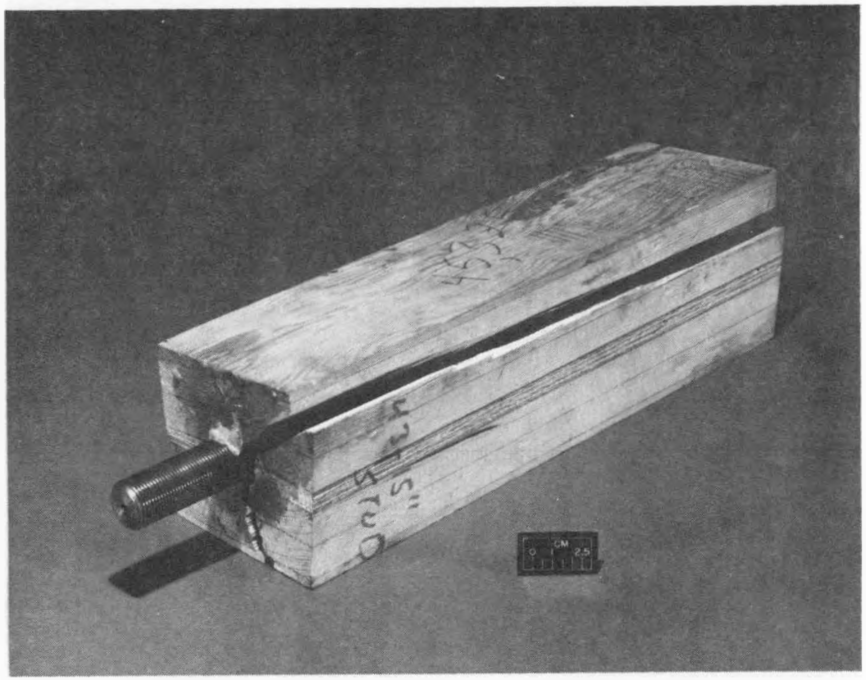


Figure 6. - Specimen without birch ply - cross grain failure.

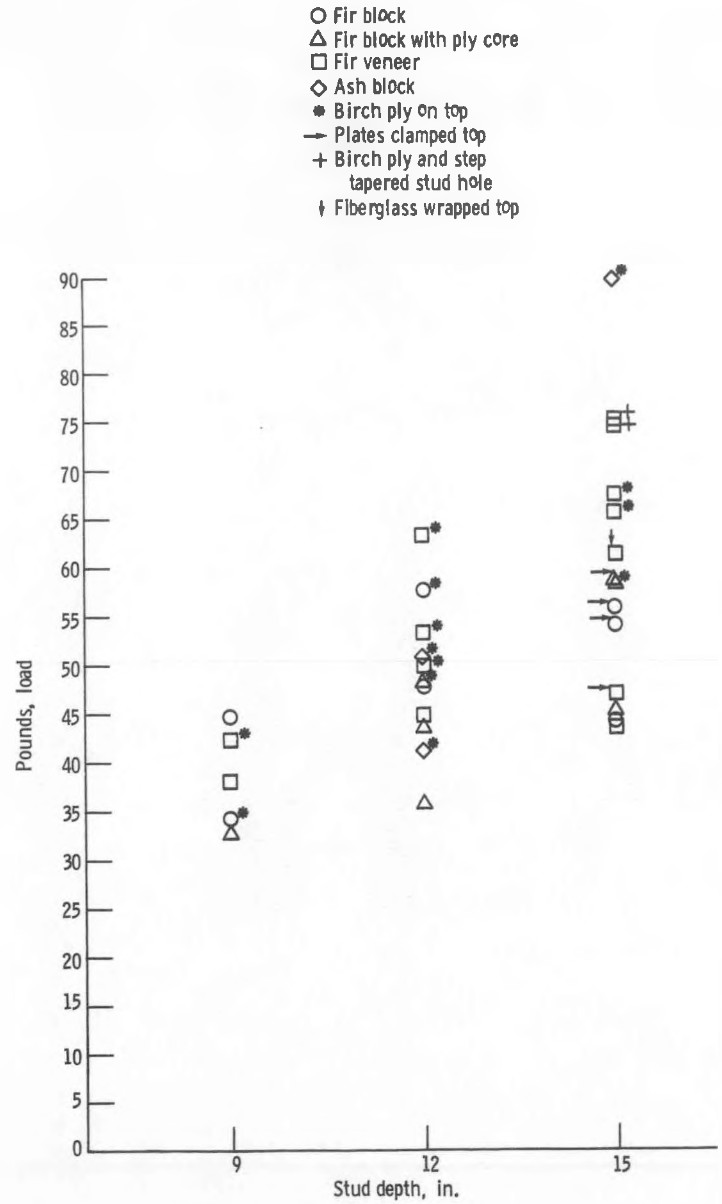


Figure 7. - Wood specimen tensile pull test results.

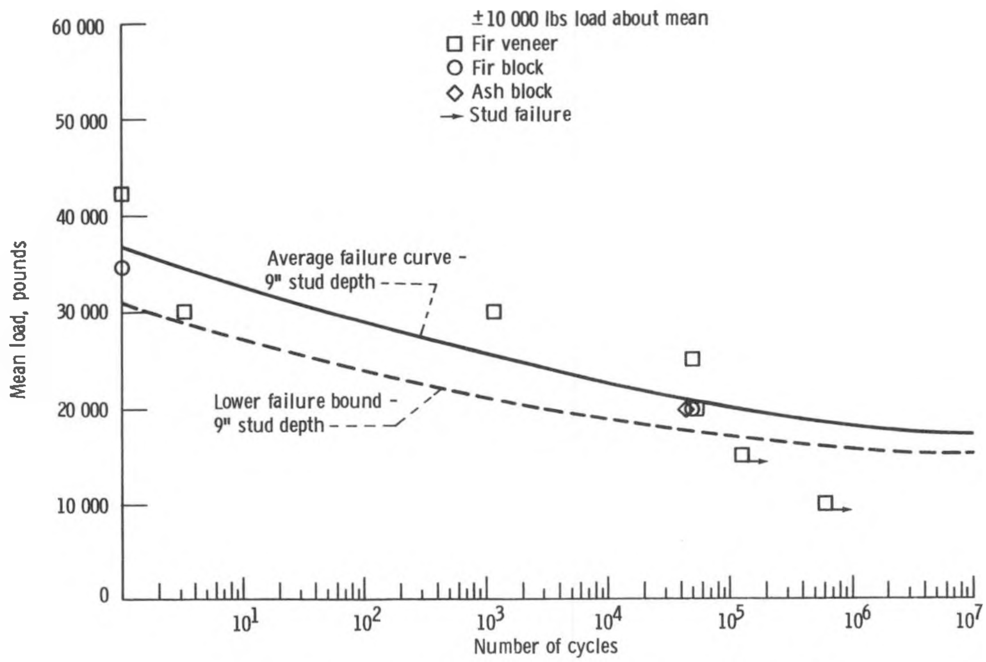


Figure 8. - Wood specimen cyclic fatigue test results 9" stud depth.

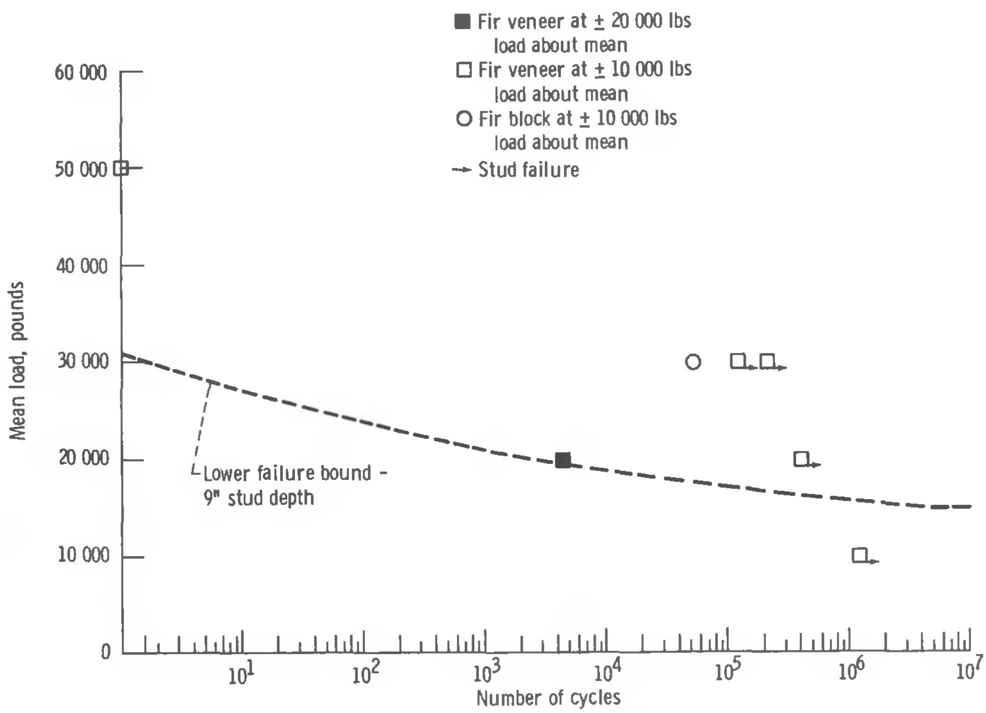


Figure 9. - Wood specimen cyclic fatigue test results 12" stud depth.

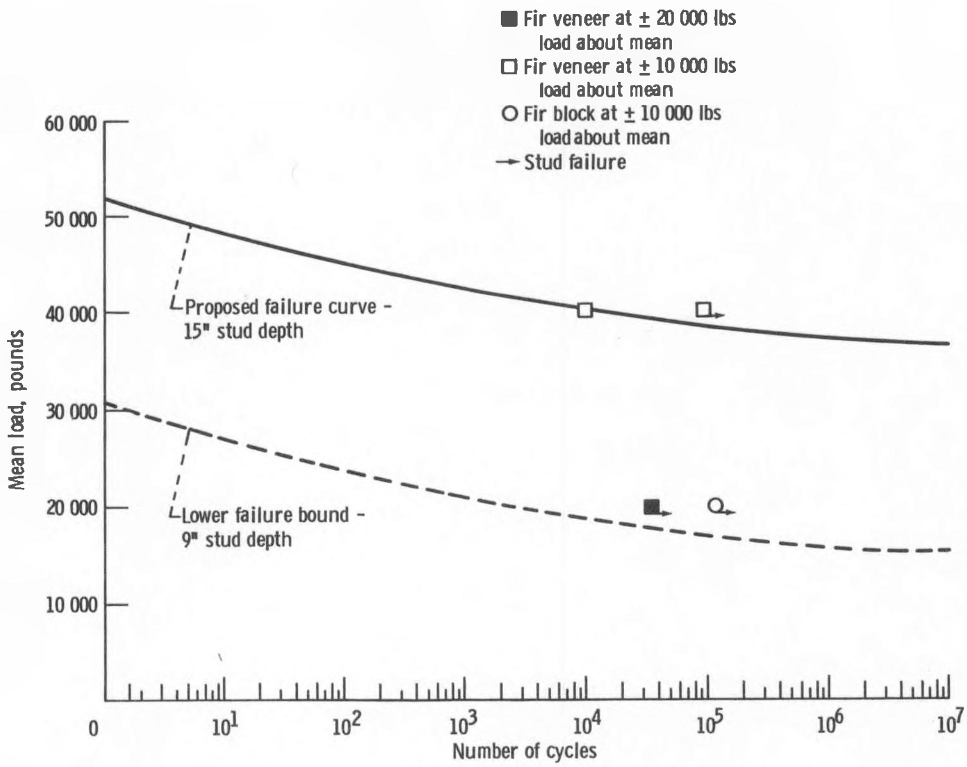


Figure 10. - Wood specimen cyclic fatigue test results 15" stud depth.

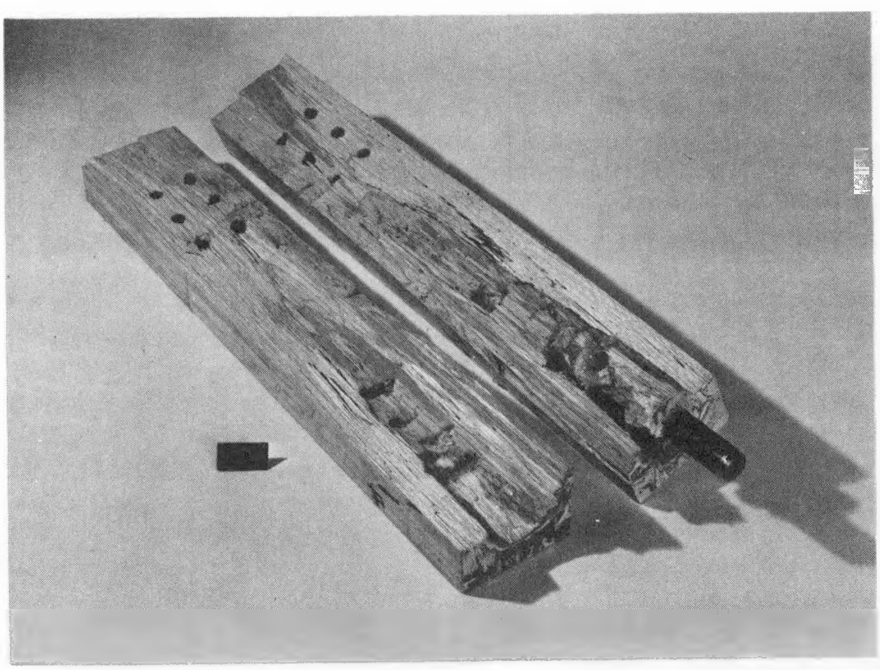


Figure 11. - Failure typical of stud pull out in specimens using a step tapered hole.

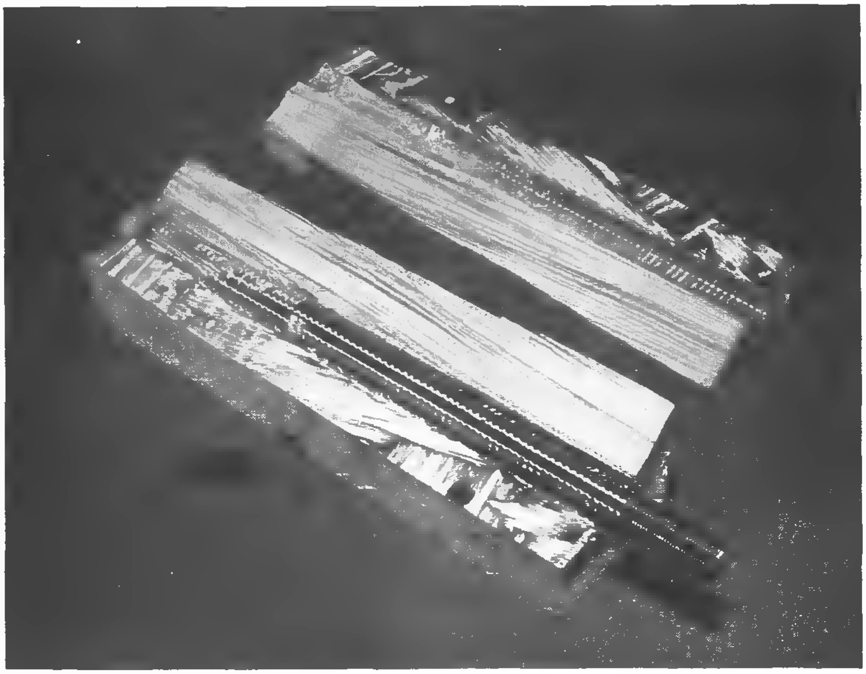


Figure 12. - Failure of plywood layer.

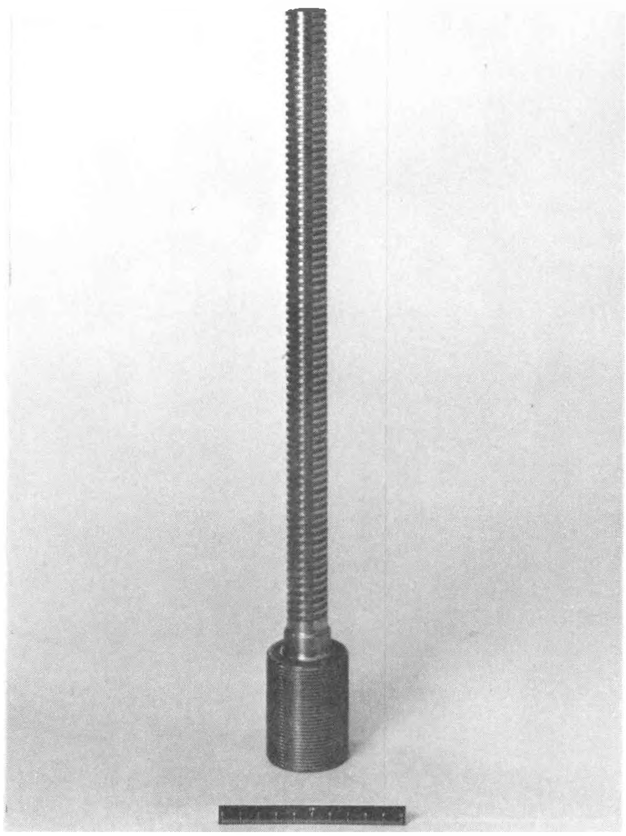


Figure 13. - Photograph of 15 inch long stud with 15 inch long by 1 inch diameter ACME thread used for second series of tests.

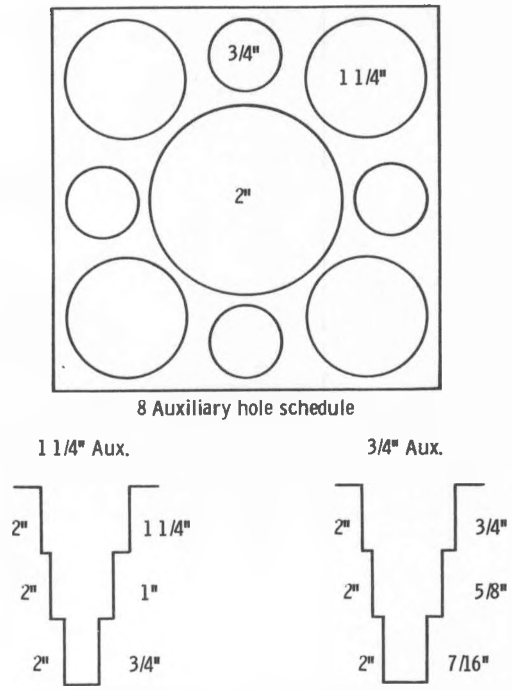
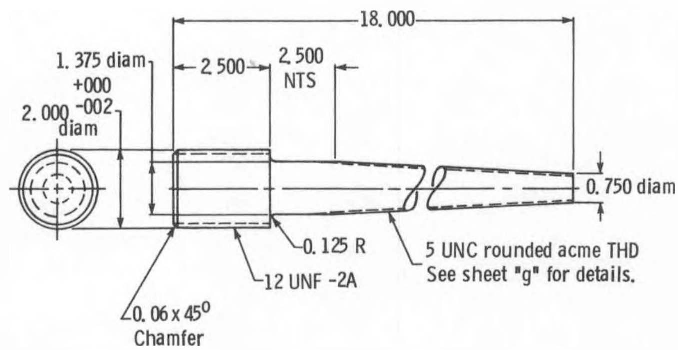


Figure 14. - Hole configuration for modifying the stiffness of the stud test specimen.

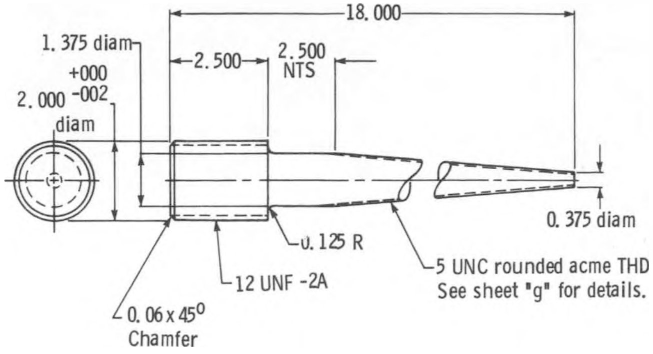


Note:

All dimension tolerances ±.005 except where noted.

(a) 1 3/8" to 3/4" taper ratio.

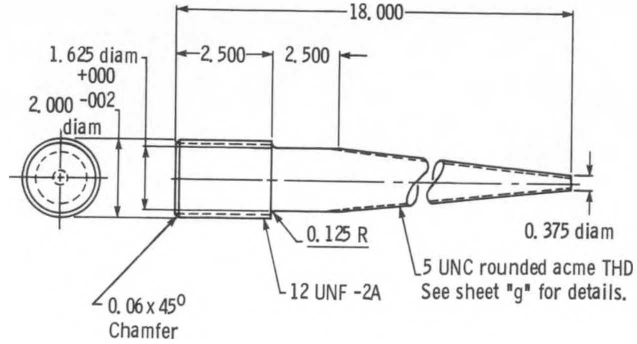
Figure 15. - Tapered stud configurations.



Note:
All dimension tolerances ±. 005 except where noted.

(b) 1 3/8" to 3/8" taper ratio.

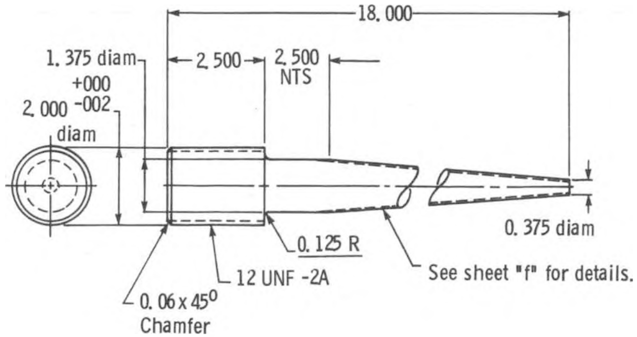
Figure 15. - Continued.



Note:
All dimension tolerances ±. 005 except where noted.

(c) 1 5/8" to 3/8" taper ratio.

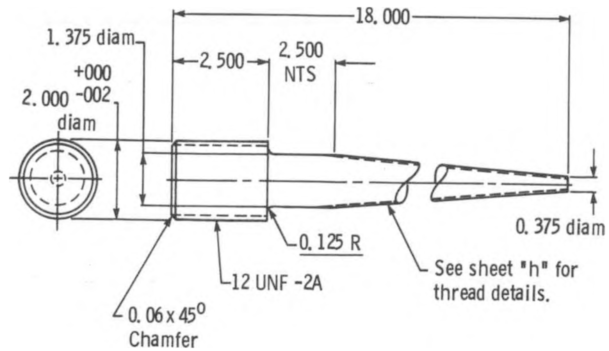
Figure 15. - Continued.



Note:
All dimension tolerances ±. 005 except where noted.

(d) 1 3/8" to 3/8" taper ratio with special thread A design.

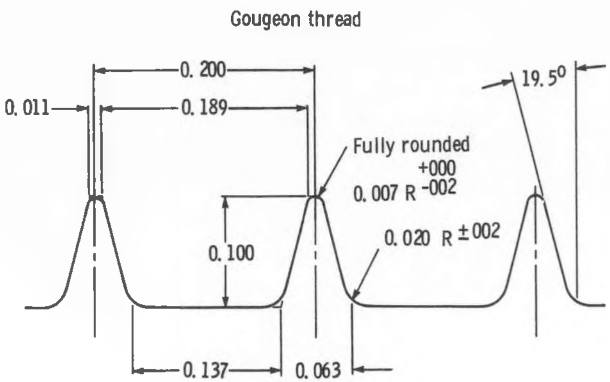
Figure 15. - Continued.



Note:
All dimension tolerances ±. 005 except where noted.

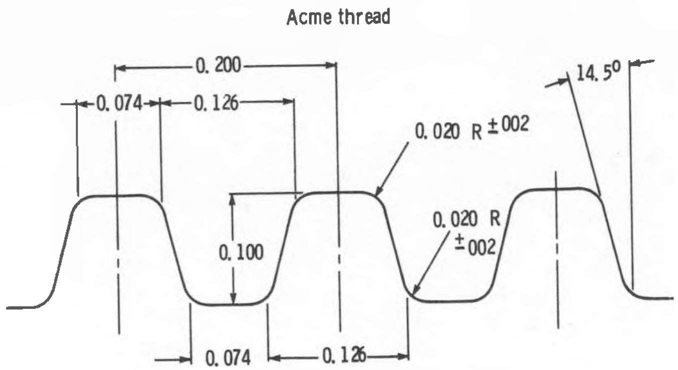
(e) 1 3/8" to 3/8" taper ratio with special thread C design.

Figure 15. - Continued.



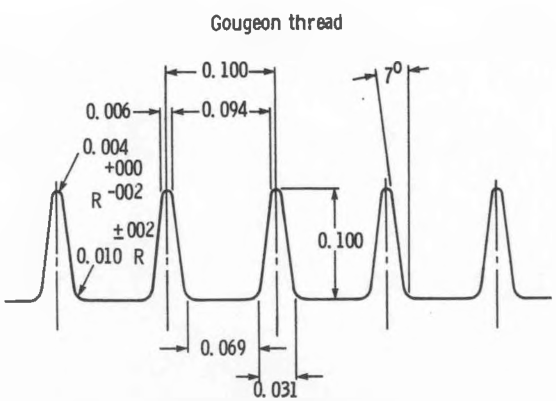
(f) Special thread A design.

Figure 15. - Continued.



(g) Modified acme thread (baseline) design for tapered studs.

Figure 15. - Continued.



(h) Special thread C design.

Figure 15. - Concluded.

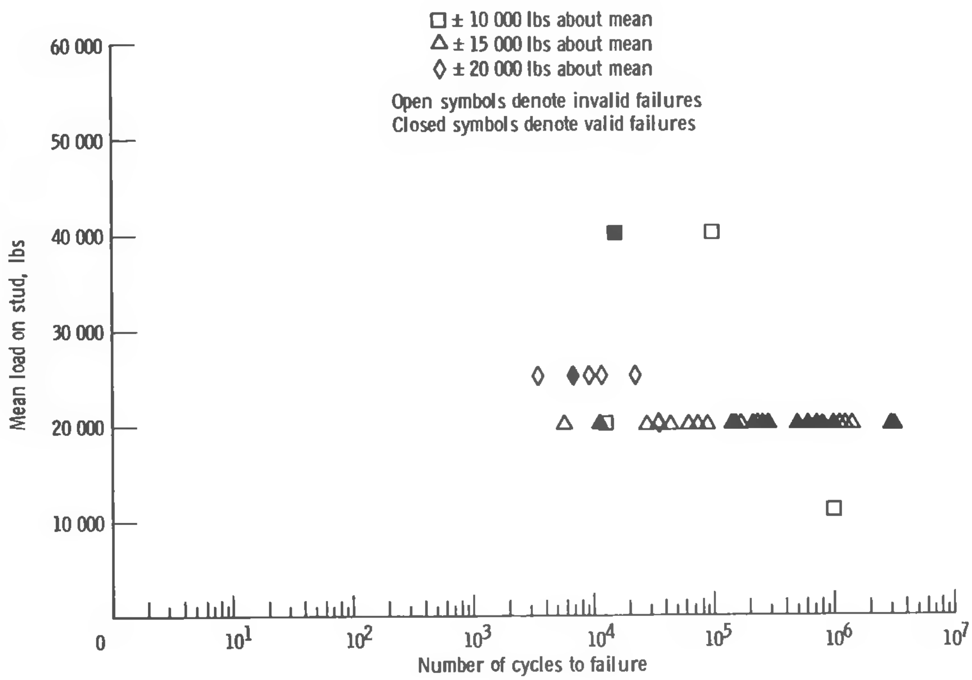


Figure 16. - Fatigue test results for 15 inch long studs.

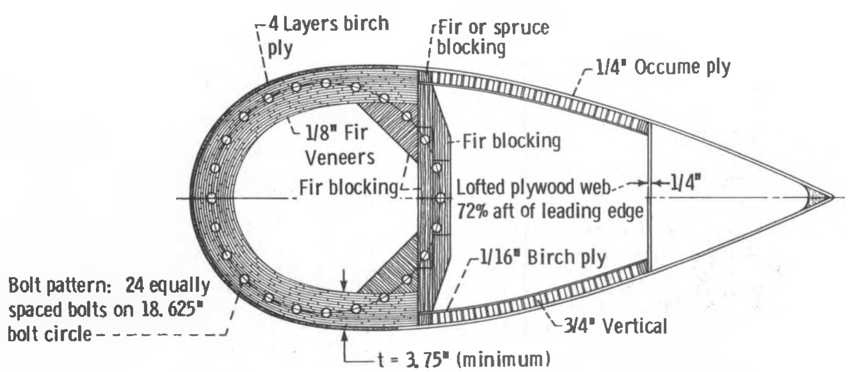


Figure 17. - Laminated wood blade root end details.

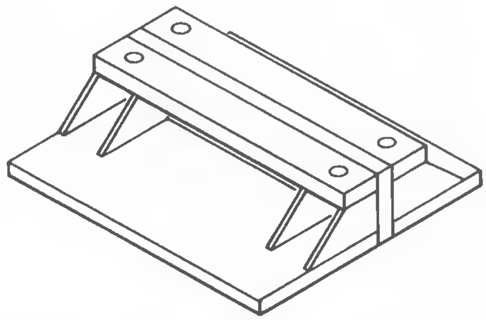


Figure 18. - Aluminum adapter for loading the 20' wood blade test specimen.

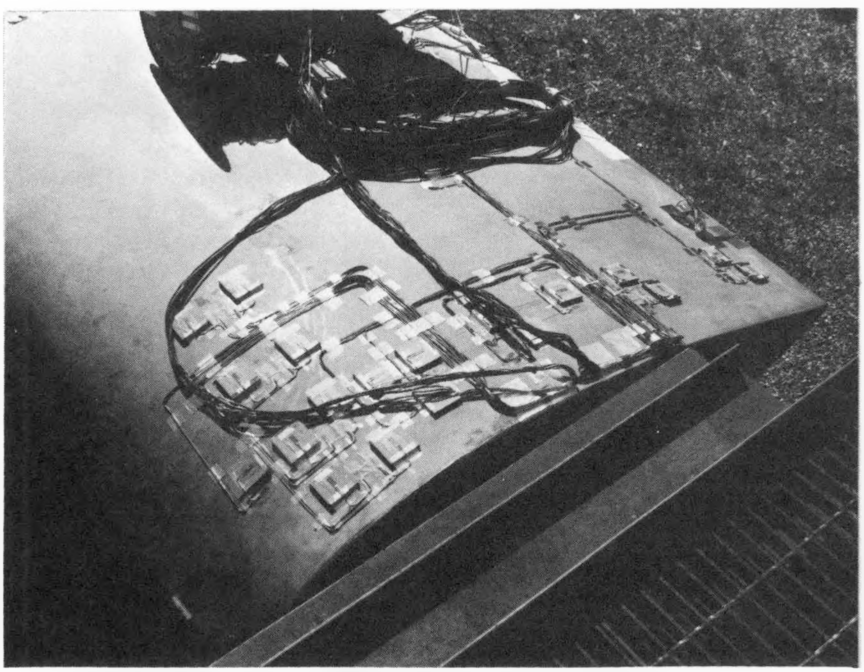


Figure 19. - Strain gages as applied in the root end area of the 20 foot wood blade test section.

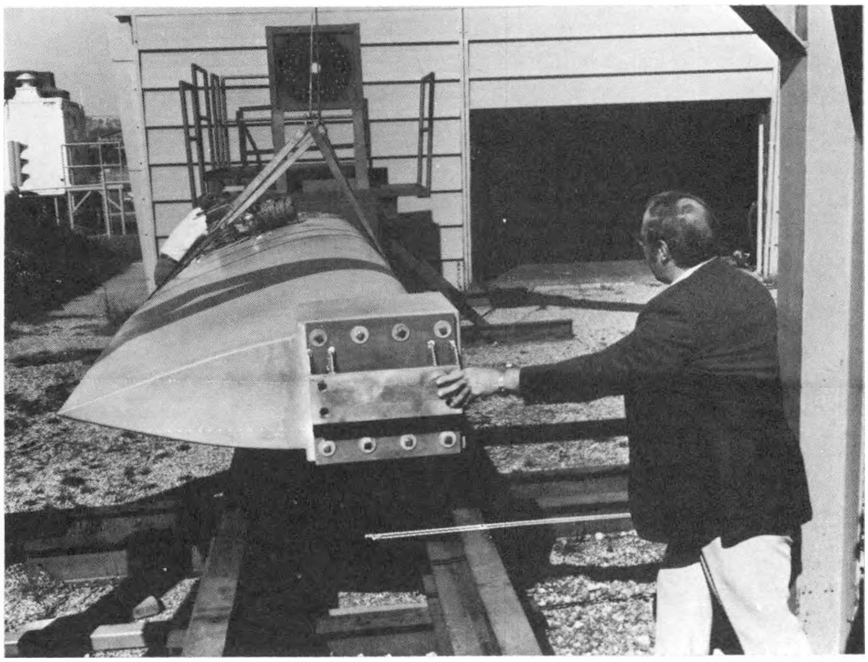
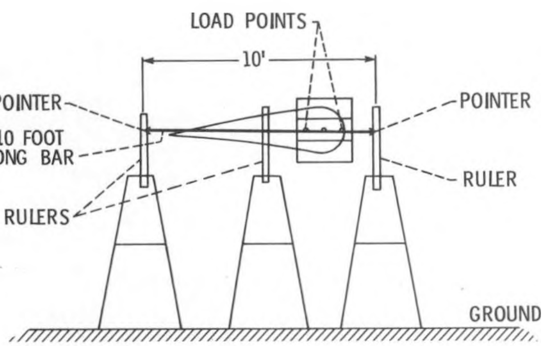
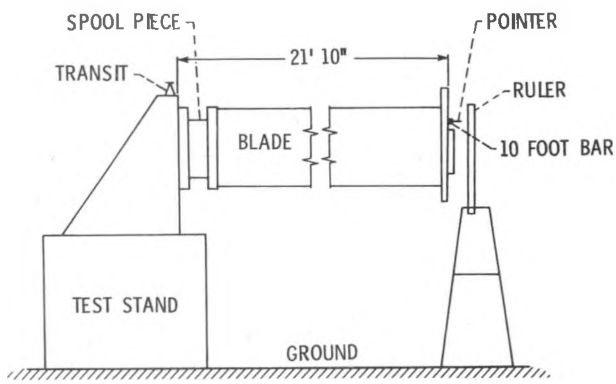


Figure 20. - Wood blade test section installed on strongback.



(a) LOOKING TOWARD TEST STAND.

Figure 21. - Static test set-up.



(b) Looking in from leading edge.

Figure 21. - Concluded.

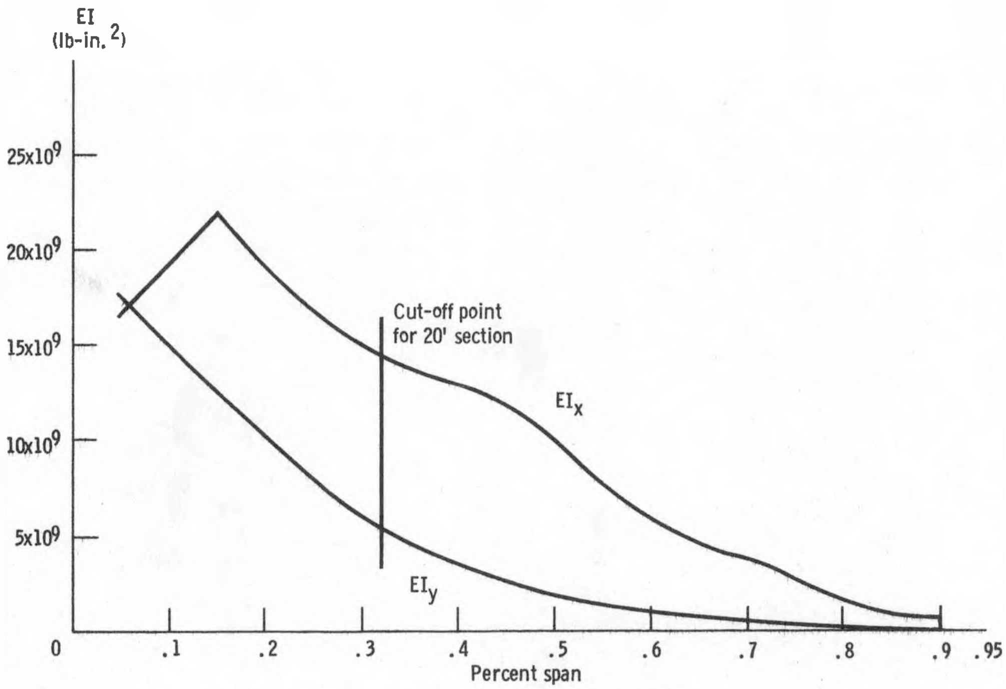
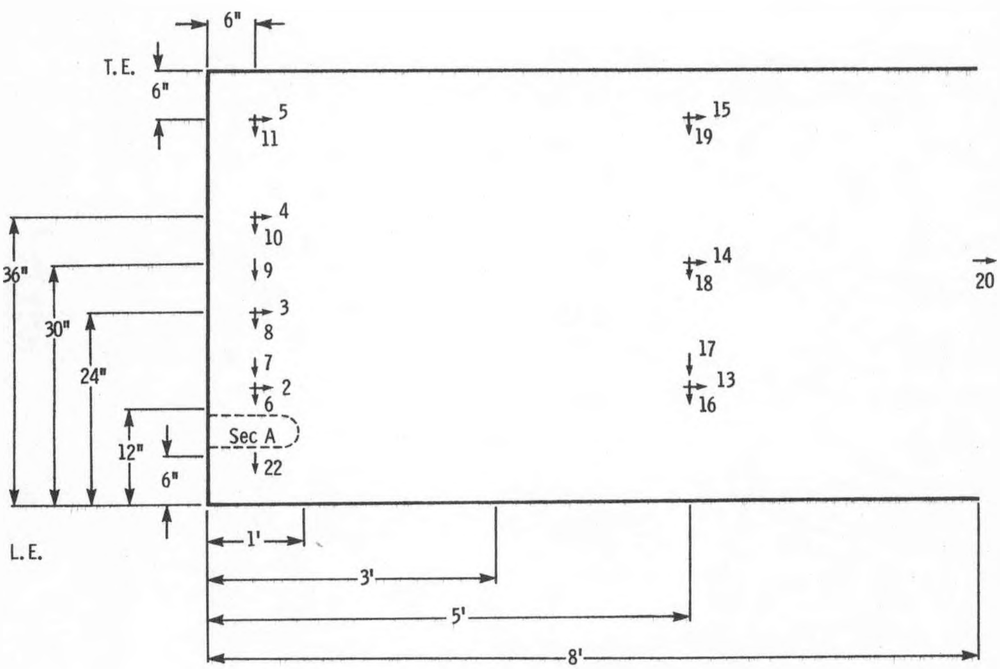
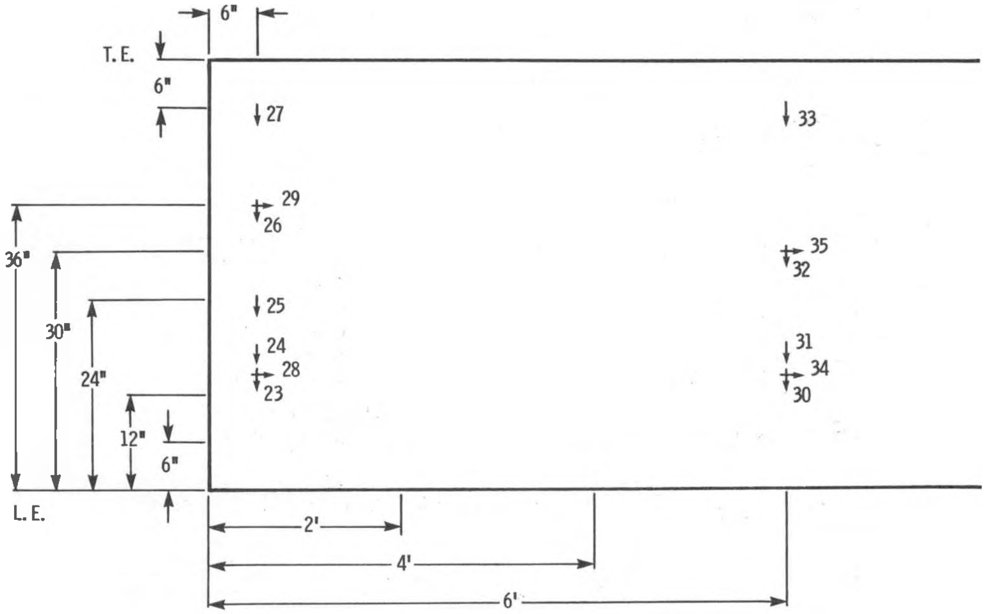


Figure 22. - Blade stiffness as function of span.



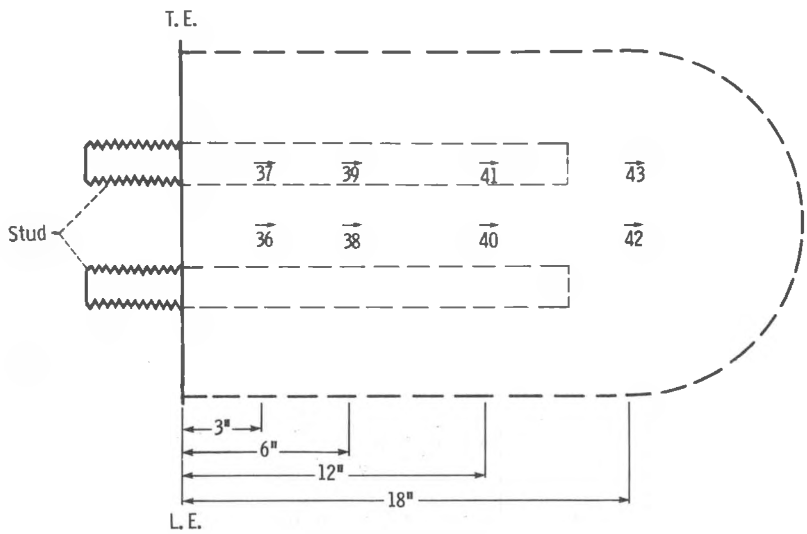
(a) Top view.

Figure 23. - Strain gage locations.



(b) Bottom view.

Figure 23. - Continued.



(c) Magnification of section A. (See figure 23-A)

Figure 23. - Concluded.

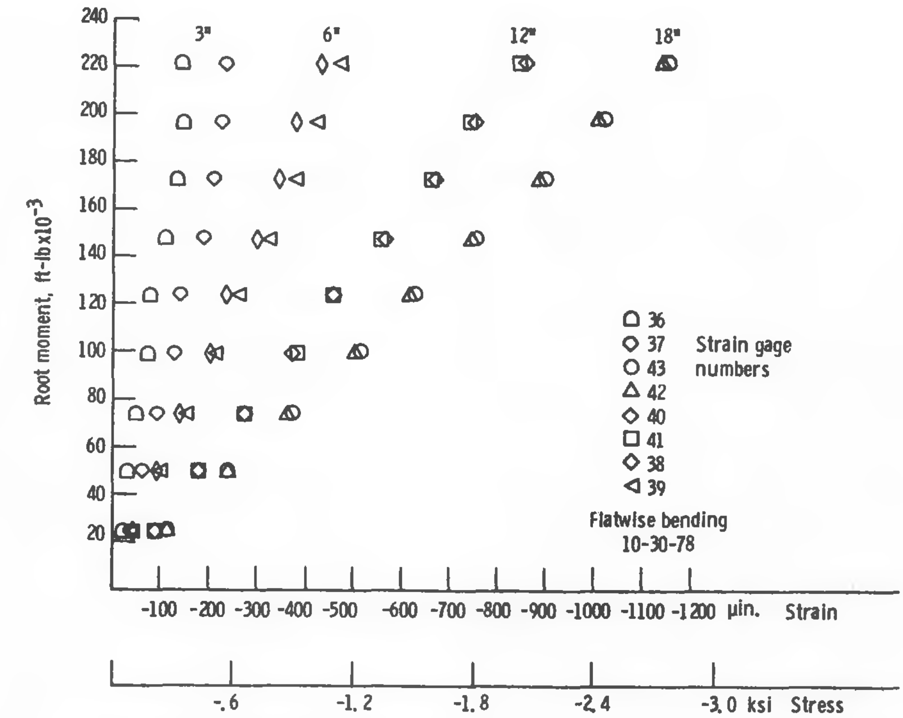


Figure 24. - Wood compressive stress over and between studs as measured during flatwise bending.

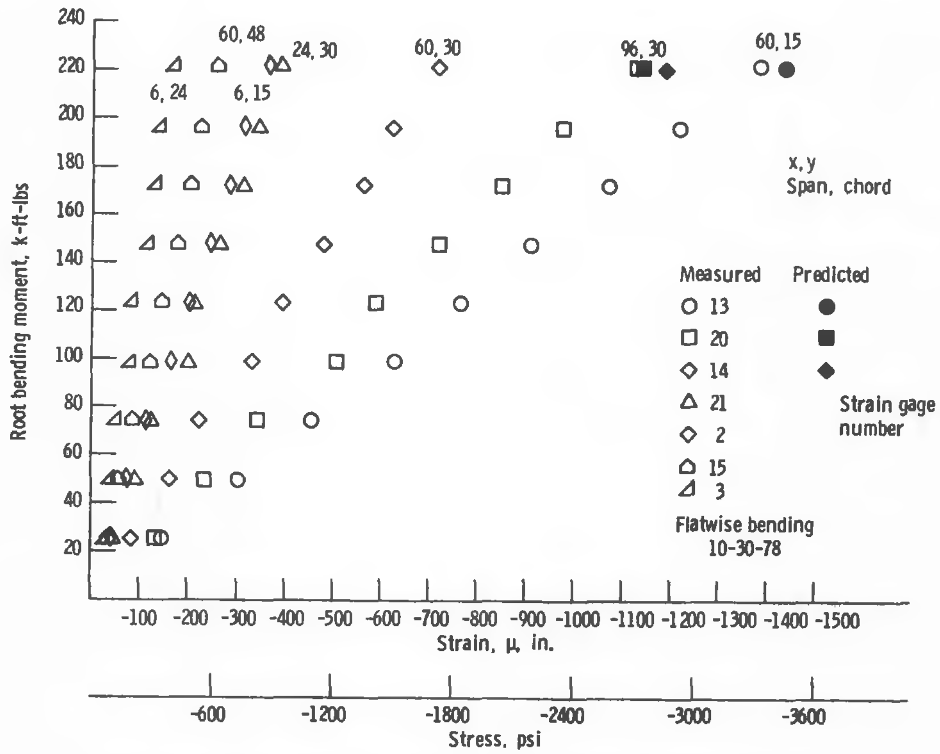


Figure 25. - Spanwise strain measurements for flatwise bending. (Maximum compressive readings - upper surface)

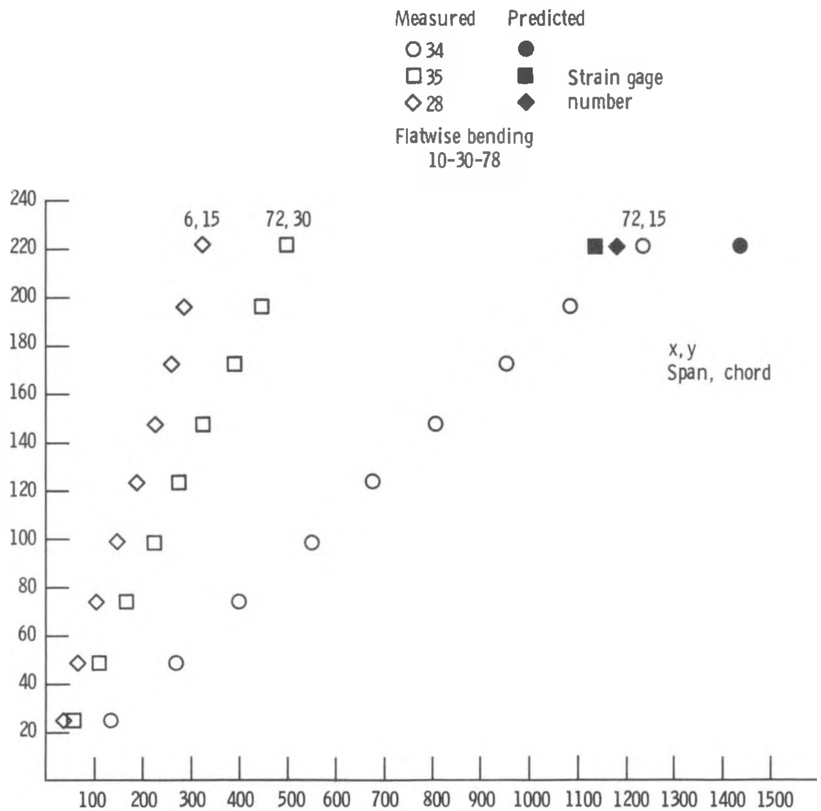


Figure 26. - Spanwise strain measurements for flatwise bending. (Maximum tensile readings - lower surface)

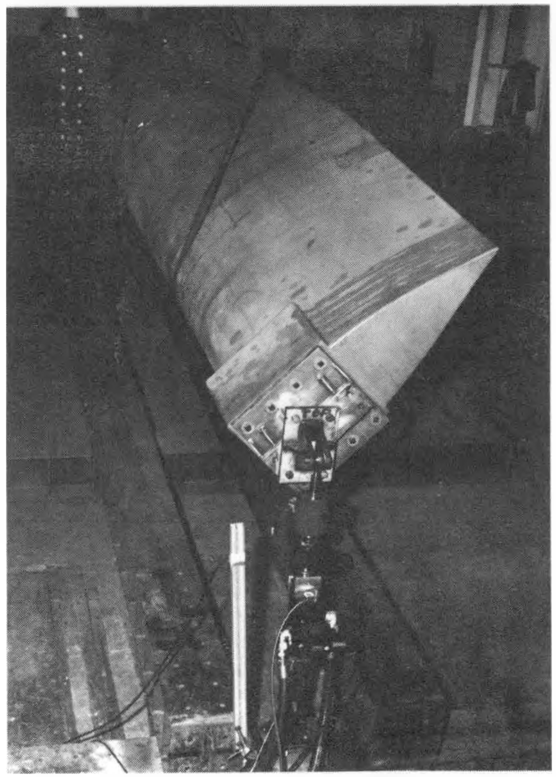


Figure 27. - Twenty foot blade section mounted and ready for test in USARTL (Ft. Eustis) Facility.

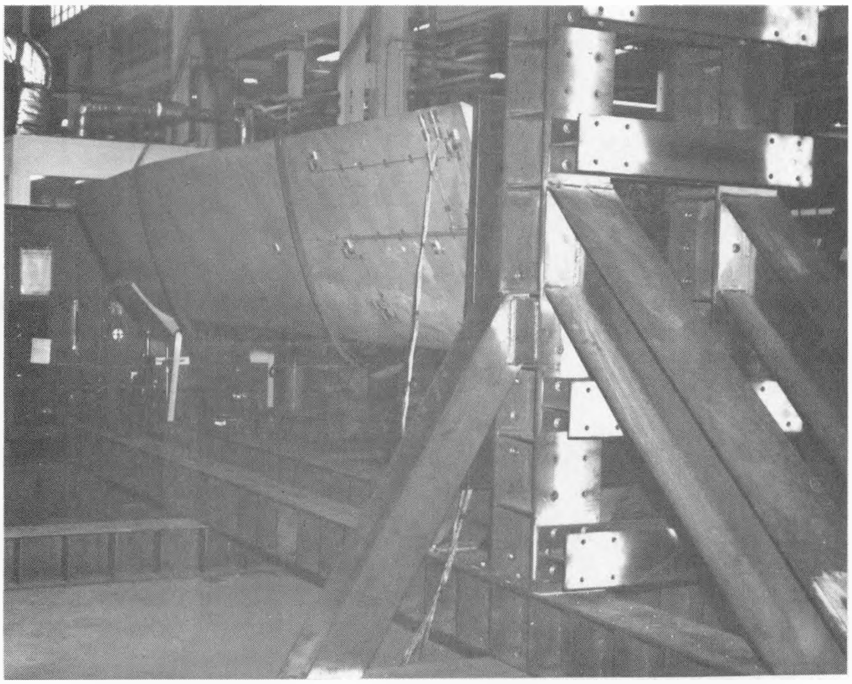


Figure 28. - Mounting and strongback for 20 foot blade test at USARTL (Ft. Eustis) Facility.

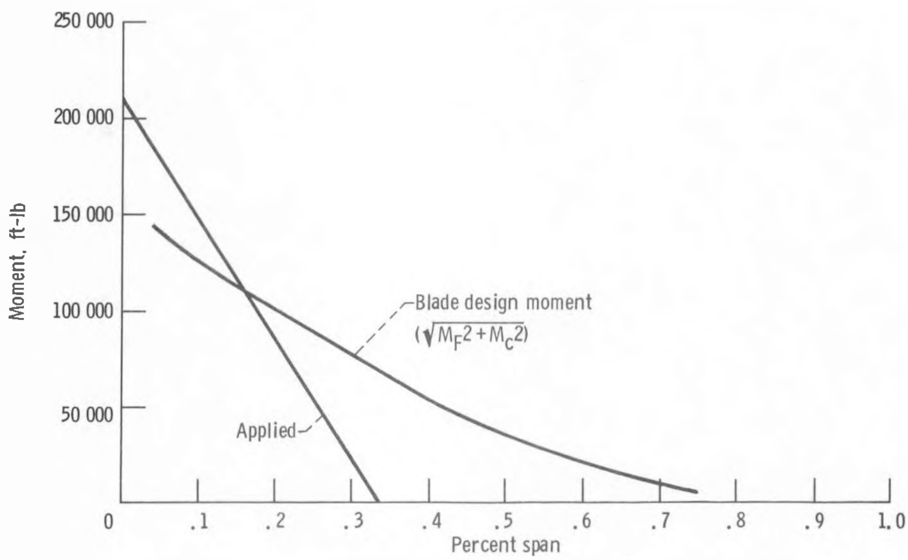


Figure 29. - Comparison of moment applied during test to that predicted during machine operation.

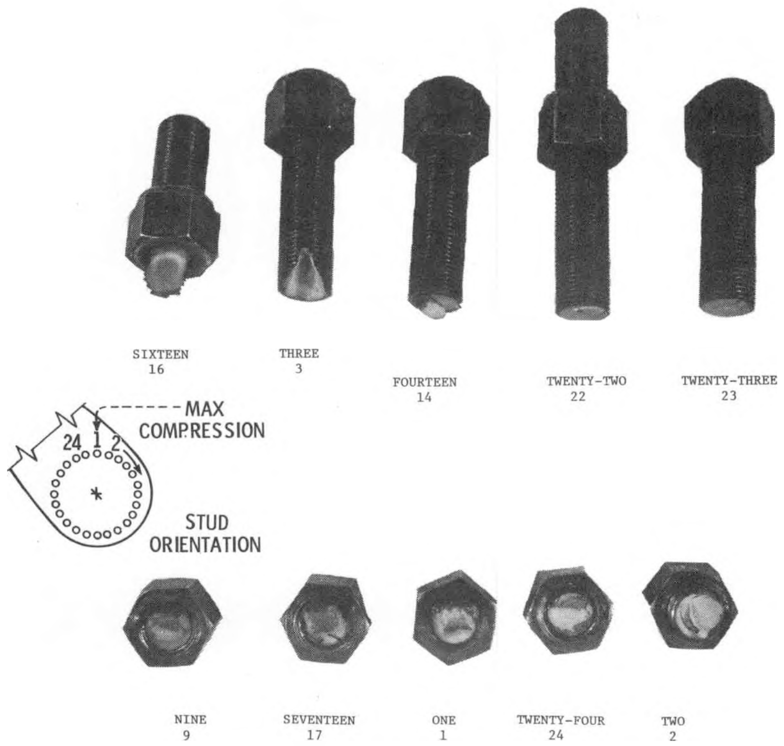
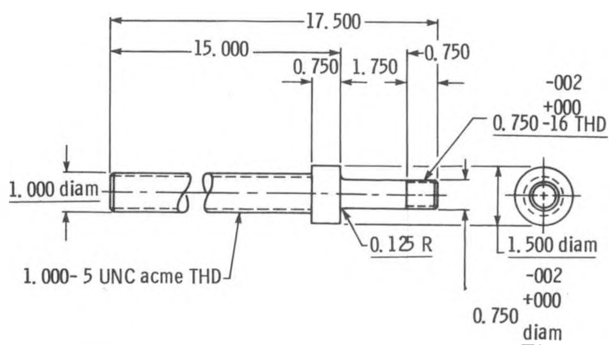


Figure 30. - Photograph of broken bolts.



Note:

All dimension tolerances ±.005 except where noted.

Figure 31. - Drawing of replacement stud in 20' wood blade test section.

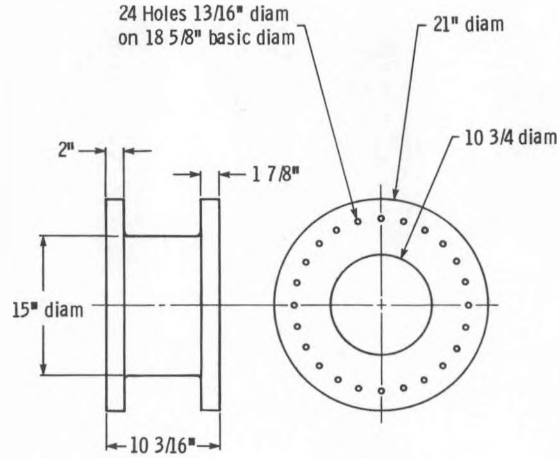


Figure 32. - Spool piece adapter for Fort Eustis testing.

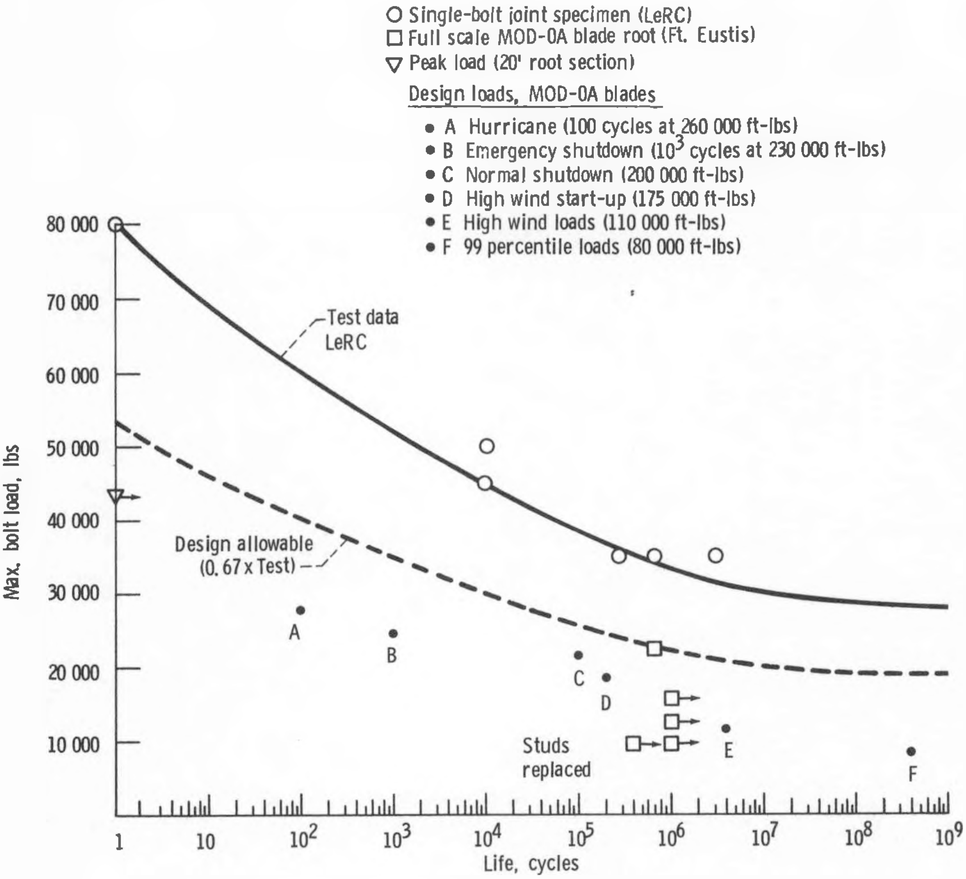


Figure 33. - Fatigue data for bolt-to-wood tension joints fabricated by Gougeon Bros., Inc.

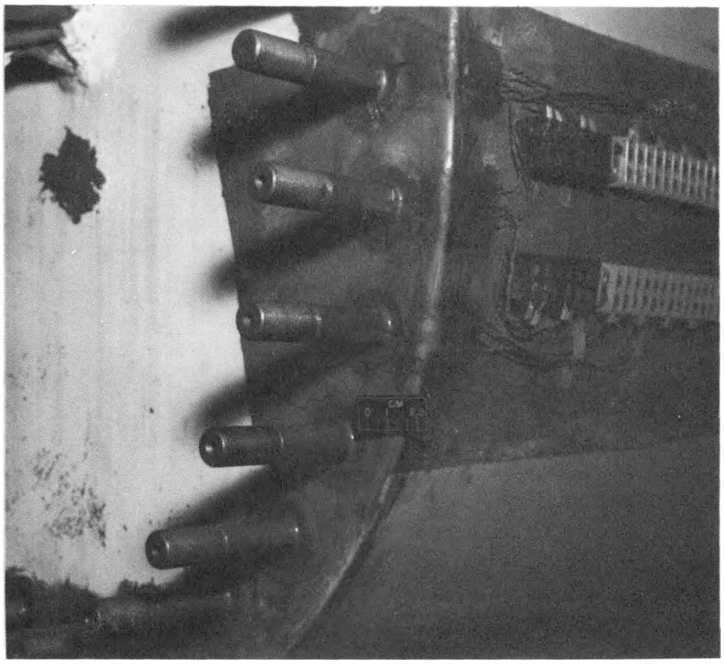


Figure 34. - Studs with flats for strain gages (lead wires and strain gages removed.

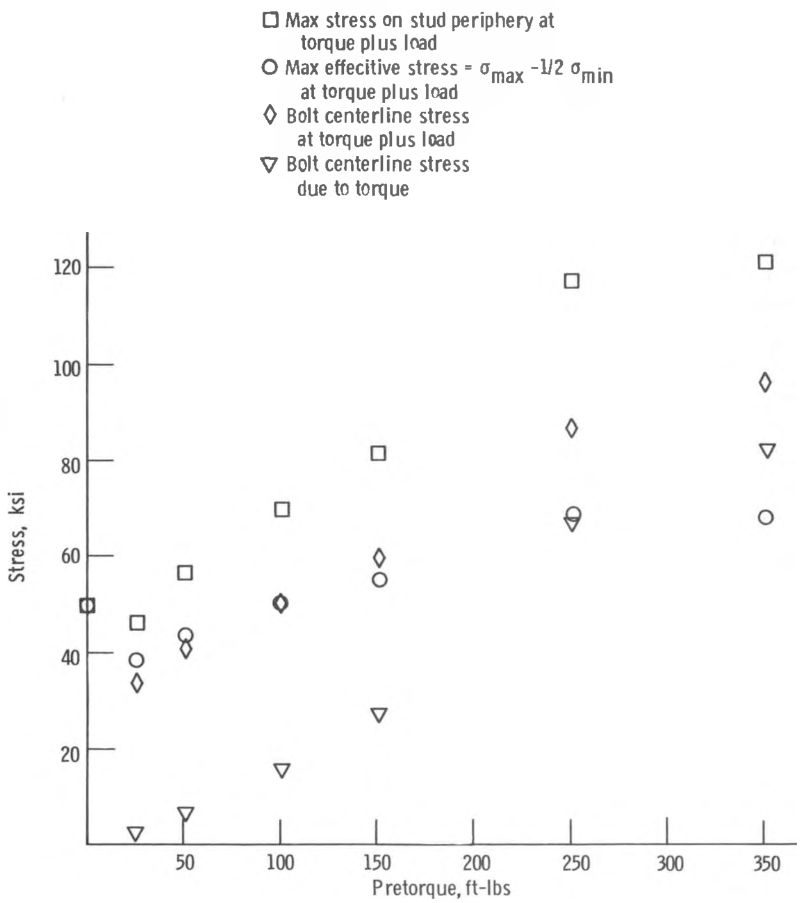


Figure 35. - Effect of pretorque on bolt stresses. (Max loaded tensile stud.)

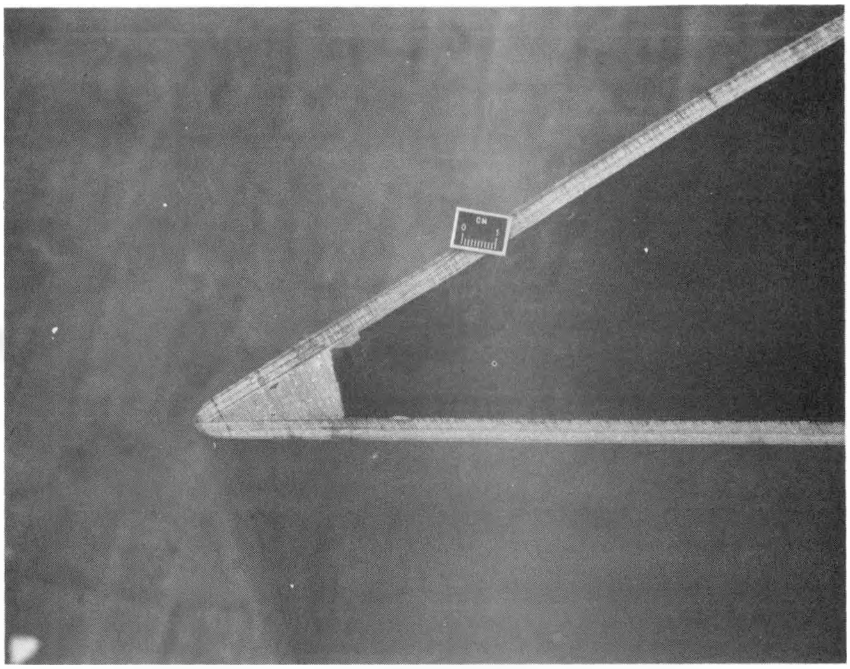


Figure 36. - Trailing edge bond of sectioned 20 foot blade test specimen.

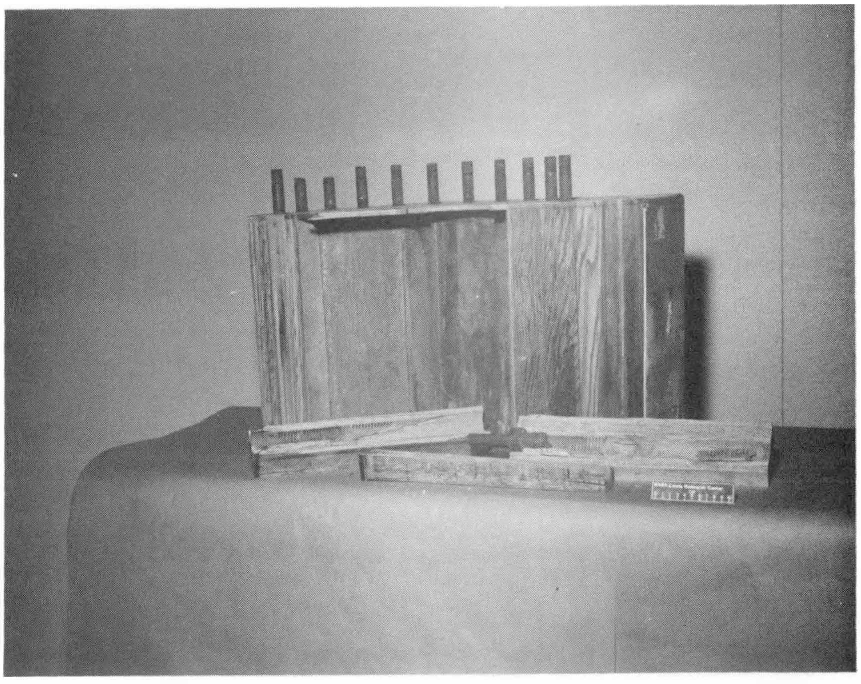


Figure 37. - Root end of sectioned 20 foot blade showing broken studs and integrity of wood laminate.

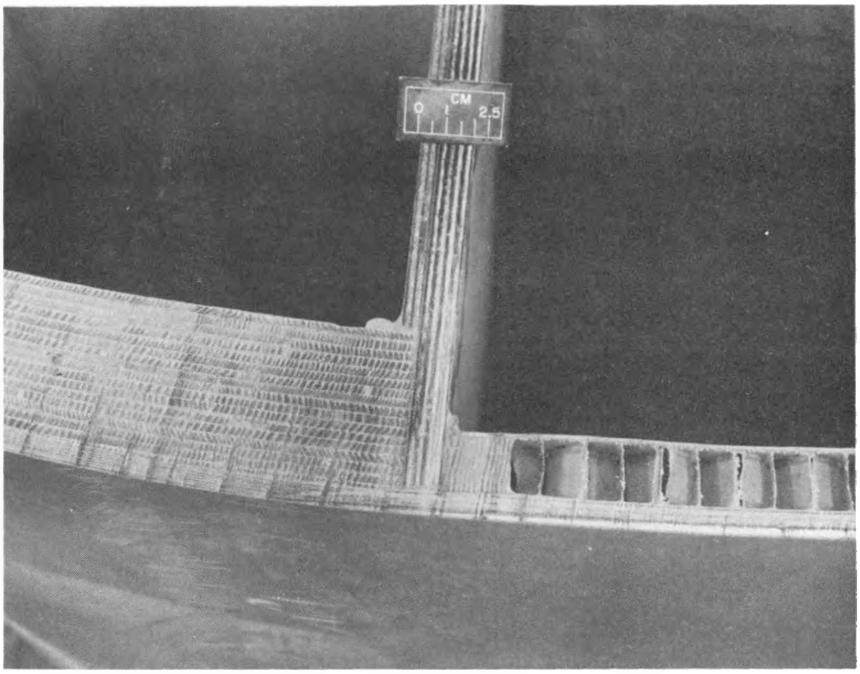


Figure 38. - "D" Spar/Shear web/trailing edge connection of 20 foot wood specimen.

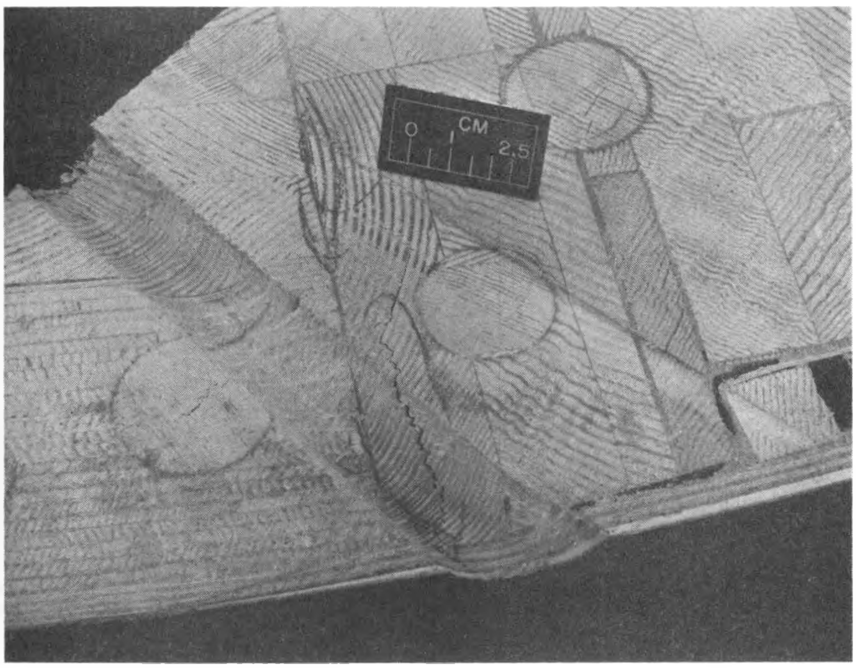


Figure 39. - Root end build-up for stud installation showing only crack found in entire 20 foot wood test section.

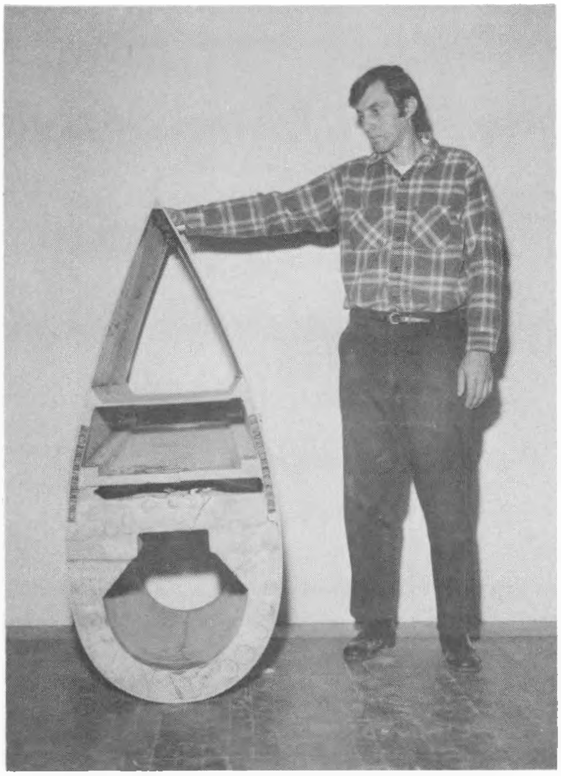


Figure 40. - Inboard section cut from 20 foot wood blade test specimen.

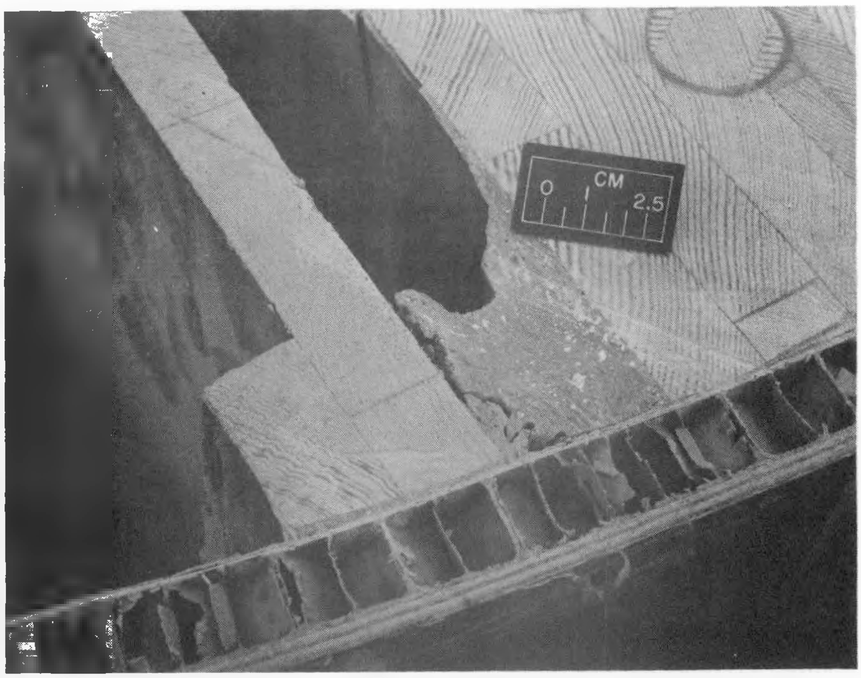


Figure 41. - Excess epoxy between root end blocking and diagonal rib.

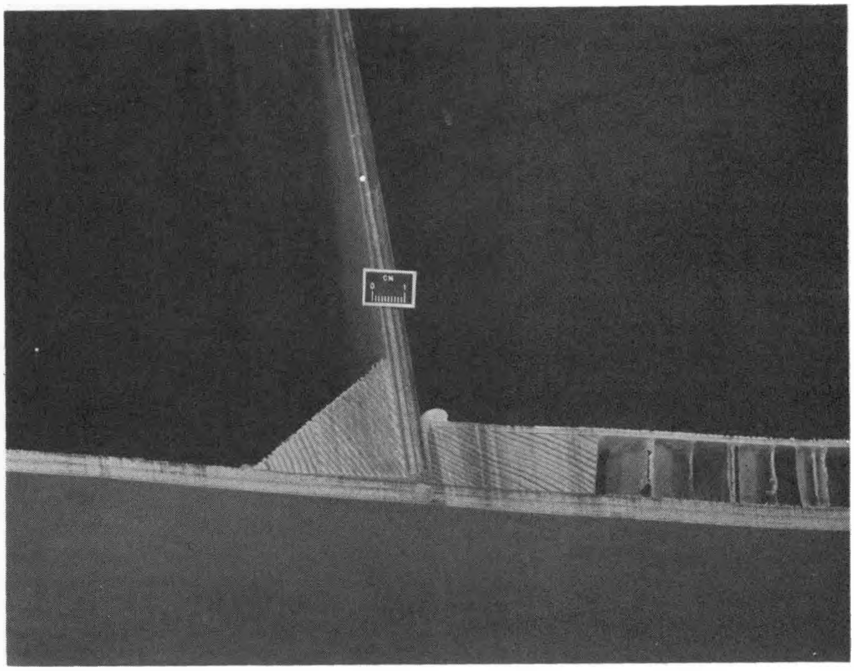


Figure 42. - Shear web and Verticel reinforced afterbody panel in outboard portion of 20 foot test section.

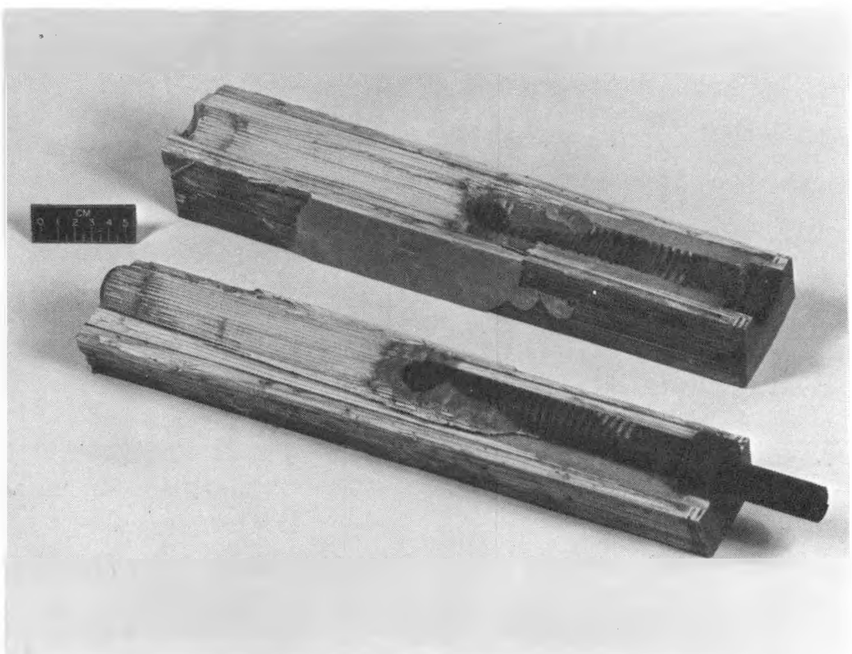


Figure 43. - Stud removed from root end of 20 foot section after test - wood and epoxy cut and pryed open for examination.

1. Report No.
NASA TM-81719

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle
TEST EVALUATION OF A LAMINATED WOOD WIND TURBINE BLADE CONCEPT

5. Report Date
May 1981

6. Performing Organization Code
776-33-41

7. Author(s)
James R. Faddoul

8. Performing Organization Report No.
E-753

9. Performing Organization Name and Address
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

10. Work Unit No.

11. Contract or Grant No.

12. Sponsoring Agency Name and Address
U.S. Department of Energy
Division of Wind Energy Systems
Washington, D.C. 20545

13. Type of Report and Period Covered
Technical Memorandum

14. Sponsoring Agency ~~Code~~ Report No.
DOE/NASA/20320-30

15. Supplementary Notes
Final report. Prepared under Interagency Agreement DE-AI01-76ET20320.

16. Abstract
This report presents the results of a series of tests conducted on a root end section of a laminated wood wind turbine blade. The blade-to-hub transition of the wood blade uses steel studs cast into the wood "D" spar with a filled epoxy. Both individual studs and a full scale, short length, root section were tested. Results indicate that the bonded stud concept is more than adequate for both the 30-year-life fatigue loads and for the high wind or hurricane gust loads.

17. Key Words (Suggested by Author(s))
Rotor blades
Wind turbine
Rotors
Fatigue testing
Laminated wood
Fan blades
Bonded parts

18. Distribution Statement
Unclassified - unlimited
STAR Category 44
DOE Category UC-60

19. Security Classif. (of this report)
Unclassified

20. Security Classif. (of this page)
Unclassified

21. No. of Pages

22. Price*

* For sale by the National Technical Information Service, Springfield, Virginia 22161