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National Aeronautics and Space Administration
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Work performed for
U.S. DEPARTMENT OF ENERGY
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Prepared for
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NOTICE

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CONSTRUCTION OF LOW-COST, MOD-OA WOOD COMPOSITE WIND TURBINE BLADES

by

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NASA-Lewis Research Center
Cleveland, Ohio 44135

Abstract

A contract was awarded to Gougeon Brothers, Inc. by the Wind Energy Project Office of NASA-Lewis, under Department of Energy sponsorship, for the design and construction of two sixty-foot, low-cost, wood composite blades for service on 200 kW Mod-OA wind turbines. This report provides a description of the construction phase of this project.

The blades were constructed of epoxy resin-bonded Douglas fir veneers for the leading edge sections, and paper honeycomb-cored, birch plywood faced panels for the afterbody sections. The blades were joined to the wind turbine hub by epoxy resin-bonded steel load take-off studs embedded into the root end of the blades. The blades were installed on the 200 kW Mod-OA wind turbine facility at Kahuku, Hawaii.

The blades have completed nearly 8,000 hours of operation over an 18 month period at an average power of 150 kW prior to replacement with another set of wood composite blades. The blades were replaced because of a corrosion failure of the steel shank on one stud. Inspections at NASA-Lewis showed that the wood composite structure remains in excellent condition.

1.0 INTRODUCTION

The Department of Energy assigned to NASA-Lewis the task of developing large diameter, cost-effective, horizontal axis wind turbine machines for electrical power generation. Preliminary studies indicated that rotor blades constitute the largest element of the total machine cost. Programs were therefore funded to develop low cost wind turbine blades.

Prototype, Mod-OA wind turbines were designed, constructed and tested for operational experience. The Mod-OA wind turbine is a 200 kW, horizontal axis, down-wind machine using a two-bladed rotor having a diameter of 125 feet. This wind turbine generates electric power in winds ranging from 7 to 40 mph and uses blade pitching to control power output. The Mod-OA wind turbines were originally equipped with aluminum blades made by using aircraft wing construction processes. Experience with these blades indicated that this aluminum blade design did not have adequate long-term fatigue properties and the blades were high in cost. The aluminum blade experience indicated that a new approach to blade construction would be needed to provide blades having both low-cost and long-term operational properties.

The feasibility of designing and constructing Mod-OA blades from a laminated wood structure was evaluated by an exploratory study awarded to Gougeon Brothers, Inc. (GBI). This study showed that it was feasible to construct wood composite blades that would meet Mod-OA structural requirements[1]. A contract was awarded to GBI to design and construct 2 blades for the Mod-OA wind turbine. The results of the GBI effort was the design and construction of a set of laminated wood composite blades which were installed and operated on the newest Mod-OA wind turbine (fig. 1) located in Kahuku, Hawaii.

This report provides a description of the blade construction phase of the above contract. The design phase is described in reference 2.

2.0 DESIGN SPECIFICATIONS & BLADE DESCRIPTION

The contract specified that the 125-foot wood composite rotor be designed to generate an electrical power output of 200 kW at a rotor rotational velocity of 40 rpm, and at a wind speed of 15 mph.

Specifications for maximum blade weight and root gravity moment were 3,000 lbs. and 47,000 ft. lbs. respectively. Two design load conditions were specified: (1) limit hurricane load modeled by a 50 lb/sq ft load on the blade planform area, and (2) a 4 x 10^8 cyclic fatigue capability (30 year life).

The blades were to interface with a spool piece by use of steel load take-off studs that were embedded and bonded into the wood structure at the root end.

Figure 2(a), (b), and (c) schematically shows blade planform, thickness variations, and twist from Station 50 to Station 750, respectively. Station numbers refer to the number of inches in blade span from the axis of rotation. The blade planform was linearly tapered outboard from Station 168 to the blade tip at Station 750. A NACA 230XX series airfoil was used for the blade airfoil shape in the power producing portion of the blade (Stations 168 to 750). This blade section had a twist of 4.8-degrees. The blade shape inboard of Station 168 was a truncated section formed with no twist. The leading edge (nose) structure of the blade at Station 168 down to the root end at Station 50 was increased in thickness to provide a thickened wood structure for the insertion and bonding of 24 steel load take-off studs in a 18-5/8-inch dia. bolt circle. Installation of each stud required drilling of a 15-inch deep step-tapered hole in the root end section. The studs were then cast into the holes using a thickened adhesive. The root end attachment arrangement is shown schematically in figure 3.

The steel load take-off stud design evolved from tests conducted by NASA-Lewis personnel that evaluated the effects of materials and dimensional variables on stud specimen static and fatigue performance[3].

The blade design included a lightning protection scheme that consisted of an aluminum screen just below the blade surface. At the root end of the blade the screening was electrically coupled to the wind turbine by means of aluminum straps.

3.0 BLADE MATERIALS

3.1 D-Spar or Nose Laminate

Douglas fir in the form of sliced, 1/16-inch veneers was used for the construction of the nose laminate. The number of plies ranged from 74 at the root end (4.5-inch thick) to 8 plies at the tip (0.6-inch thick).

3.2 Other Blade Structures

Other blade structures such as the shear web, afterbody panel, and root end and tip caps were constructed from birch plywood in thicknesses ranging from 1/16 to 1/4-inches.

3.3 Steel Load Take-Off Studs

The steel studs were made from 41L40 steel heat treated to a 40-42 Rockwell C hardness.

3.4 Adhesive

The adhesive used for blade construction and bonding of all structures was the WEST System[R] adhesive formulated by GBI. This adhesive is a room temperature curing epoxy resin (1.5 hour working life). Several types of filler additives were used with the adhesive, when required, to minimize adhesive flow until curing had been completed.

3.5 Honeycomb Core Material

The honeycomb core material, used to stiffen the blade afterbody, was made from phenolic resin-impregnated Kraft paper.

4.0 MOLDING PROCESS & BLADE STRUCTURAL ELEMENTS

4.1 Molding Process

A process using vacuum compaction of the laminate in a female mold was selected for blade construction because of good reproductibility of surface contours from blade to blade and low labor costs. The female mold was used to construct the wood composite blade in two half-shells (high and low pressure blade sides) as shown schematically in figure 4.

4.2 Shear Web

The shear web (fig. 4) provides rigidity to the overall blade structure. The shear web was constructed from 1/4-inch birch plywood in four foot lengths having scarfed ends. Joining cleats were bonded to both sides of the top of the shear web to provide the necessary shear area when the two blade half shells were bonded together. The shear web was gradully thickened from 1/4-inch at Station 168 to 4.5 inches at Station 50 by bonding layers of veneers to the shear web. The thickened shear web, along with the thickened nose laminate, provide the necessary build-up for insertion and bonding of the load take-off studs in the root end blade section.

4.3 Afterbody

The afterbody of the blade was made from a honeycomb core sandwiched between 1/4-inch birch plywood sheets.

The afterbody was constructed in several phases that included the outer blade skin structure composed of fiberglass cloth and aluminum screening, and the outer birch plywood panel previously made in one piece on a layout table. Additional afterbody components include sawn lumber frames and stringers, a honeycomb core and the inner birch plywood face sheet. All of these components were bonded to each other, under vacuum compaction, prior to the construction of the nose laminate.

4.3 Nose Laminate

The nose laminate extends from the blade leading edge to approximately the point of maximum airfoil thickness. This blade section was constructed as a curved laminate made from bonded veneers, as shown schematically in figure 4.

5.0 BLADE CONSTRUCTION TOOLING

5.1 Blade Construction Molds

Male molds, representing the high and low pressure sides of the blade, were constructed from sawn lumber and plywood. The surfaces of the male molds were made of plaster over a wood framework. The plaster surface was accurately contoured to the required airfoil surfaces by the use of blade chord templates. The mold surfaces were then optically checked for correct alignment and blade twist.

The female molds were constructed upside down on the male molds using fiberglass cloth, a paper honeycomb core, and plywood backing. The core, plywood, and fiberglass cloth were bonded to each other by vacuum bag compaction. Afterwards plywood ribs and longitudinal stiffening members, and supporting legs and braces were bonded to the plywood backing. After completion, the female molds were lifted off the male molds. The female molds were leveled, optically aligned, and the legs were bonded into place on the shop floor.

5.2 Veneer Stitching Machine

This machine joined two, or more veneers, longitudinally, by applying resin-impregnated fiberglass roving over the joint surfaces on one side of the veneer in a zig zag pattern.

5.3 Adhesive Application Machine

The adhesive application machine applied a uniform coating of adhesive on both sides of a veneer. Adhesive thickness was controlled by a spreader blade that applied adhesive to two rubber rolls, which in turn, transferred adhesive to the veneer surfaces. About 40 lbs. of adhesive was applied per 1,000 sq. ft. of veneer during construction of the Mod-0A blades described in this report.

5.4 Stud Hole Drilling Fixture

Figure 5 shows a view of the fixture for drilling of holes in the wood structure at the root end of the blades. The fixture was equipped to index the drilling fixture face plate to provide accurate placement of the studs.

5.5 Band Saw

A specially designed band saw, shown in figure 6, was used to trim each blade half-shell. During trimming, the band saw traversed on guide tracks built into the female molds.

6.0 BLADE CONSTRUCTION

Blade construction was performed in accordance with detailed blade design drawings shown on figures 7 and 8 (a) through (c).

6.1 Material Loading into Female Molds

Construction of the blade started by the application of an adhesive coating to the mold surfaces (treated with release agent). Precut fiberglass cloth was then inserted into the mold and coated with adhesive. This was followed by precut aluminum screening and sufficient adhesive to coat the screening surface. Next the preassembled (on a layout table) 1/8-inch outer birch plywood afterbody panel, equipped with the longitudinal shear web stringer, was inserted. This was followed by two 1/16-in. birch plywood outer nose plies that were butt joined to the outer plywood afterbody panel. The remainder of the afterbody components, such as the sawn lumber frames, honeycomb core, and the inner birch plywood face panels, were then assembled into place onto the outer plywood panel. All of the blade assembly completed thus far was then vacuum bag compacted and the adhesive was allowed to cure. After curing was completed, the vacuum bag was removed and blade construction was continued by the assembly of the shear web.

The shear web was constructed from scarfed 4-ft. lengths of 1/4-inch birch plywood cut to required widths. The shear web pieces were bonded to the longitudinal shear web stringer and to each other. Sawn lumber cleats were then bonded to each side of the shear web top.

The next phase involved lay-up of adhesive coated Douglas fir nose veneers (previously cut to width and length) onto the double layer of 1/16-in. birch plywood nose plies already in the mold. As each adhesive-coated veneer was inserted into the mold, thickened adhesive was applied to all veneer butt joints and to the longitudinal joint where the veneers interfaced with the shear web. The laminate was vacuum bag compacted during adhesive cure.

After curing, an inspection was made to assure that all components were adequately bonded. Additional adhesive, where required, was added to fill in any voids. All remaining components such as root end stringers and the blade tip honeycomb material were then inserted into the molds and bonded into place.

6.2 Blade Half-Shell Trimming

After installation and bonding of the blade components in each half-shell was completed, the bandsaw was set on the track guides. The blade half-shells were trimmed to the required centerline in one continuous pass of the bandsaw. Figure 6 shows the simultaneous bandsaw cutting of the nose laminate, shear web, and the afterbody sections. A rib structure, constructed from 1/4-inch birch plywood, was then installed in each half-shell at Station 168.

6.3 Blade Assembly

After both half-shells were completed the two half-shells were bonded into a complete blade structure, shown schematically in figure 9. All faying surfaces were coated with a prime coat of unfilled adhesive to fill the wood pores. The lower faying surfaces were then coated with thickened adhesive to fill in any gaps. The two half-shells were then brought together and weights were applied to the top half-shell until curing was completed.

6.4 Tip and Root-End Close-Out

After completion of bonding, the blade was lifted out of the female mold and the blade tip and root end sections were trimmed and capped with 1/4-in. birch plywood.

6.5 Insertion of Load Take-off Studs

Prior to stud hole drilling, the blade was accurately positioned with respect to the drill fixture and anchored to prevent movement during drilling and stud insertion.

After drilling was completed, the studs were fastened to the faceplate of the drilling fixture with centering nuts. The flatness of the faceplate was critical since it was necessary to provide accuracy of adjacent stud faces to within +/- 0.0005-inches of lying in the same plane. This was the most critical tolerance for blade construction. Inaccuracies greater than about 0.001 inches between faces of adjacent studs could result in early fatigue failure of the epoxy bond in the wood structure, or early fatigue failure of the stud shanks. The drilled wood surfaces were prime coated with unfilled adhesive and each hole was then partially filled with thickened adhesive. Care was taken to assure that no air pockets were formed during adhesive addition. Thickened adhesive was also applied to the stud surfaces which would be embedded into the wood. The studs were inserted into the holes allowing excess adhesive to flow out. This process minimized entrapment of air and resulting formation of voids in the adhesive bond. The faceplate was brought in contact with the plywood cap and the adhesive was allowed to cure. After cure was completed, the face plate was removed and stud bonding was inspected for completion of cure and accuracy of alignment. Figure 10 shows a view of the Mod-OA stud.

6.6 Blade Completion

Blade completion included painting, serial numbering, attachment of the root end lightning protection grounding strap, and final blade weighing. The weights of the two Mod-OA wood composite blades were 2,470 and 2,603 lbs. Thickened adhesive was added to the lighter of the two blades to achieve an accurate match of weight and center of gravity. Figure 11 shows a view of one of the completed blades being prepared for shipment to Hawaii.

6.7 Quality Assurance

To assure that the wood composite blades met all specifications and design requirements, a quality assurance program was implemented during blade construction.

An opportunity for checking the effectiveness of the quality assurance program was provided when the Hawaii blades were taken out of service after an 18 month period of operation (about 8,000 hours). The blades were replaced because one of the stud shanks failed due to stress-corrosion fatigue. The failure was attributed to lack of complete contact of the stud face with its mating spool piece flange surface. Although all of the stud faces and shanks were protected with grease before installation, moist salt air penetrated the protective film and caused pitting of the stud shank near the stud face.

An inspection of the blade at NASA-Lewis disclosed that no corrosion was evident on the stud faces when complete contact with the spool piece flange surface was achieved. The condition of the wood structure was found to be in excellent condition.

7.0 CONCLUSIONS & CONCLUDING REMARKS

1. The wood composite blade construction processes developed in this project were acceptable for use on Mod-OA wind turbine blades.

2. Unique tooling and construction procedures were developed to minimize blade labor requirements.

3. The integrity of the wood composite blade structure was demonstrated upon inspection of the Hawaii blades after an 18 month period (about 8,000 hours) of operation at an average power of 150 kW.

The inspection of the returned Hawaii blades indicated that greater precision was needed to preclude misalignment of stud faces and axes. Corrosion was either minimized or prevented when stud face contact with its mating spool piece flange approached a metal-to-metal contact condition. The inspection also indicated that an improved corrosion inhibiting primer should be used on external stud surfaces.

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2. S. Lieblein, M. Gougeon, G. Thomas, and M. Zuteck, "Design and Evaluation of Low-Cost Laminated Wood Composite Blades for Intermediate Size Wind Turbines: Blade Design, Fabrication, Concept, and Cost Analysis," DOE/NASA/0101-1, NASA CR-165463, December 1982.

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9.0 BIOGRAPHY

Mr. Lark is assigned to the Structures Research Section, Structures & Mechanical Technologies Division of the NASA-Lewis Research Center, Cleveland, Ohio. He received his B.S. in Chemical Engineering (1948) from Case Institute of Technology. His current work assignment involves the project management of in-house and contractural programs for the development of composite pressure vessels, composite structures for aircraft engine components, and low-cost, wind turbine rotor technology for the Wind Energy Project Office. Other experience includes the development of positive explusion devices, and advanced fibers, resins, and adhesives. He has contributed significantly to the advancement of composite pressure vessels constructed from aramid and carbon fibers, impact-resistant hybrid and superhybrid composites, and advanced composites in general.

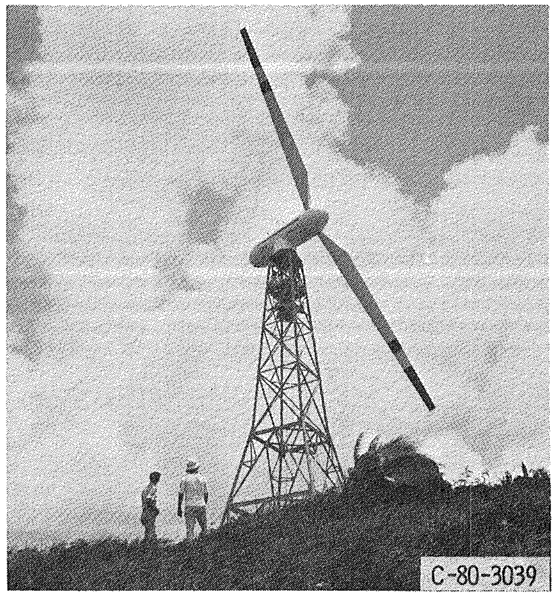
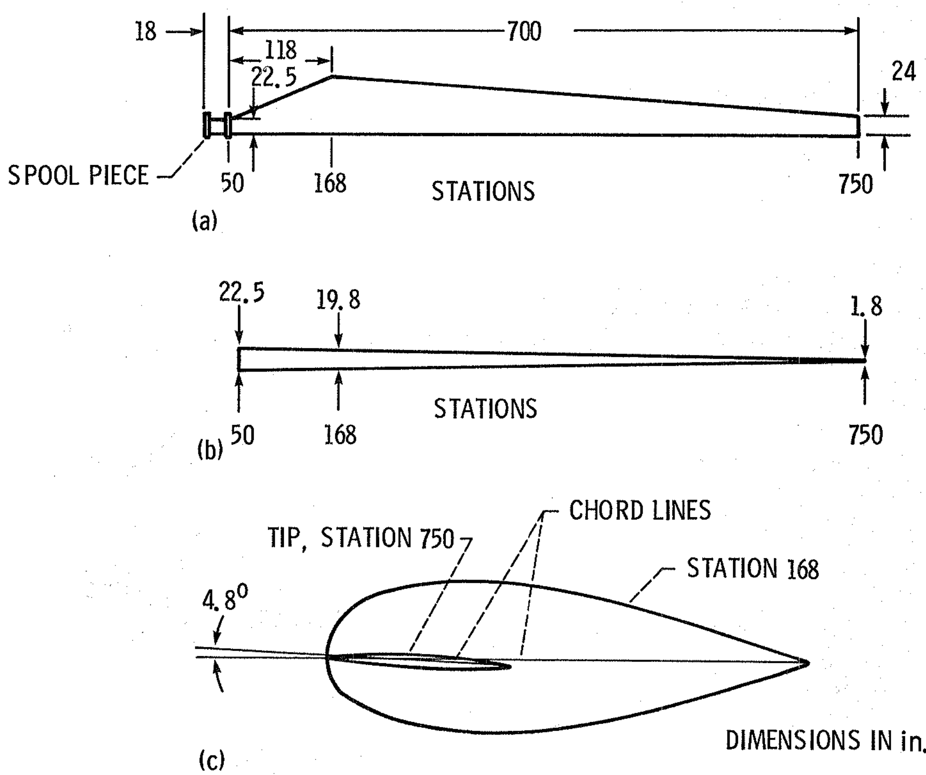


Figure 1. - DOE/NASA experimental MOD-OA wind turbine, Kahuku, Hawaii.



(a) Planform.
(b) Thickness.
(c) Profile.

Figure 2. - External geometry of mod-oa wood composite blade.

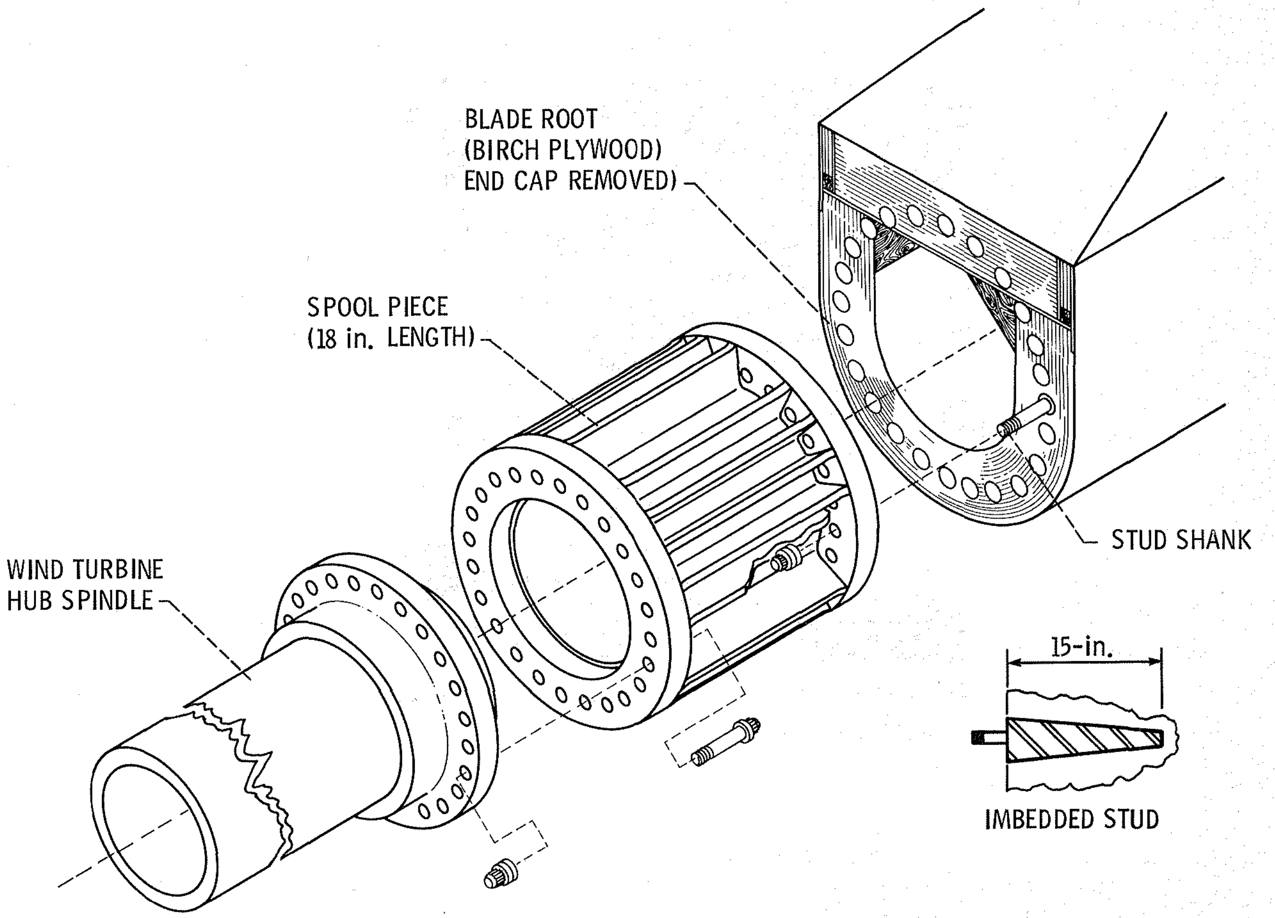


Figure 3. - Schematic of hub attachment for wood composite blade.

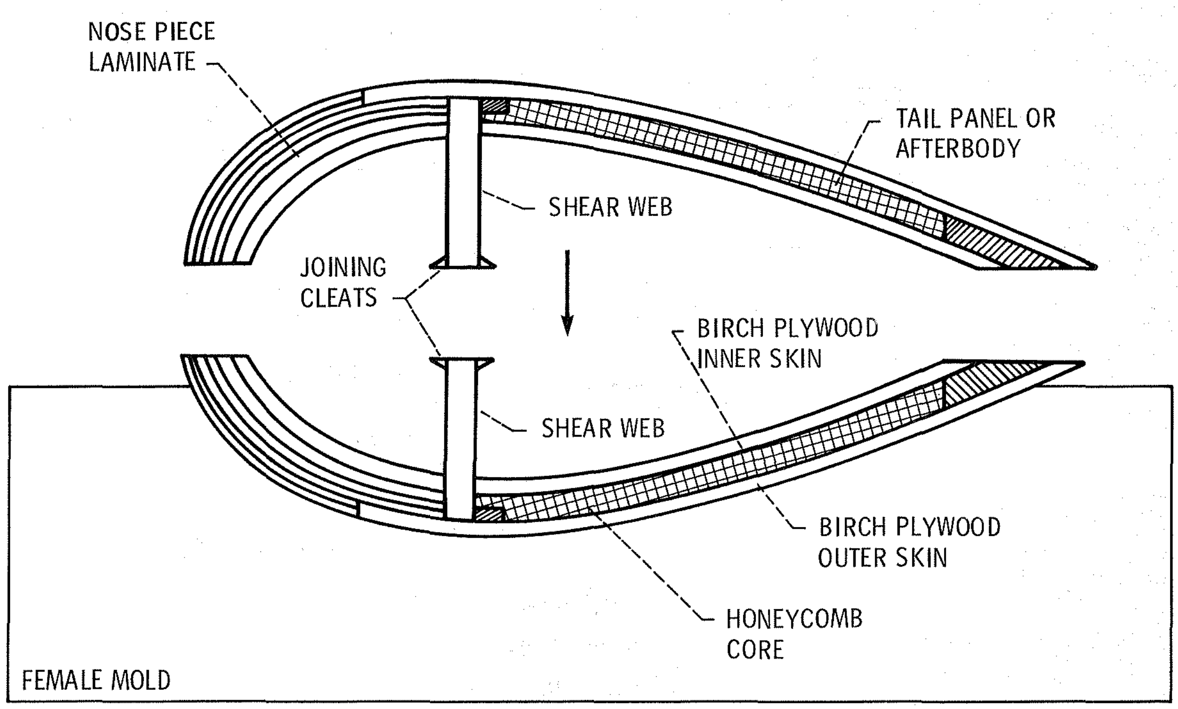


Figure 4. - Schematic of two-part half-shell mold.

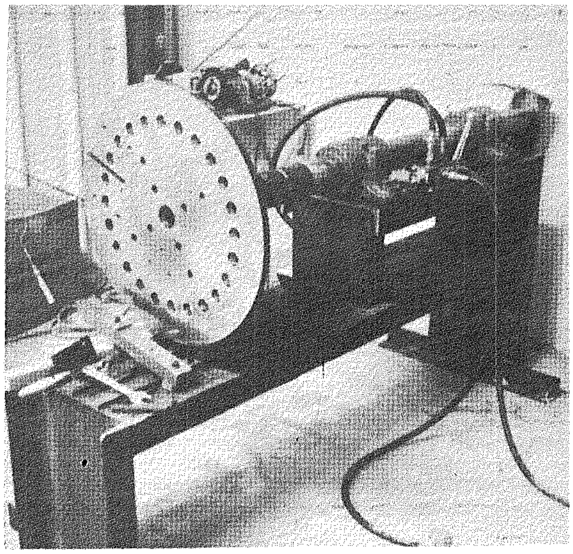


Figure 5. - Drilling and stud placement fixture.

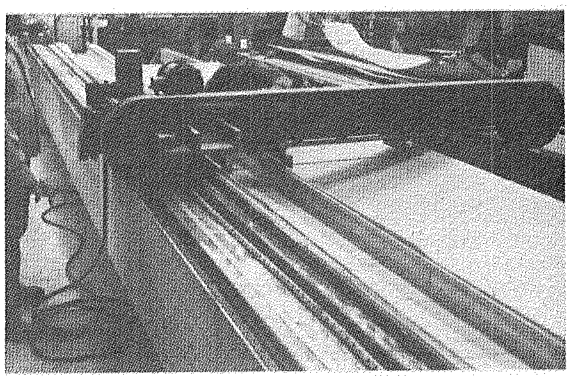


Figure 6. - Band saw trimming of blade half-shell.

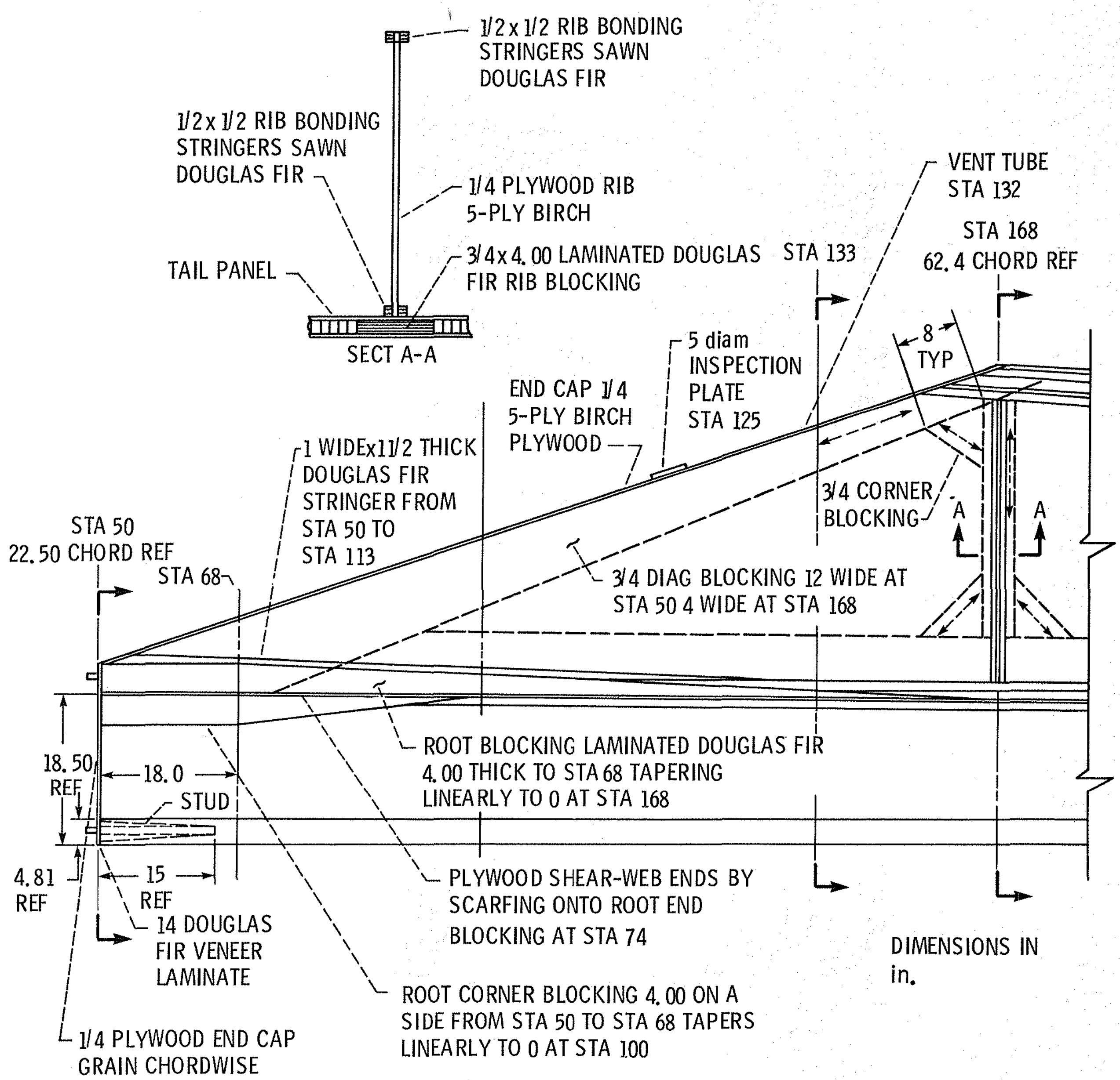
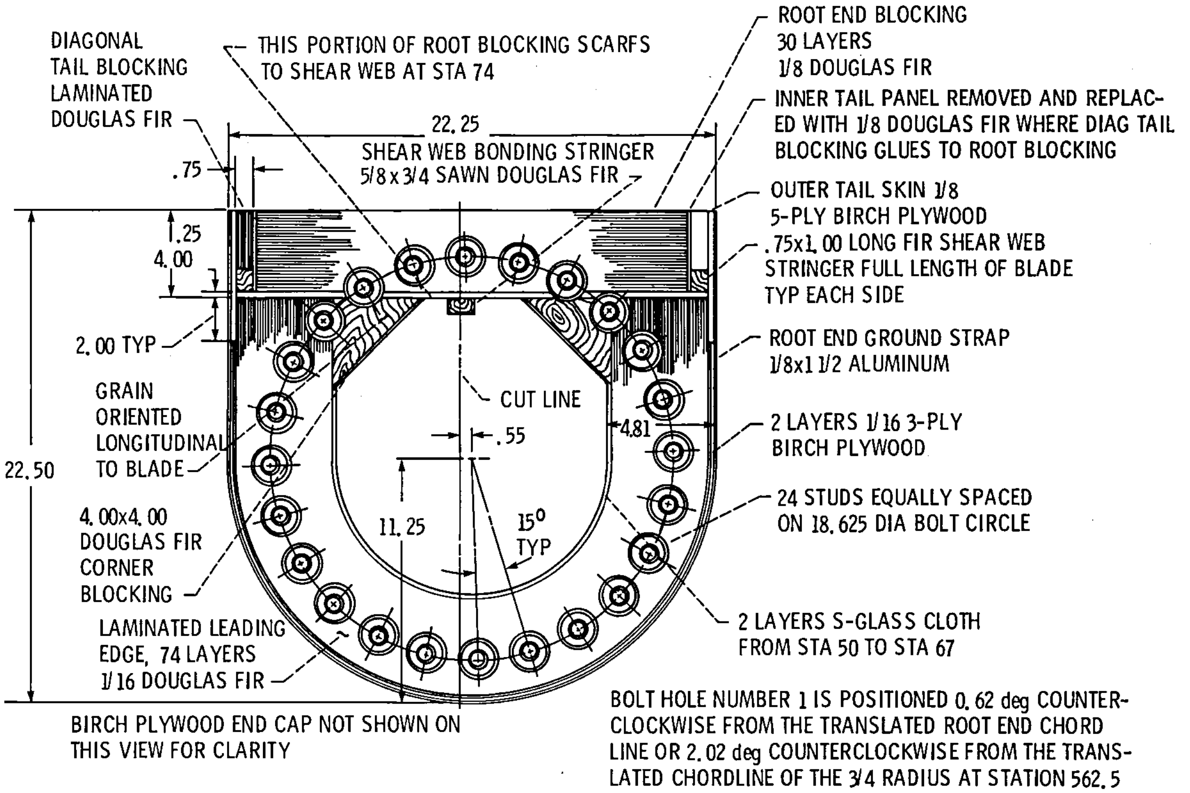
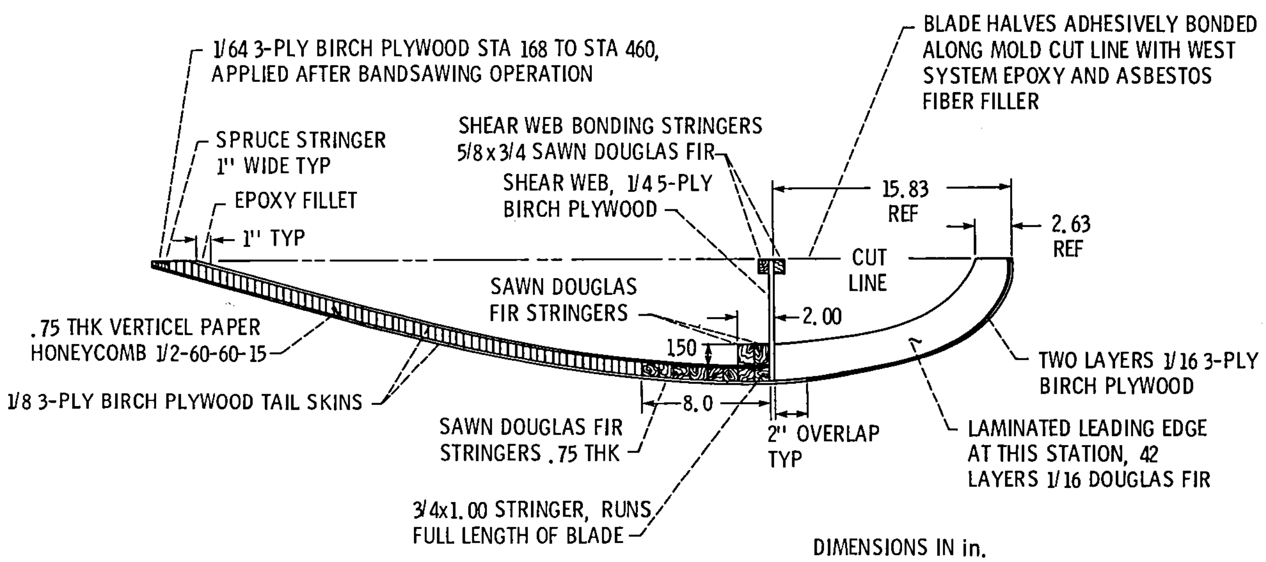


Figure 7. - Details of blade construction, planform view of lower blade half, stations 50 to 168.



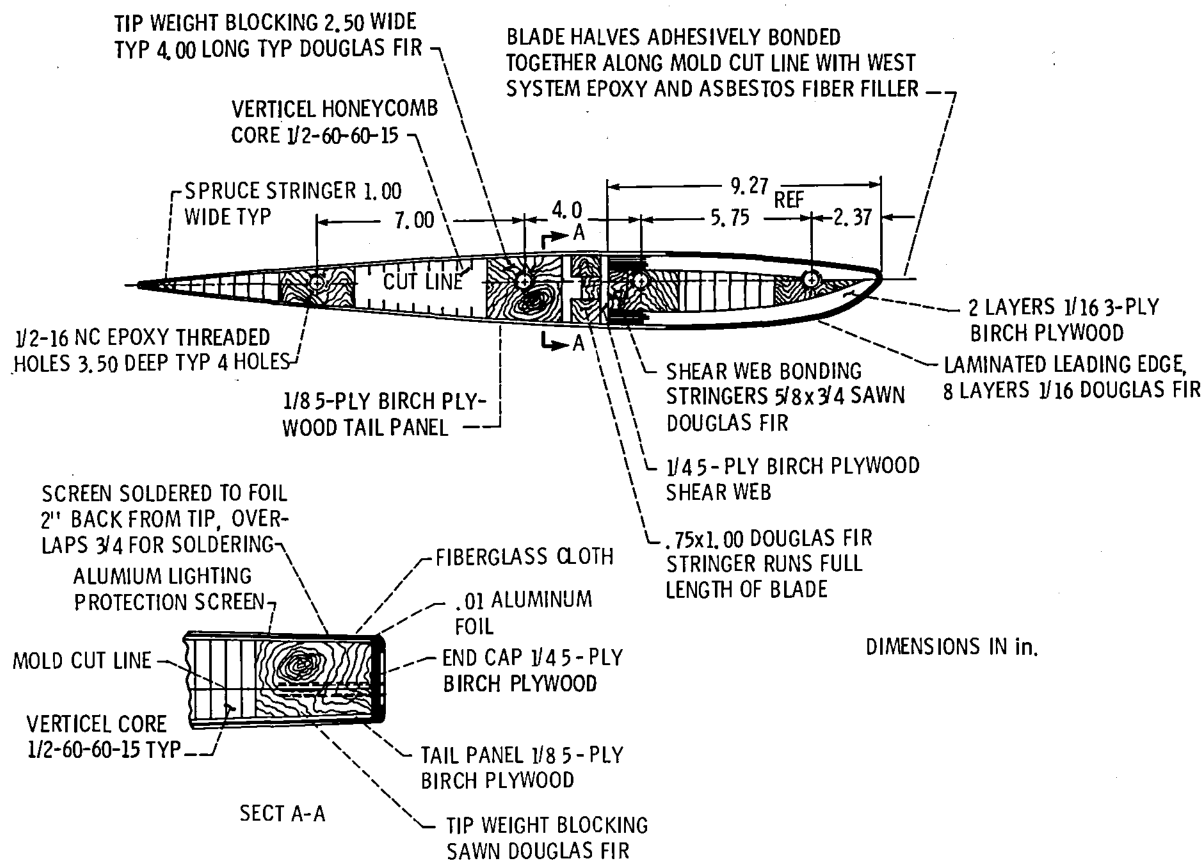
(a) Blade root end, station 50.

Figure 8. - Detailed views of blade cross sections.



(b) Station 312.

Figure 8. - Continued.



(c) STATION 750

Figure 8. - Concluded.

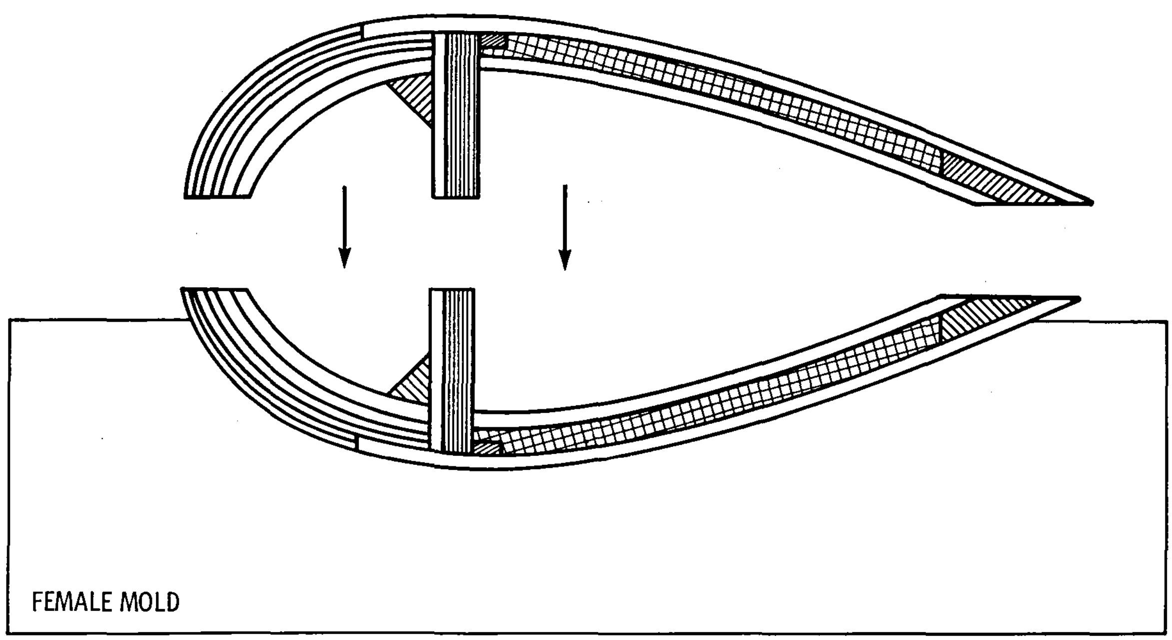


Figure 9. - Bonding of half-shells into complete blade structure.

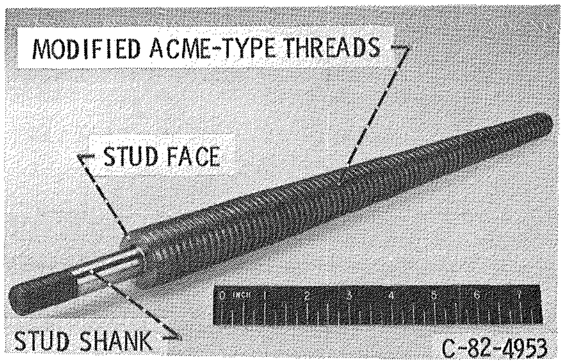


Figure 10. - MOD-OA steel load take-off stud.

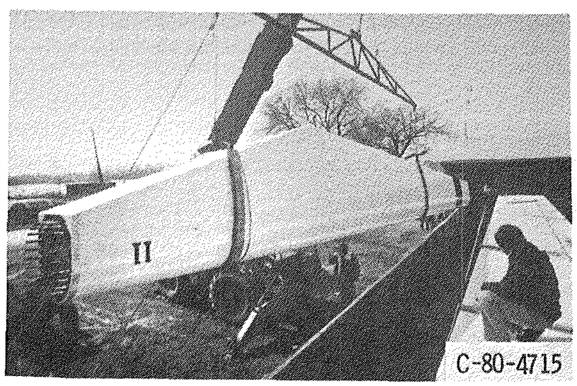


Figure 11. - Preparation for shipment.

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15. Supplementary Notes

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