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IMPROVED STUD CONFIGURATIONS FOR ATTACHING LAMINATED WOOD WIND TURBINE BLADES

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SUMMARY

In order to improve joint strength for bonded studs in laminated wood structures (wind turbine blades) a series of designs was developed and tested. Each design systematically varied a parameter which was expected to have a significant effect on performance. The structural capability of each design was established based on tension-tension fatigue tests, and it was found that a stud with a concave tapered carrot design, bonded in place with an epoxy thickened with chopped carbon fiber, was the most effective design. Further improvements in joint performance could be made by augmenting the laminated wood with thin plies of carbon cloth (10 percent thickness buildup) in the area of the stud. Two designs were selected for further testing, which demonstrated that joint strengths approaching the membrane wood strength could be achieved. For a 3- by 3-inch wood block, an ultimate load exceeding 100 000 lbs could be introduced through a single bonded stud. For the same type of specimen in cyclic tension at an R-ratio of 0.1, the bonded studs were projected to have a fatigue life of 4×10^8 cycles at maximum loads of 30 000 lbs. For reversed axial fatigue, a reduction of 25 percent from these numbers was shown to be appropriate. These values represent an improvement of 100 percent over the stud designs used previously for laminated wood wind turbine blades. However, temperatures of 100 °F with humidity at 100 percent in certain cases caused a loss of ultimate load capability approaching 35 percent and a loss of fatigue capacity approaching 50 percent. While this result may have been specimen-related, additional testing or a change in the epoxy resin system should be considered before using the bonded stud designs in hot, humid environments.

INTRODUCTION

Since 1977, NASA Lewis has been pursuing the development of low-cost rotor blade technology for large horizontal axis wind turbines (HAWT). This work has been sponsored by the Department of Energy in an attempt to establish wind turbines as economical energy alternatives. The economic success, or failure, of a wind turbine is measured by the cost of the electricity (COE) which it generates. Since the rotor generally represents a substantial portion (greater than 25 percent) of the wind turbine cost, the rotor is a major item in determining COE. Consequently, low-cost, long-life (30 yr), low-maintenance rotor systems are essential for a cost efficient wind turbine generator. Laminated wood that is manufactured by bonding 1/10 inch thick veneers (plies) together with epoxy resin is a particularly attractive candidate material for a rotor blade since the raw material is low in cost and, in the grain direction, has high specific strength (strength-to-density ratio) and high specific stiffness (modulus-to-density ratio).

Laminated wood does present one major engineering problem for this application. Without a rigorous design and analysis effort, it cannot be effectively connected directly to other components such as a steel hub. This problem was addressed in early development efforts, and a solution was found which employed a series of bonded steel studs. Stud designs were thoroughly tested and evaluated (refs. 1 to 4) but were not optimized. The maximum stud loads achieved for the early stud concepts were equivalent to wood strengths of about 5000 psi statically and 1750 psi in high cycle (10^7 cycles) fatigue. Since these strengths were well below the laboratory demonstrated wood capability of 10 000 to 12 000 psi tensile ultimate and 5000 psi in high cycle fatigue, it was believed that the stud design could be reconfigured to provide greater load transfer capacity and therefore reduce the weight and cost of laminated wood components.

Thus the objective of the program was to examine stud concepts and empirically evaluate the effect of stud design parameters in an attempt to achieve a 50 to 100 percent improvement in the structural capability of the bonded stud joint. An additional objective of this program was to generate structural design curves for two of the most promising configurations. Accordingly, Gougeon Brothers, Inc. was awarded a contract to design and fabricate stud test specimens and IIT Research Institute was chosen to conduct the appropriate ultimate and fatigue tests on the specimens.

DISCUSSION

Stud Design Evaluation

The initial stud designs were documented in references 1 and 2. The first configuration was a 1-inch-diameter cylindrical body, embedded in the wood over a length of 15 inch with a standard 0.1-inch-depth ACME thread. Studs were cast in place in constant-diameter holes by a filled and thickened epoxy (fig. 1). The initial individual stud test specimens were fabricated by casting the stud into a 4-inch-square wood block which was 24 inches long. A section of the stud was allowed to protrude from the wood for direct connection to the test machine. The other end of the wood block had clevis plates glued and bolted in place which accepted a pin fitted to the test machine (fig. 2).

As might be expected, most of the early failures were shear failures in the wood, resulting from the large mismatch in stiffness between the stud and the wood. In an attempt to break up the shear planes at the interface between the epoxy and the wood, a step-tapered hole was tried. This provided a significant increase in both static and fatigue strength. In a further attempt to reduce high peak shear stresses, a tapered stud configuration (fig. 3) was developed and tested. The tapered configuration was then used in the manufacture of four pairs of 60-foot wind turbine blades, which operated successfully on the 200 kW Mod-OA wind turbines (refs. 4 and 5). Test data from the tapered stud indicated a full design life (4×10^8 cycles) at 10 000±10 000 lbs, and a one-time pullout load of over 70 000 lbs for a single stud in a 4-inch-square block.

While these values were more than adequate for the Mod-OA applications, the desire to reduce COE brought a need to increase blade size. Larger blades meant higher loads, and in general, the wood volume available for studs did not increase proportionally. Thus, higher performance studs were required.

Gougeon Brothers, Inc., the contractor responsible for the original stud design, was requested to reevaluate the stud design and develop potentially higher performance designs. The testing phase of this effort, conducted by IIT Research Institute, consisted of testing to screen candidate designs followed by further, more extensive evaluation of the two most successful designs. Several candidate designs were prepared, from which the eight shown in figure 4 were selected for manufacture and subsequent screening tests. The initial selection of the designs was based on the desire to provide insight into the impact of various design parameters on stud performance by systematically varying an isolated parameter while holding all other parameters constant. Except where noted, the following additional parameters were held constant.

Stud length	18 in
Stud material	4140 steel (hardness 36-38 Rockwell)
Test block	3- by 3-inch square laminated Douglas fir
Epoxy type and thickness	WEST System 0.15 inch (minimum)
Thread type	0.050 inch deep, 10 per inch concentric rings (special thread form)
Minimum thickness of steel at tip . . .	0.020 inch

All designs were tip drilled. Table I lists the details of the stud design variations.

Tip drilling. - Mod-OA studs used a linear taper and were formed of solid 4340 steel with a modulus of about 30×10^6 psi. This combination led to high peak shear stresses near the tip of the stud. It was predicted that reducing the steel cross-sectional area by hollowing the tip end of the stud would provide a softer load transition and consequently a lowering of the local shear stress. This technique had been used successfully by Gougeon Brothers, Inc. on studs used for attaching wood fatigue specimens to test machines. However, these studs had not been tested to their ultimate capacity in either one-time loading or fatigue. Nevertheless, it was decided to make a linear taper, tip-drilled (hollow) stud the baseline configuration. The stud design designated "1" in table I resulted (see fig. 4(a)). To determine the effect of tip drilling, stud design 2 (fig. 4(a)), was also tested in an undrilled configuration, designated design 6 (fig. 4(b)).

Tip diameter. - Preliminary analysis indicated that large tips with less taper would result in increased performance provided that the tips were drilled. Design 2 was selected to investigate the influence of the tip diameter (taper ratio) effect. As shown in table I, this also resulted in an unavoidable change in surface area, which design 4 (fig. 4(a)) and design 5 (fig. 4(a)) demonstrate.

Stud modulus. - Stud design 3 (fig. 4(a)) was developed to have the same taper ratio as design 1 but to be of greater diameter and lower modulus (maintaining the same EA product along the stud). This allowed the surface area effect introduced in the comparison between designs 1 and 2 to be evaluated, since in the design 1-to-3 comparison the change in surface area was no longer linked to a change in EA product. A stud modulus of about 17×10^6 psi (titanium) was selected.

Taper shape. - Preliminary analysis of the stud/wood stress flow indicated that a linear taper resulted in high peak shear flows at both the stud root and the tip. Optimum performance would be expected from a stud with a more nearly uniform shear stress along its length, and this could be achieved by a nonlinear taper. For a nonlinear tapered stud in a 3- by 3-inch test block, a root diameter of about 2 inches is required for optimum performance and shank prestressing. Unfortunately, a direct comparison of linear and nonlinear tapers at the same root and tip diameters was not practical in the 3- by 3-inch test block. In order to develop the optimum shear stress distribution in a test block with a 2-inch-root linear tapered steel stud, a much bigger block would be required due to the need to match the EA products of the stud and the block. Consequently, if a comparison of nonlinear versus linear design was to be made at equivalent root and tip diameters using the 3- by 3-inch test block, then one or both of the studs would have to be nonoptimal in performance. The low modulus stud, design 3, helps to solve this dilemma, as it is a linear taper design which is nearly optimal at the enlarged dimension required for the nonlinear tapered steel studs. So in addition to being a good high-performance stud in its own right, design 3 provides a good comparison of a large-diameter linear taper stud with the design 4 and 5 (fig. 4(a)) nonlinear taper studs. Design 3 also has more surface area than the nonlinear designs. Whether or not designs 4 and 5 could outperform design 3 would be a good indication of the efficiency of nonlinear tapering.

Block modulus. - Increasing the modulus of the block by selecting higher density and higher modulus fir, or by interspersing carbon fiber or other high-modulus fiber between the veneer plies, provides another way to reduce the block versus stud modulus mismatch. Combined with a nonlinear taper design, this configuration may be capable of providing very high performance levels. In fact, if the stud joint is ever to reach full wood allowables downstream of the stud, an upgrade of material properties at the stud is very desirable in order to handle the local stress concentrations which inevitably occur near the stud. This is particularly advantageous for high-performance applications, and it may in fact turn out to be a quite reasonable manufacturing operation. Testing this variation by comparing design 4 to design 5 (fig. 4(a)) is important to reaching the highest performance levels.

Verification of improvements. - To verify the improvement of the new stud designs, a series of two Mod-OA type studs were tested (fig. 4(b)). Design 8 was identical to the one used in the Mod-OA wind turbine blade program and was installed and tested in a 4-inch-square block. Design 7 was the Mod-OA stud scaled by 0.75 to match the standard 3- by 3-inch block. These two stud designs would provide direct test evidence of the effectiveness of the "improved" designs. In addition, several other important pieces of data could be obtained from the Mod-OA stud design specimens. First, as it may be necessary to scale stud sizes up or down to fit different models, the comparison of design 7 and 8 would provide validation of the scaling analysis. Also, since the effect of surface area was left as a semi-unknown in designs 1, 2, and 3, design 8, which was very close in area to design 1, and design 7, which was 44 percent smaller in surface area, would be used to provide inferential data on area effects.

Test Specimen Design

The test specimen configuration was designed and developed by IIT Research Institute and is illustrated in figures 5 through 8. To provide for load transfer from the stud to the test machine, a 1-1/4-inch threaded shaft was machined on the end of the stud protruding from the 3- by 3-inch wood block. The 1-1/4-inch shaft was preloaded by the assembly shown in figure 6. First, the stud grip was slipped onto the shaft, followed by the stud lock nut which was threaded onto the 1-1/4-inch shaft. Tension was introduced into the shaft by installing and torquing eight 1/2-20 bolts to force separation between the stud grip and the stud lock nut. The actuator connector plate was then bolted to the stud grip by eight 3/4-20 bolts. The whole assembly was fixed to the machine by a 2-1/2-by 13-inch mounting stud. On the opposite end of the test specimen, the wood cross section was built up to a 4-inch-square dimension and 1-inch-thick steel clevis plates were bolted and epoxied in place as shown in figure 7. The clevis plates transferred the test load to the test machine through a 1-1/2-inch-diameter adaptor pin. To maximize the effectiveness of the bolts, heavy steel plates were clamped to the two 4-inch-wide sides which did not have clevis plates, as shown in figure 8. With this arrangement, it was possible to introduce large compression stresses in the clevis end of the test specimens. Although this technique was quite successful, a few specimens were lost due to failure of the clevis plates.

Test Procedure

Three different types of tests, ultimate load, uniaxial fatigue and elevated temperature/humidity, were conducted. Static tests were run by installing the test specimen in a 108 000-lbs capacity MTS tensile machine and increasing load at a constant rate until failure occurred. The rate was basically the same for all static specimens (16 000 lbs/min). Both tension and compression static tests were conducted. Figure 8 shows a test specimen mounted in the test machine that is typical of either static or fatigue testing.

Fatigue tests were run by installing the specimen in either a 108 000 lbs or a 120 000-lbs MTS tensile machine and applying a sinusoidally alternating load between the minimum and maximum load. For compression fatigue the minimum load was ten times the maximum load, while for tensile fatigue the maximum load was ten times the minimum load. Tension-compression fatigue tests were run by alternating a fixed number of cycles in compression - compression with the same number of cycles in tension - tension. This procedure was repeated until failure occurred. For determining the number of cycles to failure in tension-compression fatigue, only the tension - tension cycles were counted. This procedure was necessary in order to simulate an $R = -1$ condition, since the clevis end configuration of the test specimen would not permit true compression/tension cycling at high rates. Banging of the clevis pin would occur as the load changed signs.

The third type of test was a high temperature/high humidity test. To achieve the desired conditions, an insulated box was built around the specimen and a steam generator was connected to the box through a manifold system to provide uniform distribution of temperature and humidity within the box. Relative humidity was recorded and generally was in excess of 95 percent. Temperature was controlled to either 120 or 100 °F by throttling the incoming steam. All specimens tested at the elevated temperature/humidity condition were held in the specified environment for 24 hours prior to the first application of load. Both static and fatigue tests were run in this environment. Figure 9 shows the setup for the high temperature/high humidity tests.

TEST RESULTS

Screening

Screening tests were conducted on specimens of each of the eight designs. These tests were run in tension-tension fatigue at an R-ratio of 0.14. Results are tabulated in table II and plotted in figure 10. Also shown in figure 10 is a dashed curve which represents the typical failure curve of Mod-OA studs as established from the 4- by 4-inch test block and anchored by the two design 8 (Mod-OA) tests. The scaled Mod-OA studs (design 7) in a 3- by 3-inch block fall below the line by approximately the area ratio of the block (i.e., 9 in^2/16 in^2). All other data fall near or above the line and represent a significant improvement, since the new designs are stressing only 9 in^2 of wood. Designs 1, 2, and 6 are all linear taper designs and are fairly close in performance, although design 2 may be a few percent better than design 1, which is in turn a few percent better than Design 6. If surface area had a significant effect, then design 6, which has a 10 percent greater area than design 1, would be expected to be a superior performer.

Tip drilling does exhibit an advantage, as design 6, the undrilled equivalent of design 2, shows about a 6 percent drop in performance. Although this is not a large margin of difference, the data base is limited to only two specimens of each design. Independent testing by Gougeon Brothers, Inc. has shown a more significant difference, and it is predicted that if a larger number of specimens were tested, the spread between design 2 and design 6 would widen.

Design 3 did exceptionally well, indicating that a closer match in modulus between the wood and the stud and greater surface area provide a significant gain in fatigue performance. Design 4, on the other hand, did not perform as well as expected. The nonlinear taper was predicted to show a sizable performance improvement over the linear taper designs, but the two design 4 samples proved to be only about 5 percent better than the Mod-OA line and were actually 13 percent less effective than design 3. However, when the failed stud specimens were cut open for evaluation, it was found, as shown in figure 11, that in both specimens the inner 5 inches of stud tip failed in fatigue due to the thin wall and a possible flaw in the steel. Consequently, only about 70 to 75 percent of the stud was effective in transferring the load for much of the cyclic life of the specimen, since it appeared that the inner portion had broken off early in the cyclic testing. The third design 4 specimen did not experience the same type of failure, and when tested in fatigue it exhibited a 23 percent improvement over the Mod-OA stud performance. Because of the failure of the two design 4 studs, the 0.625 inch tip drill diameter was changed to 0.609 inch for all subsequent studs (except Design 1, which had a smaller tip and used a 0.437 inch tip drill diameter).

Design 5 tests showed the most significant performance increases, with a 6 percent improvement over the projected design 3 performance and a 33 percent improvement over the 4- by 4-inch Mod-OA test line. On the average, design 5 produced 421 713 cycles between 6310 lbs and 45 000 lbs load, which represents a 5000 psi maximum stress in the 9 in^2 of wood. With such performance, the stud is no longer the limiting feature of the joint, as the stud strength exceeds the design allowable fatigue strength for large wood structures.

Examination of figure 10 indicates that designs 3, 4, and 5 all might be logical candidates for additional testing. Because of limited funding, however, it was possible to carry only two of these designs on to further testing. Design 5 was selected because on the basis of both the preliminary analysis and the test data it should have had the highest structural capability. Design 4 was then selected over design 3 due to the following factors: (a) The one high cycle data point (2 228 652 cycles to 32 000 lbs maximum load) appeared very promising; (b) The two tests at 40 000 lbs maximum load, while not as good as the design 3 data points at 45 000 lbs, did not represent the true capability of design 4, and yet still showed a reasonably high fatigue capability; (c) Preliminary analysis indicated design 4 should be better than design 3; and (d) Design 3 was a titanium stud, which was expected to result in higher manufacturing costs and potential problems with material availability and handling. Consequently, designs 4 and 5 were selected for further testing in order to define the allowable ultimate and fatigue strengths.

Resin System Changes

At the conclusion of the screening phase of testing, Gougeon Brothers, Inc. was in the process of developing a new filler for the resin system used to bond the studs. The asbestos fibers which had previously been used became subject to stringent requirements for environmental control which were economically untenable and made a substitution mandatory. As some success had been noted in previous work with a carbon fiber filler (ref. 1), it was decided to use a carbon-filled resin to bond all new stud specimens. Several different mix ratios were tried and one selected based on its satisfactory viscosity. No strength or physical properties tests were conducted. Effects of this change are noted and discussed in section C below, but the overall effect was to improve stud performance.

Fatigue Tests

A total of 24 design 4 and 22 design 5 studs were fatigue tested at room temperature and at various load levels. Four specimens of each design were fatigue tested at elevated temperature and humidity conditions. Tables III and IV list all the pertinent fatigue test data. As mentioned in section II above, when a carbon-filled resin was used to bond the studs, greater fatigue performance was realized as compared to an asbestos-filled resin. This improvement is quite evident in figures 12(a) and (b), which show the tension-tension fatigue curves for design 4 and design 5 studs with carbon and asbestos fillers. For design 5, eight carbon-filled resin and eight asbestos-filled resin fatigue tests were run, and the results were dramatic. For an equivalent number of cycles, an increase in load of 13 to 15 percent could be maintained for a design 5 carbon-filled resin bonded stud as compared to one bonded with asbestos-filled resin. Although there were only three data points for the design 4 stud bonded with asbestos-filled resin, the effect was even greater; a 23 to 28 percent improvement over asbestos-filled resin was shown by the carbon-filled resin.

Tension-tension. - Figure 13 is a replot of figure 12(a) and (b) with the data for the studs bonded with asbestos-filled resin removed. The projected $4x10^8$ cycle design life for both designs is about 30 000 lbs (maximum load). Design 4 is about 25 percent less structurally effective at the 100 cycle point on the curve. It should be noted, however, that the stud test specimens demonstrated average ultimate strengths of 102 903 lbs for design 5 and 100 453 lbs for design 4; as the fatigue curve approaches the single cycle line, they must again come together.

The projected 10^7 cycle load for design 4 is 38 300 lbs while design 5 can sustain 42 700 lbs at an "R" ratio of 0.1 or greater. These loads represent a wood stress of 4255 psi for design 4 and 4744 psi for design 5. In contrast, the original stud concept as used in Mod-OA had a laboratory demonstrated capability of only 1750 psi in the wood at the same 10^7 cycle fatigue level. Thus, both the design 4 and 5 studs demonstrated more than a 100 percent improvement over the Mod-OA stud. Also, as stated earlier, the laboratory demonstrated wood capability is only 5000 psi in 10^7 cycle fatigue. Consequently, the design 5 stud provides a joint which almost equals the wood capability, while the design 4 stud has an 85 percent joint efficiency. Further, in large blade structures it is expected that both stud designs would have allowables that exceed the wood allowables as reduced for size and moisture content uncertainties.

It should also be noted in figure 13 that all test data was used to calculate the logarithmic regression curve, even the points which represented grip or stud thread failures. Even so, the data fit has a R^2 value (correlation coefficient) of 0.957 for design 5 and 0.853 for design 4. This degree of correlation is excellent, especially for fatigue data, and was achieved with specimens which were manufactured over a period of 18 months, during which a number of subtle changes (as introduced by the human factor) would have occurred. Also, as can be seen in figure 13, almost all the data points that fall below the calculated lines are premature failures due to grip or thread problems. Consequently, the calculated lines can be taken as conservative estimates of the laboratory generated tension-tension fatigue test data.

Although the tensile fatigue performance of the bonded-in steel stud was comparable to the membrane wood performance, the cost of manufacturing the studs could be a drawback in some applications. To avoid this problem, a production version of the design 4 stud was developed for computer controlled, high production rate turning equipment. The modified thread design on the embedded portion of the stud is shown in figure 14. Six of these stud specimens were manufactured and tested (serial numbers R, DD, FF, GG, HH and II). The tensile fatigue data from these specimens were included in figure 12(a) and are replotted in figure 15. Only two of the tests produced valid failures, but all results were well within the range of all design 4 stud fatigue data. Cost of the redesigned stud is estimated to be 150 dollars per stud in production quantities, which compares with 250 dollars per stud for the original design shown in figure 4(a). The revised thread design could be used equally well on the design 5 stud and would not be expected to affect either static strength or fatigue performance.

Compression fatigue. - Prior history of bonded joints has indicated that compression fatigue is not as severe as tensile fatigue. Three studs of each design were subjected to compression-compression fatigue testing at an R-ratio of 10 to confirm these results. The data for these specimens is plotted in figure 16 and can be seen to follow the historically indicated trend.

In both cases, the compression fatigue strength is greater than the tensile fatigue strength, although the percentage improvement is greater for design 4 than for design 5. Both cases are also similar in slope to that of the tension-tension S-N curves. Although there are only three data points for each design, they represent three orders of magnitude in cyclic performance, and all data points are in the same family. Consequently, it is recommended for bonded stud design analysis that the tension-tension S-N curve be used for both tension-tension and compression-compression load cases. This will be conservative for designs which are controlled by compressive fatigue loads.

Ultimate compressive load tests were conducted on one specimen of both design 4 and design 5. For design 4, the failure load achieved was 87 637 lbs, while design 5 achieved the machine limit of 105 447 lbs without failure. Because these ultimate compressive loads achieved 100 per cent of the nominal compressive load capability of the wood laminate material (carbon-fiber augmented, in the case of design 5) and because further fatigue testing was considered to be a more important data requirement, no additional compressive ultimate tests were conducted.

Tension/compression fatigue. - Due to the clevis end configuration of the test specimen, it was impossible to run true $R = -1$ tension/compression fatigue tests. However, the effects of combined compression/tension cycling were obtained by subjecting the specimen to alternating compression fatigue and tensile fatigue at R values of 10 and 0.1, respectively. Since most specimens tested in this manner failed during the tensile portion of the testing, only the tensile cycles were counted as contributing toward failure. This method of reversed axial testing should not be construed as a true $R = -1$ test; rather, it is only assumed to provide a reasonable approximation of data trends. True $R = -1$ testing has been performed to a limited extent by Gougeon Brothers, Inc., and the data generated support the validity of this assumption.

Data are plotted in figure 17, which shows that the simulated $R = -1$ fatigue is more severe than the $R = 0.1$ to 0.14 tensile fatigue spectrum for the higher-performing design 5 stud. At 1000 cycles, for $R = -1$ the maximum load would be on the order of 62 000 lbs, while for an equivalent number of cycles at $R = 0.1$, the design 5 stud could carry about 81 000 lbs. The effect is not as pronounced at the higher end of the cyclic spectrum, but for design conservatism and until true $R = -1$ data can be generated, a knockdown factor of 25 percent from the tension-tension fatigue capability is advised for design 5 studs. Design 4 studs appear to be unaffected by the compression portion of the cycle, as can be seen for the three data points plotted in figure 19. Again, however, design conservatism suggests a similar 25 percent knockdown factor for the design 4 studs.

Temperature effects. - Although not expected to have a large effect on performance, elevated temperature and humidity conditions were introduced into the testing of a series of designs 4 and 5 fatigue specimens. At first, 120 °F and 100 percent RH were used, but after 4 specimens showed very severe degradation, the conditions were dropped to 100 °F and 100 percent RH. Test results are tabulated in table IV and shown graphically in figures 18 and 19. Test procedures were as previously described in section III. The first tests conducted were at 120 °F; as shown in figures 18 and 19, the results were far below the room temperature capability. It was then decided to drop the temperature to 100 °F for the remaining specimen tests, and again the data indicated a severe effect on cyclic capability.

These results were both unexpected and discouraging, indicating that for tropic applications a resin system change may be required. The exact cause of the problem is unknown. Previous wood testing at high temperature and humidity had indicated only a 25 percent loss in performance (ref. 6). Similar testing of studs at elevated temperatures and normal humidity had, in fact, shown an increase in performance (ref. 7). These earlier tests involved studs with much larger surface areas, however, and their performance increase was attributed to a reduction in discontinuity stresses due to softening and flow of the resin in areas where high peak shear stresses occurred. For the design 4 and design 5 studs, where the stress is more uniform and higher in general, the resin softening which occurs at elevated temperatures is expected to be a major detriment.

This factor combined with the effect of increased humidity on wood and epoxy strengths has resulted in failures at less than 50 percent of the room temperature/humidity test levels. The failure mode was at the bond between the filled epoxy resin and the wood, which also indicates that the humidity may have been a contributor to the problem. However, humidity effects would not be expected to be as severe in a wind turbine blade application, where protective coatings are applied to all surfaces to preclude the intrusion of moisture. The need for further testing toward a resolution of this problem is indicated.

CONCLUSIONS

As a result of this design and test effort, the following conclusions have been reached.

(1) Metal studs can be bonded into laminated wood structures to develop joint efficiencies in fatigue on the order of 100 percent.

(2) Bonded steel studs achieved ultimate strengths on the order of 100 000 lbs in a 3 in^2 block (9 in^2).

(3) For a design life of 4×10^8 cycles at an R - ratio of 0.1, the bonded studs sustained maximum loads of 30 000 lbs in a 3 in^2 wood block.

(4) For a reversed axial block loading fatigue (simulated $R = -1$) in a laminated wood structure with a bonded stud joint, strength was reduced by 25 percent as compared to tensile fatigue ($R = 0.1$).

(5) In a laminated wood structure, compression fatigue is less severe than tensile fatigue for a bonded stud joint.

(6) Carbon fiber filler in the epoxy resin improves the fatigue capability of the stud joint as compared to an asbestos fiber filled resin.

(7) The improved stud designs provided a fatigue stress capability twice that achieved by the stud design used for the Mod-0A laminated wood blades.

(8) Temperatures of 100 °F combined with 100 percent relative humidity degraded the fatigue performance of bonded test specimens by 30 to 50 percent. While this effect may not be as severe in a wind turbine blade application, further testing is required, and it may be necessary to develop a new resin system for stud bonding in tropic environments.

(9) Design modifications can be developed which provide low-cost manufacturability without sacrificing performance. The stud cost is projected to be 150 dollars apiece in production quantities of 100 or more units.

(10) Tip drilling was effective in improving performance, although for the limited tests run in this series, there was not a large margin of difference.

(11) Proper matching of the stud modulus to the block modulus is very beneficial to performance. Designs 3 and 5 were both highly effective in transferring cyclic loads to the wood, and either design concept would meet or exceed the wood design allowables for large structures.

(12) Surface area was not the dominant factor in determining stud performance. The eight designs included a wide range of surface areas, but there was no relationship between area and allowable load other than that directly attributable to scaling (up or down) a specific stud design.

(13) Larger tip diameters (smaller taper ratios) are somewhat effective in improving stud performance but do not appear to produce major improvements, as design 2 was only 2 or 3 percent more effective than design 1.

(14) Taper ratio can be effective in improving stud performance, but only by going to a nonlinear taper, as was shown by comparing design 4 to design 2. Nonlinear tapers are cost-effective, and on a production run basis, using tape controlled lathes, the machining cost is not significantly different from a linear taper.

REFERENCES

1. Faddoul, J.R.: Test Evaluation of a Laminated Wood Wind Turbine Blade Concept. NASA TM-81719, 1981.

2. Faddoul, J.R.; and Sullivan, T.L.: Structural Fatigue Test Results for Large Wind Turbine Blade Sections. In Large Horizontal-Axis Wind Turbines. by Thresher, R.W. NASA CP-2230, 1982, pp. 303-328.

3. Lieblein, S.; et al.: Design and Evaluation of Low-Cost Laminated Wood Composite Blades for Intermediate Size Wind Turbines: Blade Design, Fabrication Concept, and Cost Analysis. NASA CR-165463, 1982.

4. Shaltens, R.K.; and Birchenough, A.G.: Operational Results for the Experimental DOE/NASA Mod-OA Wind Turbine Project. NASA TM-83517, 1983.

5. Faddoul, J.R.: Examination, Evaluation and Repair of Laminated Wood Blades After Service on the Mod-OA Wind Turbine. NASA TM-83483, 1983.

6. Wood Handbook: Wood as an Engineering Material. Forest Products Laboratory, Forest Service, U.S. Dept. of Agriculture, Agriculture Handbook No. 72, 1974.

7. Mod-5A Wind Turbine Generator Program Design Report.
   Volume I - Executive Summary. NASA CR-174734, 1984.
   Volume II - Conceptual and Preliminary Design, Books 1 and 2. NASA CR-174735, 1984.
   Volume III - Final Design and System Description, Books 1 and 2. NASA CR-174736, 1984.
   Volume IV - Drawings and Specifications, Books 1 and 5. NASA CR-174736, 1984.

TABLE I. - SUMMARY OF PRIMARY TEST SERIES DESIGN PARAMETERS

Designation/ description	Taper	Root diameter, in	Tip diameter, in	Tip drilling		Surface[b] area, in^2	Modulus, psi	
				Diameter, in	Depth, in		Stud	Block
Design 1; small tip-linear	Linear	1.47	0.562	0.437	8	57.5	30×10^6	2.2×10^6
Design 2; large tip-linear	Linear	1.47	.750	.609	8	62.8	30×10^6	2.2×10^6
Design 3; low modulus-linear	Linear	1.975	.750	.609	8	77	17×10^6	2.2×10^6
Design 4; standard non-linear	Non-linear	1.975	.750	[a].609	15	64.2	30×10^6	2.2×10^6
Design 5; non-linear with stiff block	Non-linear	1.975	.750	.609	15	70.8	30×10^6	3.2×10^6
Design 6; large tip-linear, nontip drilled	Linear	1.47	.750	-----	--	62.8	30×10^6	2.2×10^6
Design 7; Mod-OA stud scaled to a 3- by 3-inch block	Linear	1.13	.563	-----	--	32.0	30×10^6	2.2×10^6
Design 8; Mod-OA stud 4- by 4-inch test block	Linear	1.5	.750	-----	--	53.0	30×10^6	2.2×10^6

[a]First 5 "design 4" studs used a tip drill diameter of 0.625 in.
[b]Surface area equals surface area of smooth surface of revolution which intersects tips of stud threads.

TABLE II. - SCREENING TESTS OF EIGHT BONDED STUD CONFIGURATIONS

TENSION-TENSION FATIGUE AT R = 0.14

Spec. number	Maximum load (1000 lbs)	Cycles	Comments
1A	30	1037952	No failure
	35	16704	Pullout
1B	33	494058	Pullout
2A	33	666000	Grip
2B	33	929382	Pullout
3A	45	160380	Pullout
3B	45	122364	Pullout
4B	40	171190	Pullout
4C	40	124608	Pullout
4D	32	2228652	Pullout
5A	45	404766	Pullout
5B	45	438660	Pullout
6A	20	1122624	No failure
	25	506880	No failure
6B	25	1062720	No failure
	27.5	261252	No failure
	30	95940	No failure
	32.5	231732	No failure
	35.0	91512	Pullout
7A	20	663130	Pullout
7B	20	283392	Pullout
8A	40	74073	Pullout
8B	35	217729	Pullout

TABLE III. - ROOM TEMPERATURE TESTS

[Carbon filled resin unless noted.]

(a) Design 4 Stud

Specimen	Test[a] type	Maximum load (ab. vl.) KIPS	R ratio	Frequency, Hz	1000 cycles	Failure mode	Comments
4A	T-U	67.6	-----	-------	-------	Grip	Asbestos filter
4E	T-U	70.2	-----	-------	-------		Asbestos filter
4K	T-U	97.3	-----	-------	-------	Pullout	
4L	T-U	104.0	-----	-------	-------	Pullout	
4W	T-U	88.2	-----	-------	-------	Grip	
4Z	T-U	86.5	-----	-------	-------	Grip	
4M	T-U	100.1	-----	-------	-------	Pullout	
4S	C-U	87.6	-----	-------	-------		
4B	T-T	40	0.14	3.5	171	Pullout	Asbestos filter
4C	T-T	40	.14	3.0	125	Pullout	Asbestos filter
4D	T-T	32	.14	3.5	2229	Pullout	Asbestos filter
4F	T-T	65	.10	4.0	17	Grip	
4H	T-C[b]	45	-1.0	4.5	[b]811	Pullout	1210 Compres. cycles
4I	T-T	48	.10	4.0	433	Pullout	
4J	T-T	35	.10	4.0	8412	Grip	
4P	T-T	55	.10	4.0	261	Pullout	
4Q	C-C	55	10.0	4.0	243	Comp.	
4R	T-T	53	.10	4.0	103	Pullout	
4U	T-T	60	.10	4.0	30	Pullout	
4V	T-T	45	.10	4.0	1791	Pullout	
4X	T-T	48	.10	4.0	371	Pullout	
4Y	T-T	65	.10	4.0	6.8	Grip	
4AA	C-C	70	10.0	4.0	36	Comp.	
4BB	T-C[b]	50	-1.0	4.1	[b]176	Pullout	371 K compres. cycles
4CC	T-C[b]	65	-1.0	4.0	[b]14.2		17 K compres. cycles
4DD	T-T	48	.10	5.0	105	Grip	
4FF	T-T	60	.10	4.5	22.7	Grip	
4GG	T-T	53	.10	5.0	41.2	Grip	
4HH	T-T	48	.10	5.5	1536	Grip	
4II	T-T	50	.10	5.2	327	Grip	
4D-2	C-C	50	10.0	4.1	10127	Grip	
4E-2	C-C	60	10.0	4.0	167	Comp.	

(b) Design 5 Stud

Specimen	Test[a] type	Maximum load (ab. vl.) KIPS	R ratio	Frequency, Hz	1000 cycles	Failure mode	Comments
5A	T-T	45	0.14	4.1/3.6	405	Pullout	Asbestos filter
5B	T-T	45	.14	3.8/3.6	439	Pullout	Asbestos filter
5D	T-T	72	.10	4.0	40.3	Pullout	
5E	C-U	105.4	-----	-------		No fail	
5G	T-T	50	.10	4.0	576	Pullout	Asbestos filter
5H[d]	T-T	32.3	.10	4.5	1244	No fail	Asbestos filter
5H	T-T	48	.10	4.5/5.0	1369	Pullout	Asbestos filter
5I	T-T	46	.10	4.5	906	Pullout	Asbestos filter
5J	T-T	52	.10	4.0	196	Pullout	Asbestos filter
5L	T-T	55	.10	4.0	300	Pullout	Asbestos filter
5M	T-T	60	.10	4.0	163	Pullout	Asbestos filter
5N	T-T	80	.10	3.0	28.4	Pullout	
5Q	T-C[b]	57	-1.0	4.1	[b]170	Pullout	353 K compres. cycles
5P	T-U	98.4	-----	-------		Pullout	
5R	C-C	60	10.0	4.0	1416	Comp.	
5S	T-T	45	.10	4.0	2513	Threads	
5T	T-T	63	.10	4.2	219	Pullout	
5U	T-C[b]	60	1.0	4.0	[b]28.0	Comp.	35.4 K compres. cycles
5V	T-C[b]	50	-1.0	4.1	[b]1475	Pullout	1471 K compres. cycles
5W	C-C	55	10.0	4.5	4241	Comp.	
5X	T-T	65	.10	4.0	117	Pullout	
5Y	T-T	70	.10	3.4	46.9	Grips	
5Z	T-U	107.4	-----	-------	-------	Pullout	
5BB	T-T	57	.10	4.0	431	Pullout	
5CC	T-T	50	.10	4.0	3657	Pullout	
5DD	C-C	70	10.0	4.0	114	Comp.	

[a]T-U equals tensile-ultimate; C-U equals compression-ultimate. T-T equals tension-tension; T-C equals tension-compression; C-C equals compression-compression

[b]For T-C testing blocks of both C-C and T-T cycles were run and only the number of T-T cycles were counted toward failure.

[c]Tested at low load due to error in load cell calibration curve.

TABLE IV. - ELEVATED TEMPERATURE AND HUMIDITY TESTS

Spec. number	Temperature, °F	Maximum load (1000 lbs)	Cycles
Design 5			
5O	120	60	604
5C	120	50	1603
5F	100	50	2437
5K	100	35	50044
5AA	100	108.6	[a]1
Design 4			
4G	120	60	264
4N	120	50	125
4EE	100	50	1332
4T	100	35	8763
4O	100	67.1	[a]1

[a]Ultimate load test.

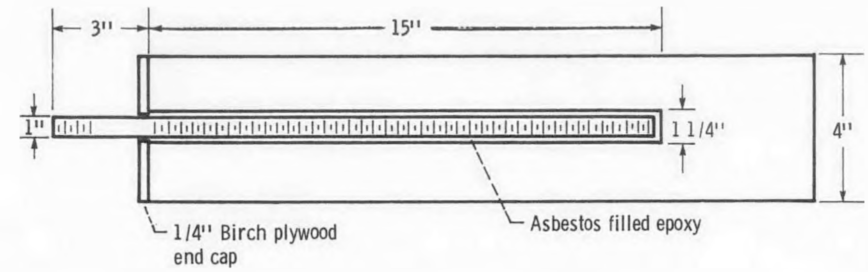


Figure 1. - Original bonded stud test specimen design.

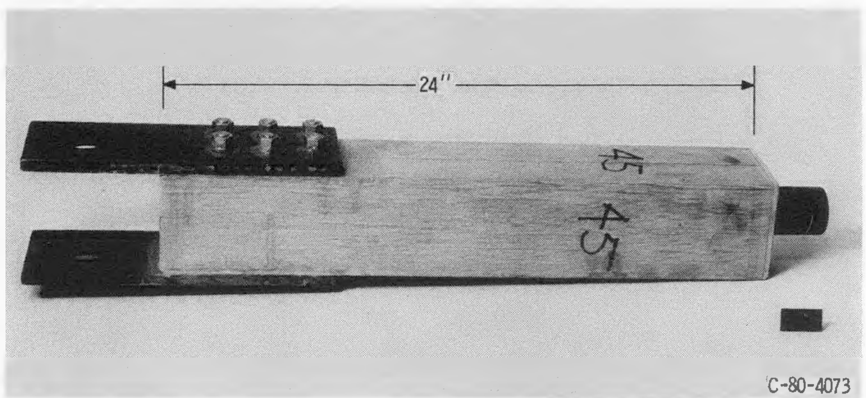
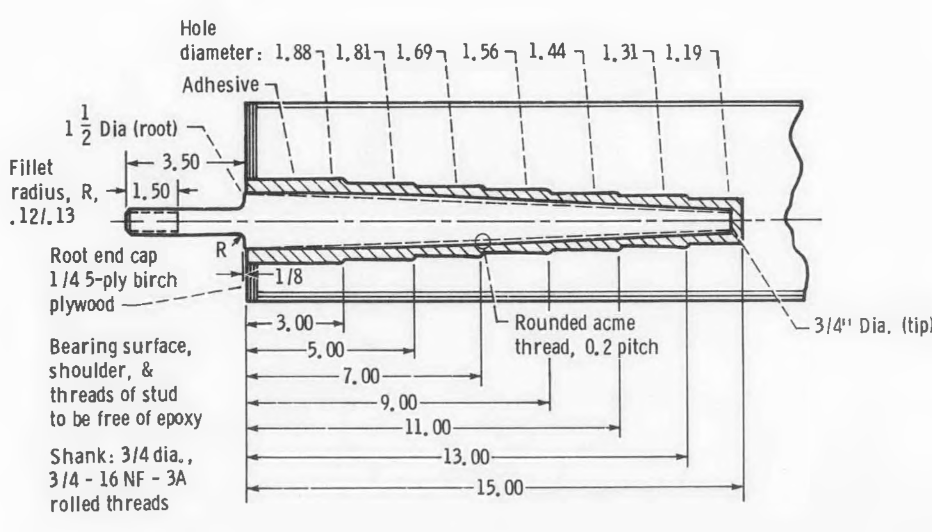
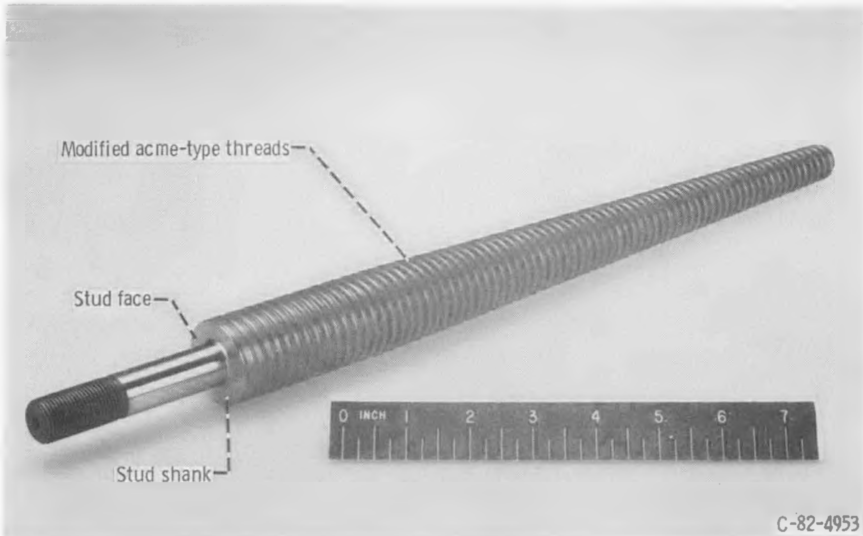


Figure 2. - Typical original stud bond test specimen.

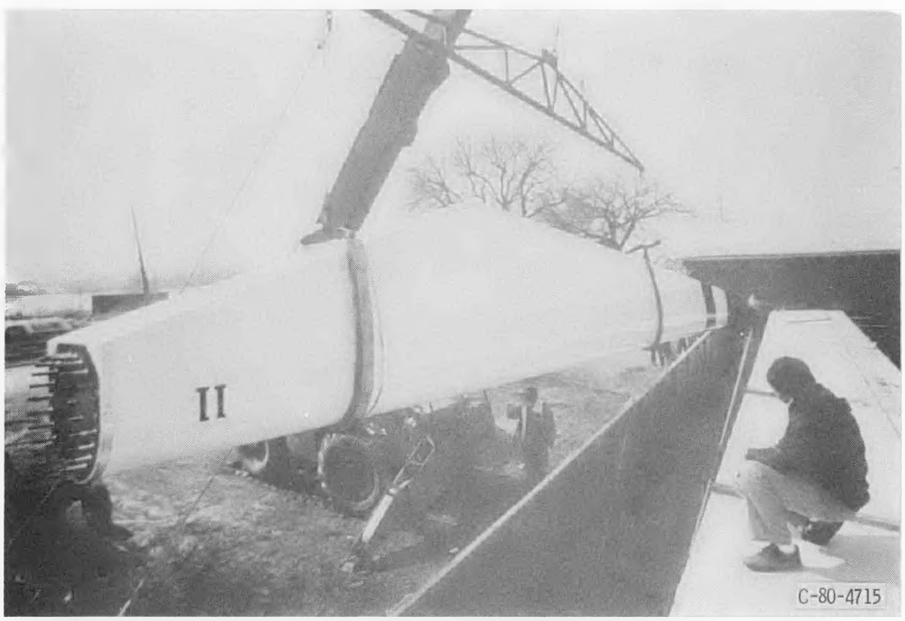


(a) Final tapered stud design configuration (dimensions in inches).

Figure 3.

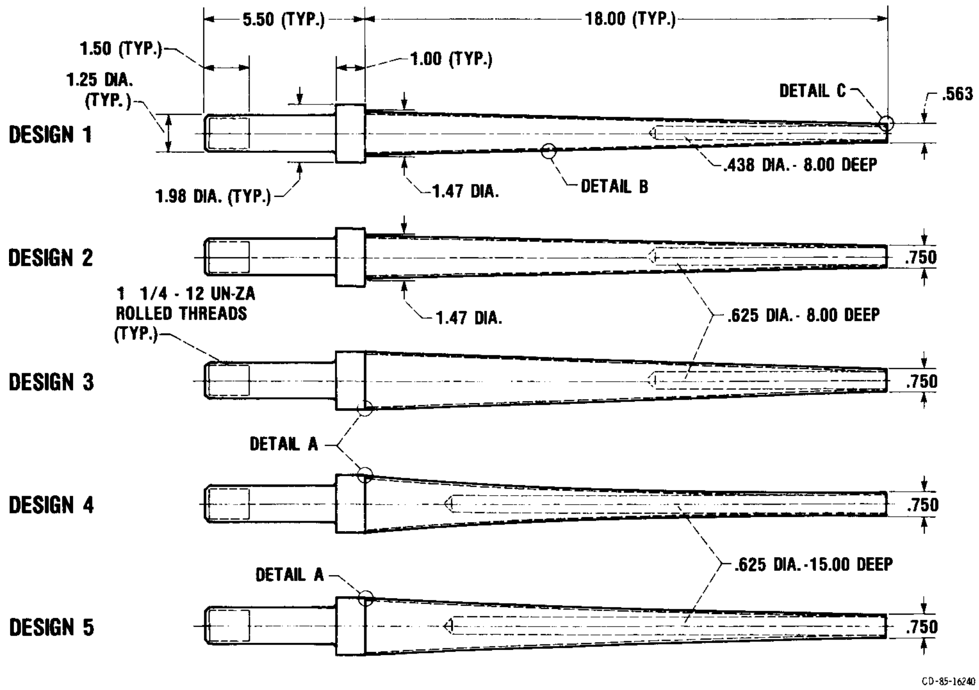


(b) MOD-OA steel take-off stud.

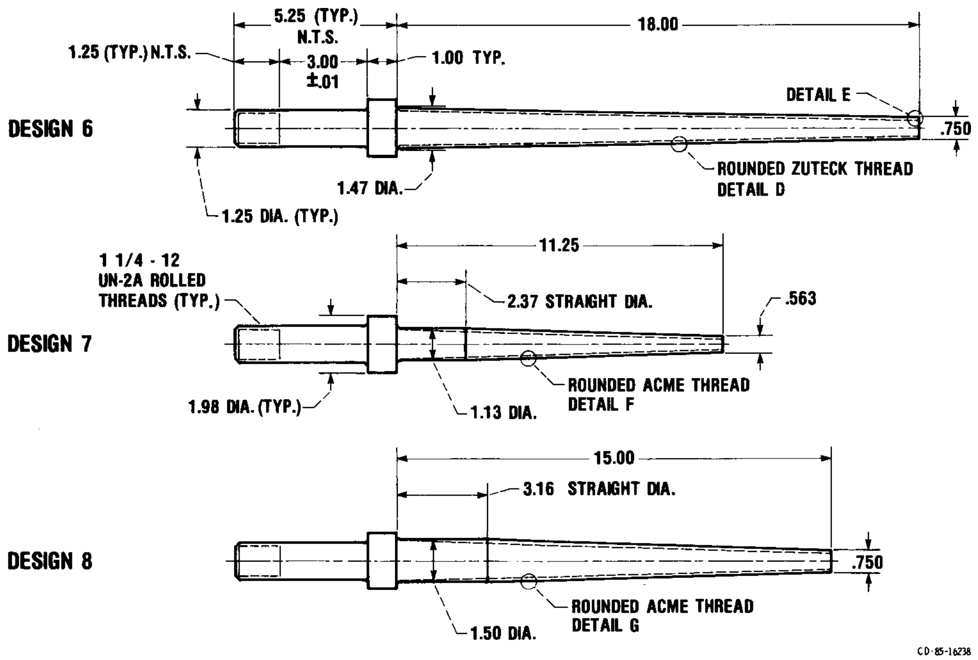


(c) MOD-OA blade showing studs.

Figure 3. - Concluded.

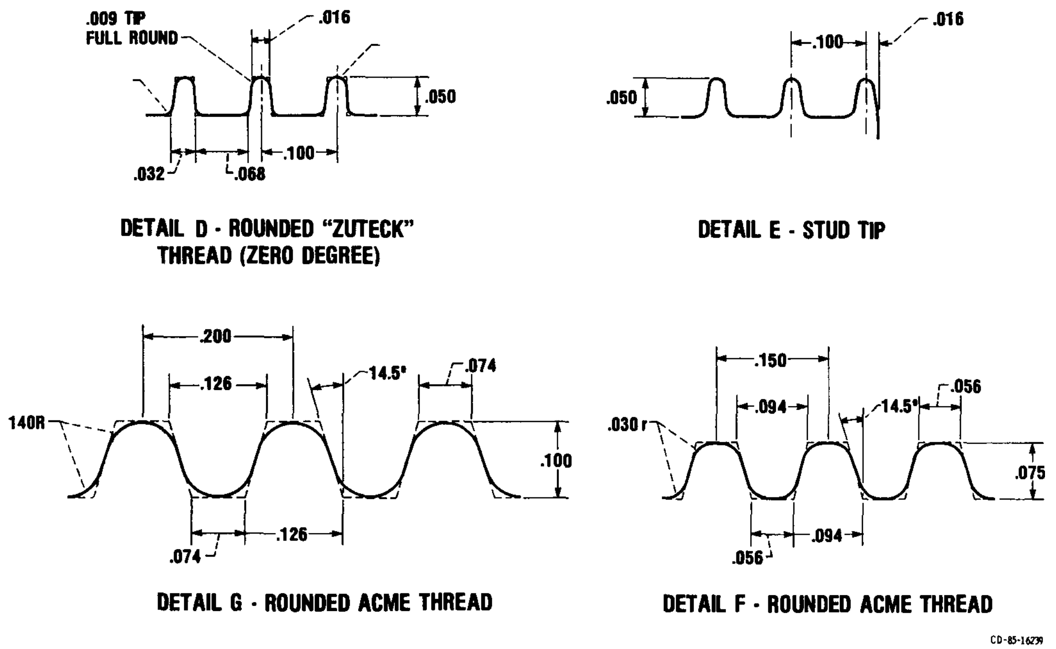


(a) Stud design details.

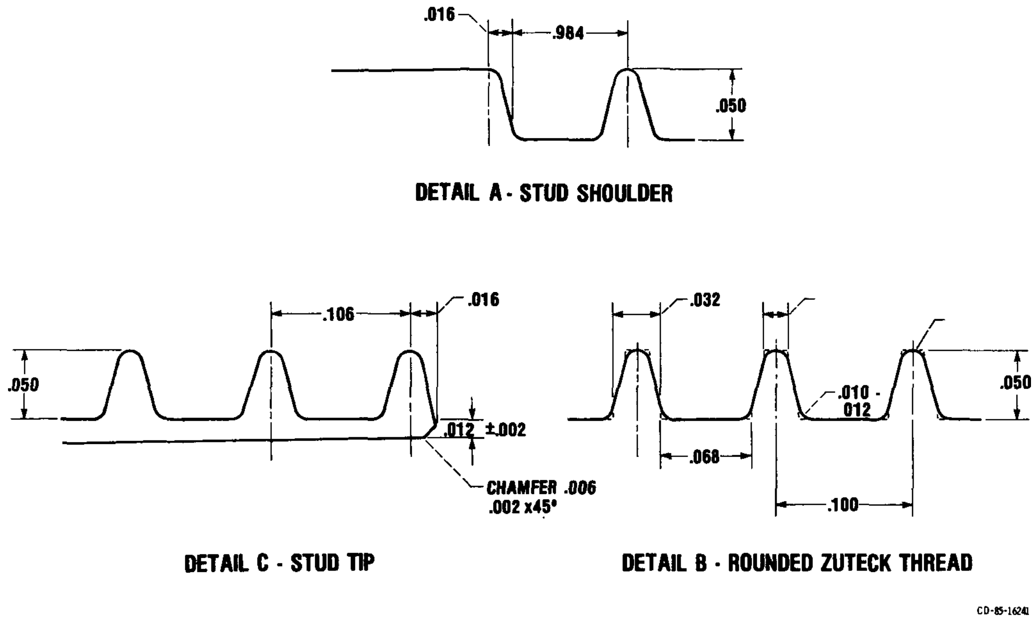


(b) Stud design details.

Figure 4. - Continued.



(c) Stud design details.



(d) Stud design details.

Figure 4. - Concluded.

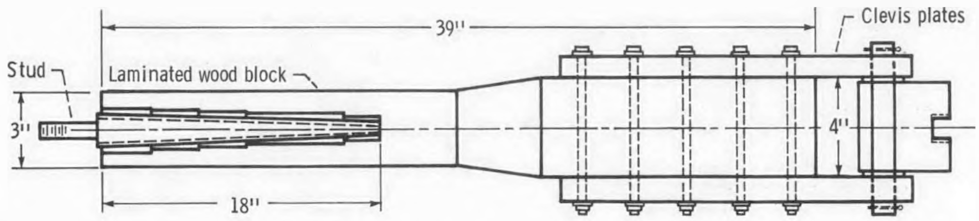


Figure 5. - IIT test specimen configuration.

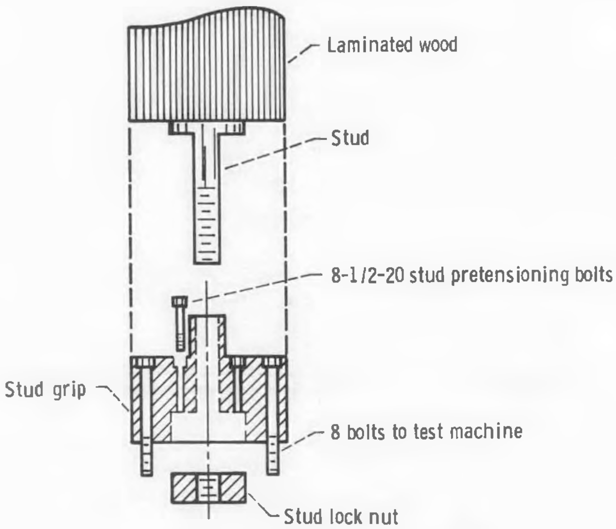


Figure 6. - Adapter to mate specimen to test machine.

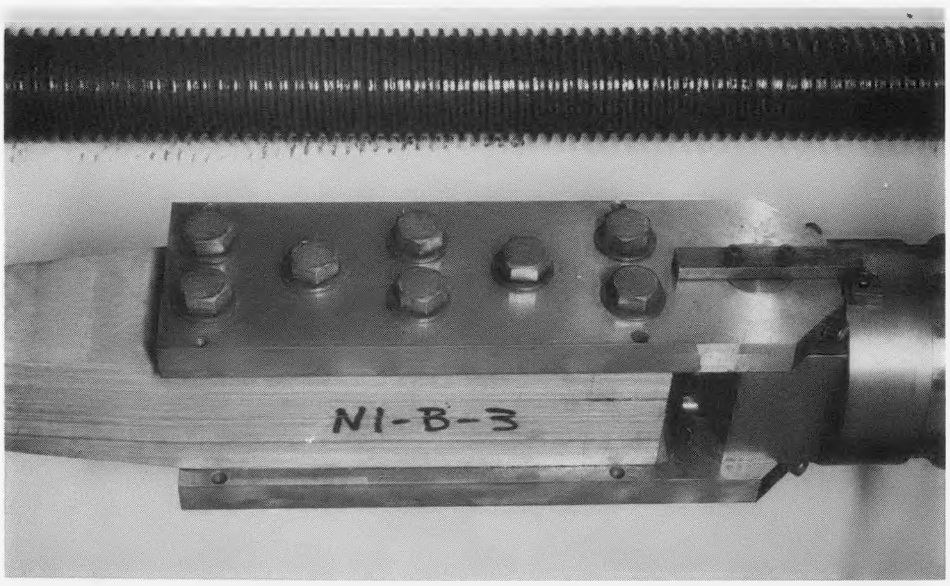


Figure 7. - Clevis mounted on specimen.

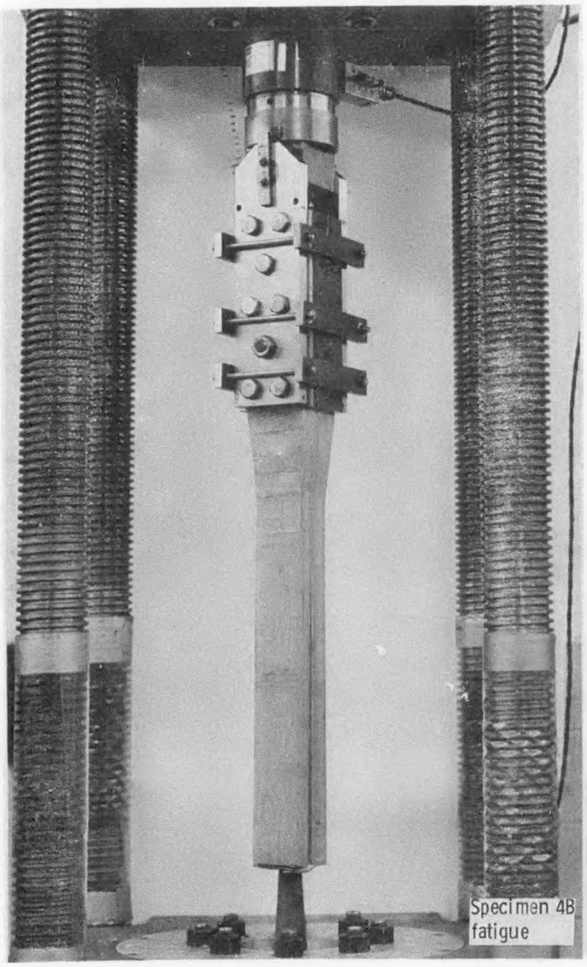


Figure 8. - Typical stud mounted in the testing machine at IITRI.

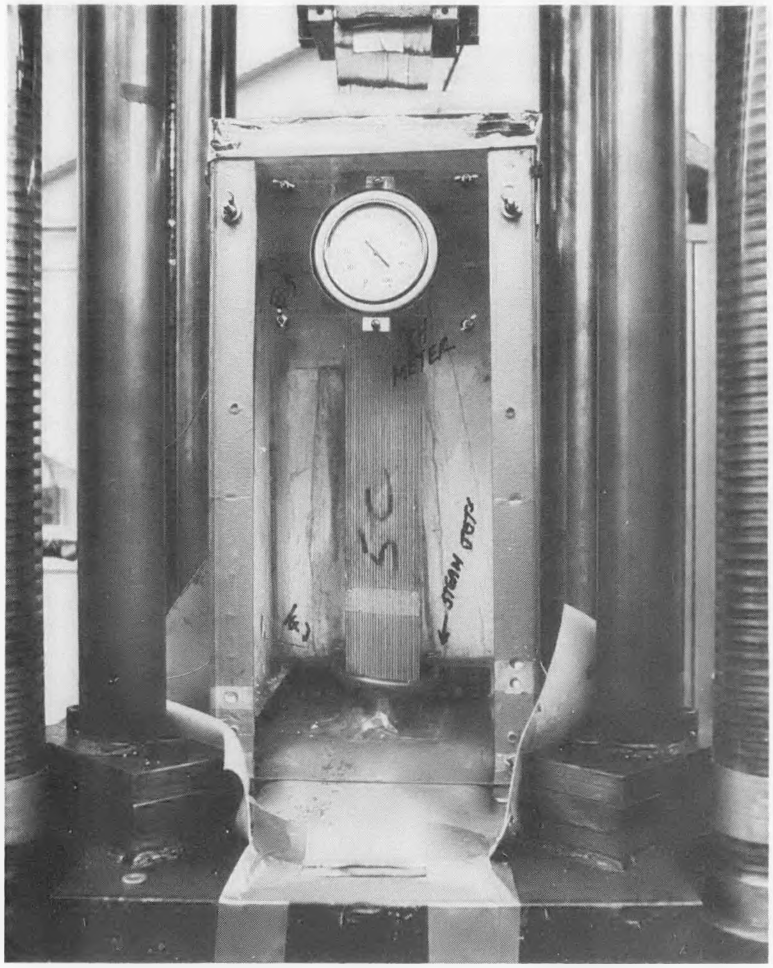


Figure 9. -Test setup for high temperature, high humidity testing.

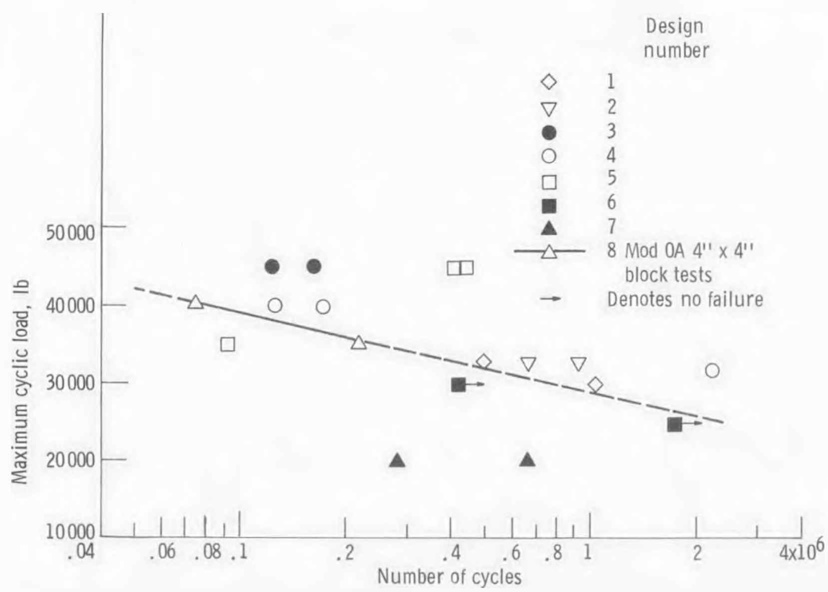
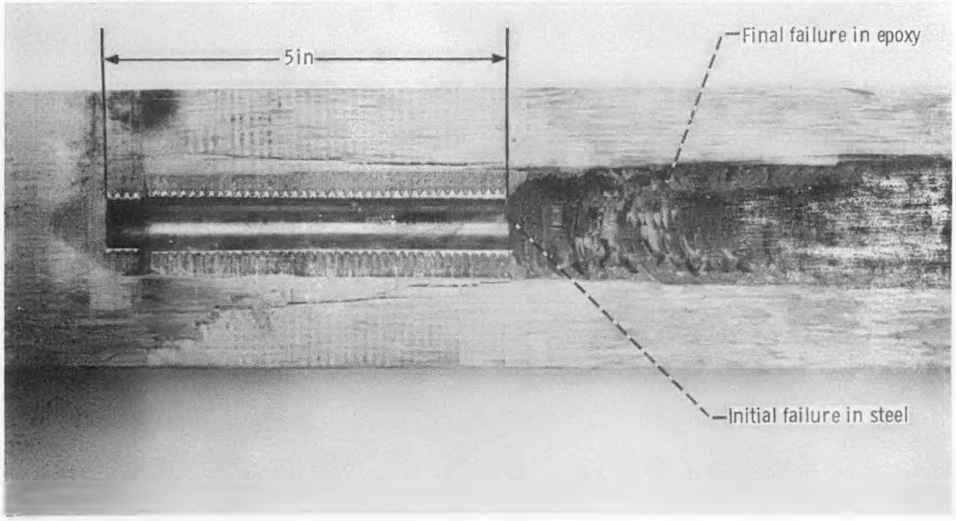
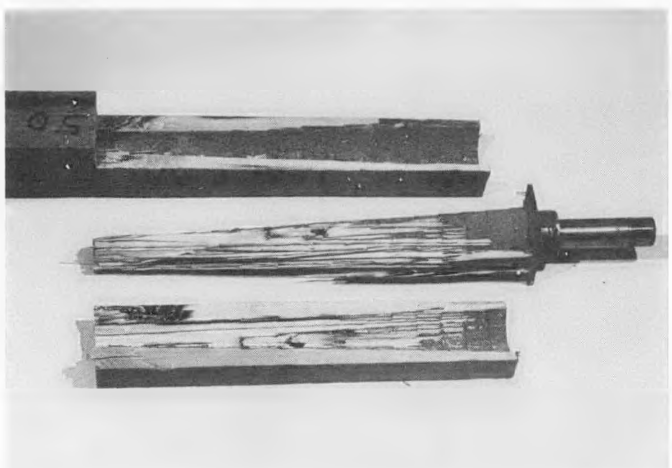


Figure 10. - Stud screening tests in 3" x 3" wood blocks. Eight design variations. All tests run in tension-tension at R = 0.14.

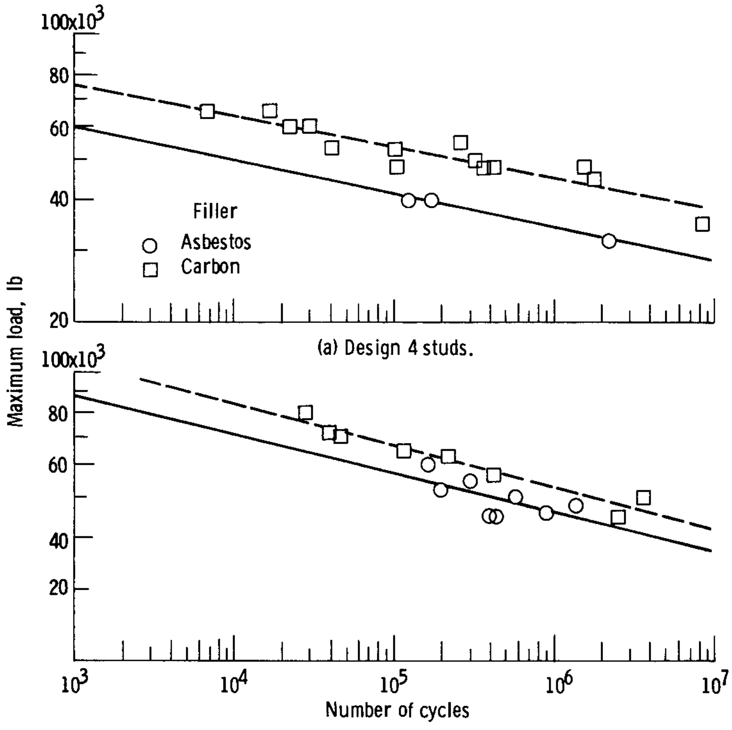


(a) Fatigue failure near steel stud tip of specimen 4B. (Tested at 75°F and 50% R. H.)



(b) Typical failure in bond.

Figure 11.



(b) Design 5 studs.

Figure 12. - Effects of asbestos and carbon fillers on studs in tension-tension. All tests run at "R" ratios between 0.1 and 0.14.

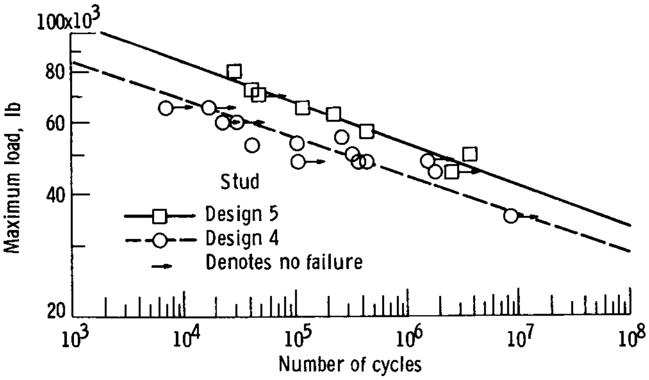


Figure 13. - Fatigue performance comparisons style four and style five studs; carbon filled resin - tension-tension test; all tests run at "R" ratios between 0.1 and 0.14.

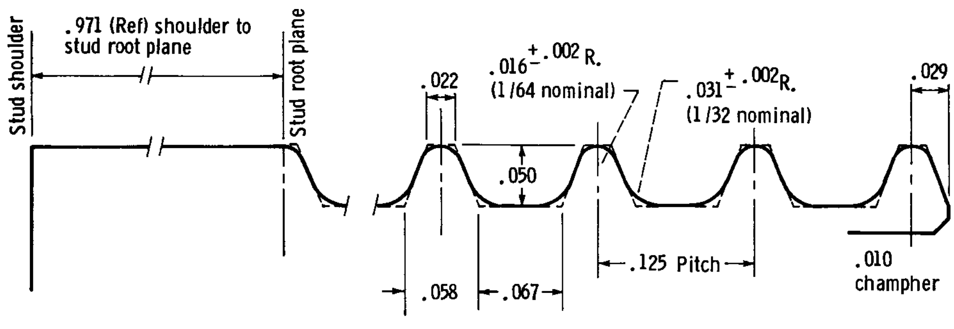


Figure 14. - Detail "A" of Mark II Zuteck thread, shoulder and tip detail zero degree Helix; dimensions in inches.

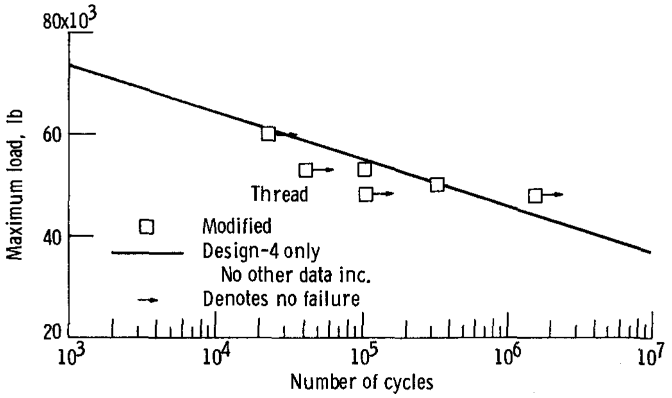


Figure 15. - Revised thread (groove) configuration tension-tension fatigue effects design-4 stud; all tests run at "R" ratios between 0.1 and 0.14.

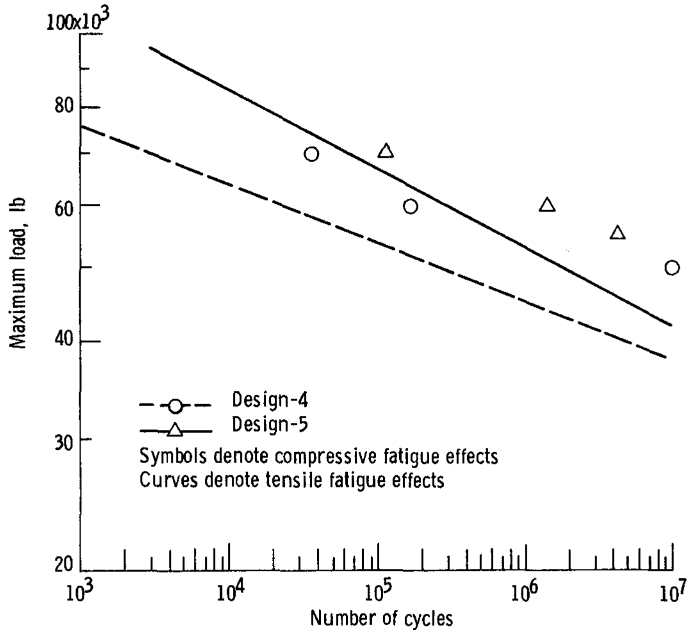


Figure 16. - Effects of compressive and tensile fatigue. Design-4 and design-5 studs; carbon-filled resin.

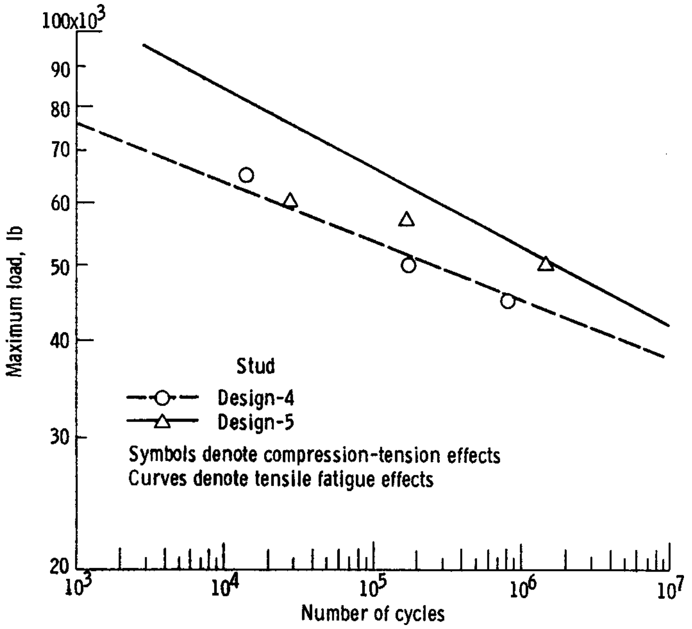


Figure 17. - Effects of compression-tension and tensile fatigue design-4 and design-5 studs; carbon-filled resin.

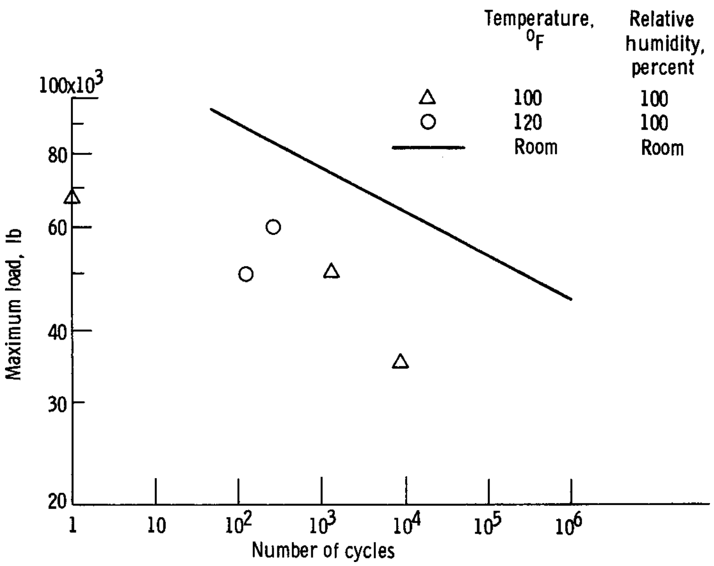


Figure 18. - Effects of temperature and humidity on tensile fatigue. Design-4 stud; carbon-filled matrix; all tests run at "R" ratios between 0.1 and 0.14.

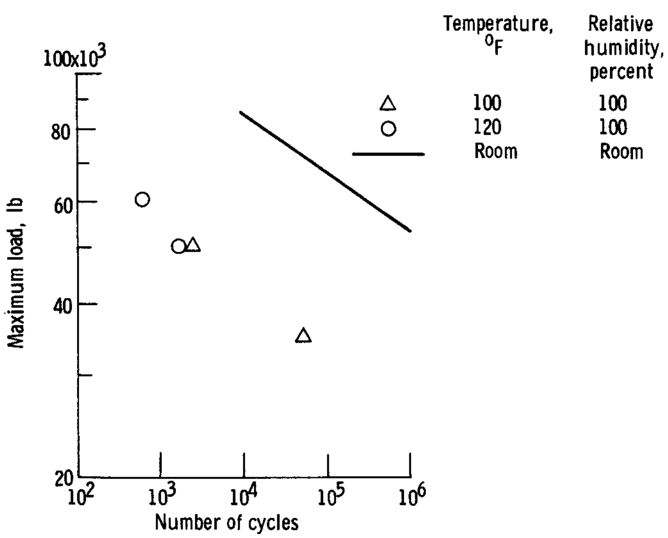


Figure 19. - Effects of temperature and humidity on tensile fatigue. Design-5 stud configuration; carbon-filled matrix; all tests run at "R" ratios between 0.1 and 0.14.

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16. Abstract

A series of bonded stud design configurations was screened on the basis of tension-tension cyclic tests to determine the structural capability of each configuration for joining a laminated wood structure (wind turbine blade) to a steel flange (wind turbine hub). Design parameters which affected the joint strength (ultimate and fatigue) were systematically varied and evaluated through appropriate testing. Two designs showing the most promise were used to fabricate additional test specimens to determine ultimate strength and fatigue curves. Test results for the bonded stud designs demonstrated that joint strengths approaching the 10 000 to 12 000 psi ultimate strength and 5000 psi high cycle fatigue strength of the wood epoxy composite could be achieved.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Wind turbine blade; Laminated wood; Wood fasteners; Joint fatigue; Wood joints	Unclassified - unlimited STAR Category 39 DOE Category UC-60

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