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THE DEVELOPMENT AND MANUFACTURE OF WOOD COMPOSITE WIND TURBINE ROTORS

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This paper considers the physical properties, operational experience, and construction methods of the wood/epoxy composite MOD OA wind turbine blades. Blades of this type have now accumulated over 10,000 hours of successful operation at the Kahuku, Hawaii and Block Island, Rhode Island test sites. That body of experience is summarized and related to the structural concepts and design drivers which motivated the original design and choice of interior layout. Actual manufacturing experience and associated low first unit costs for these blades, as well as projections for high production rates, are presented. Application of these construction techniques to a wide range of other blade sizes is also considered.

THE WOOD/EPOXY MOD OA WIND TURBINE BLADES

The MOD OA blades fabricated by Gougeon Brothers, Inc. of Bay City, Michigan are the largest blades built to date using laminated wood/epoxy composite as the primary blade structural material. They are also the most thoroughly tested, both in the laboratory and in the field, and will therefore be the primary topic of this paper.

The laboratory testing includes both component level tests of individual root end attachment studs and complete unit testing employing inner blade samples of 20 foot length. These tests supported the early design goals established for the wood/epoxy composite blades, and are reported in detail in another paper in these proceedings [1].

The wood compo[illegible] MOD OA blades have also accumulated over 10,000 hours of operation while synchronized to a utility grid in normal power producing mode (called sync time), with over 6000 hours at the Kahuku Hills, Hawaii site, and another 4000 hours at the Block Island, Rhode Island site. Since the Kahuku machine is by far the leader in total power output, and because its blades have been through a few interesting experiences, the blades of the Kahuku machine will be the primary focus as regards operating experience. For a technical and quantitative review of in-field performance and load data, the reader can consult another paper in these proceedings which covers that topic in depth [2].

MOD OA Blade Design Drivers and Concepts

This section will outline the basic blade design features, and the concepts and design drivers which lead to the selected configuration. The MOD OA design was heavily influenced by the requirement to produce a relatively stiff and lightweight blade with a chordwise center of gravity which was as far forward as practical. This led to a configuration with a rather thick laminated Douglas fir "D" spar which makes up roughly the forward 1/3 of the airfoil. The walls of this "D" spar are about 15% of the local airfoil thickness, and the nose laminate thickness is reduced by step tapering the 1.6 mm (1/16") veneer in order to maintain the desired proportions all the way out the blade. The "D" is completed by a 6.35 mm (1/4") birch plywood shear web. The aft 2/3 of the airfoil is composed of a panel with 19 mm (3/4") paper honeycomb core and 3.2 mm (1/8") birch plywood skins in order to minimize weight in the tail while still providing adequate panel strength and stiffness. See Figure 1 for a typical section layout of this type. For the tip, outboard of radial station 15.24 m (600"), the inner ply has been deleted and a solid honeycomb core used in order to provide maximum strength and shape rigidity for this outer portion of the blade where maximum airloads and energy capture occur. The transition from tail panels to solid core tail is shown in the interior layout drawing, Figure 2.

The tail panels also feature a series of 19 mm (3/4") thick fir stringers which replace the honeycomb core along the panel forward edge. These stringers serve a dual purpose. They are an edge closure and bonding block for the tail panel itself, and also strengthen and stiffen the blade in flatwise bending. To serve this latter purpose and provide the desired margin against the design driving emergency shutdown loads, these stringers reach a total width of 200 mm (8") in the inner blade and then taper away as they proceed toward the tip. There is also a stringer at the aft edge of the tail panel which closes that panel edge and serves as the trailing edge mating and bonding surface after it is trimmed.

Inboard of radial station 3.81 m (150") there is a transition region to the standard 24 bolt 473 mm (18.625") diameter MOD OA bolt circle. This involves a gradual buildup of the shear web from the 6.35 mm (1/4") birch ply used for the outer blade to over 100 mm (4") of laminated fir needed for load take-off at the root. Corner blocks of laminated fir are used to fill the corner where the nose lamination and shear web buildup meet at the root, so that all of the studs in the bolt circle will be properly embedded in fir laminate. The transition region also includes laminated fir diagonal braces built into the tail panels which serve to collect the edgewise loads from the tail panels and direct them to the root buildup. The tail panels are cut away aft of these internal diagonal braces in order to save labor and associated costs, by providing easy installation of the required diagonal rib which then also serves as the transom piece/ tail closure.

Load take-off at the root is accomplished by means of 24 bonded in place steel studs of 15" embedded length and tapered design. The laminate at the root is increased to 124 mm (4.875") of Douglas fir/ epoxy in order to better transfer load into these studs. Originally intended to bolt directly to the hub spindle at station .813 m (32"), the studs now mate a steel spool piece at radial station 1.27 m (50") due to doubts that the original MOD OA spindles were stiff enough to allow the stud attachment method to work properly. To compensate the additional .457 m length due to the spool piece, .457 m was simply trimmed from the tip for the first set of blades. That first set was

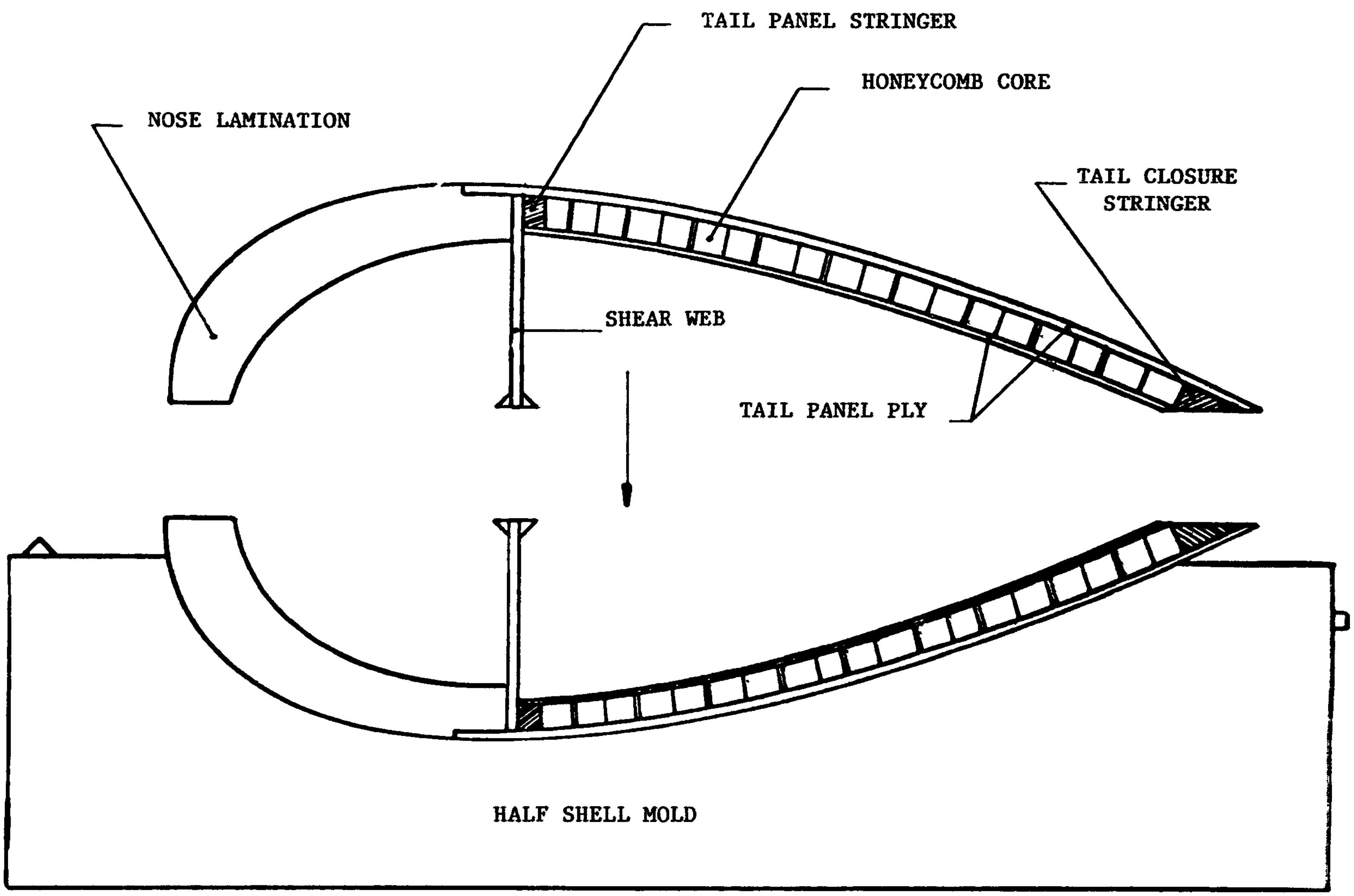

FIGURE 1

ILLUSTRATION OF TYPICAL BLADE CROSS-SECTION

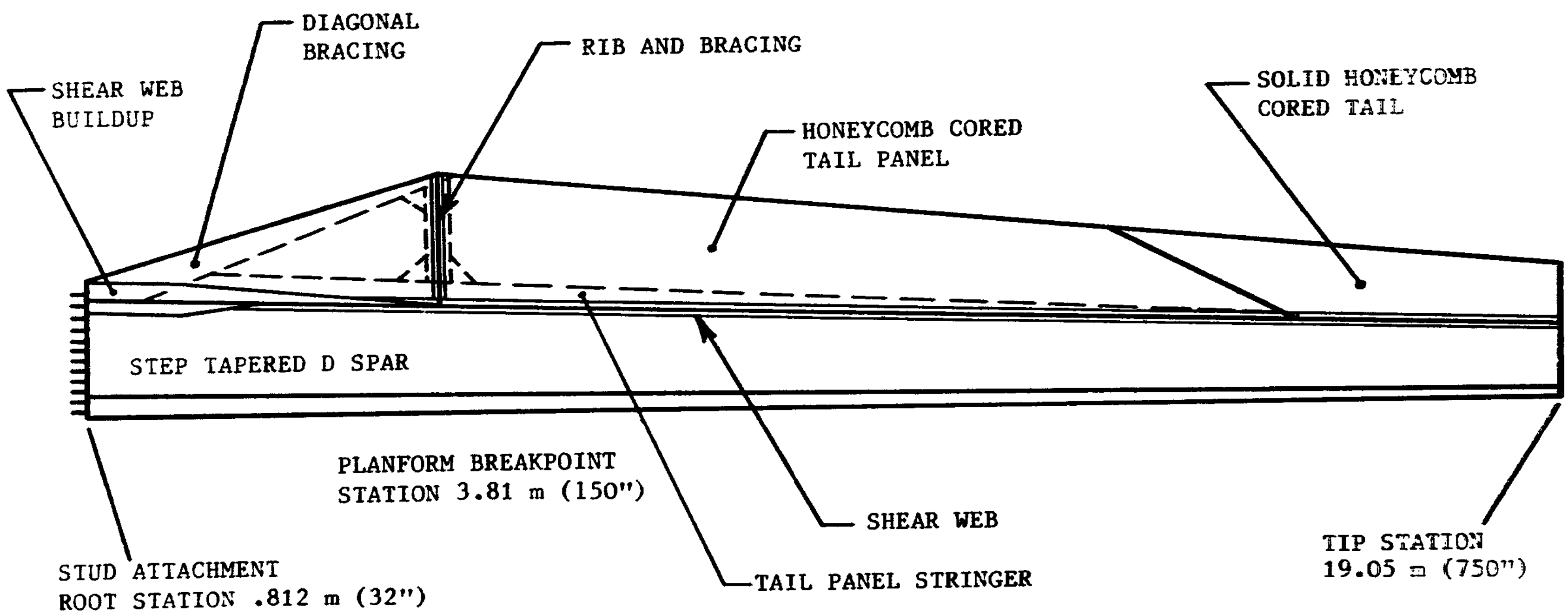

FIGURE 2
INTERIOR LAYOUT DRAWING

christened the Dave Peery blades in honor of a gentleman who provided help, guidance, and encouragement in the early work on wood/epoxy blade design. Later blades were likewise trimmed by .457 m in length, but were also reduced by roughly 3 mm (1/8") in "D" spar thickness to compensate moving the blade outboard. Presumeably a redesigned and suitably stiffened spindle would allow elimination of the heavy steel spool piece and a return to the full blade length and D spar thickness. That would save considerable weight, since the spool piece has a mass of about 180 kg (400 lbs weight), and would also reduce overall costs. Aside from that, however, the overall mechanical and aerodynamic performance of the blades would change very little from what it is today.

External Blade Geometry

The wood/epoxy MOD OA blades employ the same 230xx airfoil section as the original aluminum blades. This choice was governed primarily by the desire to hold section shape constant so that this would not be a variable factor in comparisons between different blade types. As it turned out, the loads and blade deflections experienced during high feather rate emergency shutdown turned out to be the major design driver for the geometry and thickness of the whole blade, except for the root design, which was driven by fatigue. Those loads and deflections could have been materially reduced by the choice of an airfoil section which stalls sooner when at negative attack angles, which in turn would have allowed a lighter blade or smaller t/c ratios, but at the cost of making performance comparisons more uncertain. Since research results are very important to the MOD OA program, the 230xx series airfoils were retained in spite of the resulting structural demands, and the entire geometry choice must be viewed with this in mind.

The blade planform varies linearly from 570 mm (22.5") at the root plane to 1585 mm (62.4") at the trailing edge breakpoint to 610 mm (24") at the tip. The leading edge is a straight line from tip to root except for a small pullback near the root which was introduced to smooth the root transition geometry. The trailing edge is a straight line between the trailing edge breakpoint and the tip, and provides 4.8° of twist over outer blade. The straight trailing edge was partly a manufacturing simplification, but was also found to provide a good match to the chosen planform when viewed from the standpoint of achieving good net energy capture over the whole band from cut-in to design windspeeds, as opposed to maximizing energy capture right at the design windspeed. The blade thickness varies from 566 mm (22.3") at the root, to 498 mm (19.6") at the trailing edge breakpoint (t/c = 31/4%), and linearly to 46 mm (1.80") at the tip (t/c = 7.5%). This rather thin tip was chosen to help promote early stall in the emergency shutdown condition, although some drag reduction benefit in the power producing mode could also be argued to exist. Table 1 provides a more detailed tabulation of blade planform, twist, and thickness values.

TABLE 1

MOD OA BLADE EXTERNAL GEOMETRY DATA

STATION		CHORD LENGTH		MAX THICKNESS		THICKNESS/CHORD	TWIST
m	(ins)	m	(ins)	mm	(ins)	%	degrees
.813	(32)	.571	(22.5)	566	(22.3)	-	0
2.59	(102)	1.207	(47.5)	531	(20.9)	-	0
3.81	(150)	1.585	(62.4)	503	(19.8)	31.7	0
7.62	(300)	1.341	(52.8)	389	(15.3)	29.0	0.6
10.16	(400)	1.179	(46.4)	312	(12.3)	26.5	1.0
12.70	(500)	1.016	(40.0)	236	(9.3)	23.3	1.7
15.24	(600)	.853	(33.6)	160	(6.3)	18.7	2.6
17.78	(700)	.691	(27.2)	84	(3.3)	12.1	3.9
19.05	(750)	.610	(24.0)	46	(1.8)	7.5	4.8

Manufacturing Methods

After considering several alternatives, the Gougeon Brothers organization settled upon the use of vacuum molding with female half shell molds as the most promising technique for economical volume production of laminated wood/epoxy blades. This method insures uniform clamping pressure for both the nose lamination and the tail panels during resin cure, and also conforming the wood components to the desired shape.

In practice, the molds are first coated with release agent followed by epoxy and glass cloth. This glass cloth and epoxy forms a tough, damage and weather resistant outer skin. It also serves to help tie together the nose laminate grain, which runs in the spanwise direction. Next a layer of aluminum screen is added, which serves to provide lightning protection by enclosing the main blade structure within a conductive shell. This screen covers most of the blade surface, except for a region at the tail near the breakpoint. The screen is connected to a grounding bar at the blade root so that the current can be collected and taken to ground. Next into the mold are the plywood and honeycomb which make up the tail panel, the tail panel stringers, and a ply sheath made of two layers of 1.6 mm (1/16") ply which covers and further strengthens the exterior of the "D" [illegible]. Under current procedures, these components are then vacu[illegible]d in place and allowed to cure. The half shear web and [illegible] buildup at the root is added next. The last major molding operation is the placement and bagging of the nose veneers. Each half blade is then trimmed via a special rail mounted horizontal bandsaw, and the fit of the upper and lower halves is carefully checked before they are bonded into a single unit.

The root of the blade is then trimmed to the proper plane and capped with birch plywood. The mating surfaces for the transom piece are also trimmed to size and the transom piece is bonded in place at this time.

Installation of the root attachment studs involves precise drilling of the 24 oversize step tapered stud holes and complete wetting out of the exposed laminate inside the holes. The studs are all attached to a single precisely machined plate so that relative stud positions can be assured to a high degree of accuracy. The holes are then filled with thickened epoxy and the stud assembly is accurately positioned in place and allowed to cure.

Final blade finishing operations include items such as installation of the blade tip cap and tip drain system, cleanup of excess resin along the blade half joint line, and exterior painting and addition of station marks and blade identification.

Production Results and Experience

The first set of MOD OA blades produced had a mass of 1183 kg (2603 lbs) each without the spool piece, with the center of gravity at 5.702 m (224.5") relative to the blade root plane. This was somewhat heavier than expected, and was primarily due to a larger than planned use of resin, particularly for filling the volume occupied by the lightning protection screen. A change in procedures and more restrained use of resin, along with the already mentioned slight reduction in "D" spar wall thickness allowed a reduction of blade mass to 1002 kg (2205 lbs) for last set produced, which includes 4 kg (9 lbs) in one blade and 6 kg (14 lbs) in the other to match weights and centers of gravity. The center of gravity moved inboard by 10 cm (4") to 5.602 m (220.4"), again measured from the blade root plane. The weight of this last set of blades is felt to be about the practical minimum for the present design. Significant further weight reductions would require a change in airfoil section and an adjustment in the interior proportions.

A breakdown of the major blade material weights and costs is presented in Table 2 in order to provide a better perspective on the actual makeup of the blade. The table is for a full length blade with full thickness "D" spar and consequently shows a higher total blade weight than the actual production blades.

The single step lamination of the "D" spar, which involves about 500 kg (1100 lbs) of 1.6 mm (1/16") thick fir veneer (800 m^2 (8700 ft^2)) is the largest single step vacuum lamination of veneer known. In order to accomplish this within the roughly 1 hour time limit required for the epoxy resin system used, a special veneer coating machine is used to quickly apply a precise quantity of resin to both sides of the veneer. In the early feasibility studies for the wood/epoxy blades, it was not known if it would be at all possible to move the required mass and area of veneer within the time required, but this has in fact turned out to be both practical and efficient. The upper limit has not yet been reached.

OPERATIONAL EXPERIENCE

The first set of wood/epoxy MOD OA blades were sent to the Kahuku, Hawaii site. When they were inspected upon arrival, it was found that both trailing edges were split apart for many feet and that one of the transom pieces was also split away along its edge. Since this first set of blades had not been purposely vented, it was quickly suspected that this damage could be due to a pressure buildup problem. The Bay City plant of Gougeon Brothers is about 200 m (600 ft) above sea level, and shipment to Hawaii was via ship at sea level, and that difference could not account for the splitting observed. However, when the overland route of the truck from Bay City to Los Angeles was traced, it was found that a 2100 m (7000 ft) mountain pass had to be negotiated along the way. That would result in an interior pressure of more than 1000 N/m^2 (3 psi), which was well in excess of the capability of the tail closure joint, which had not been designed for pressure vessel service. The failure was inevitable.

Meade Gougeon, chairman of Gougeon Brothers, Inc. immediately flew to Hawaii to personally lead the in-field repair effort. In a matter of a few days, the blades were repaired right at the wind site using normal WEST SYSTEM products and repair techniques. (Total expenditure

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TABLE 2
MATERIAL COST AND WEIGHT BREAKDOWN

Item	# Wt in Blade	Total Amt Needed	Unit Price	Cost Mid 1979 $
Douglas fir veneer 1.6 mm thick (1/16")	514 kg (1131) lbs	808 m^2 (8700 ft^2)	\$1.61/m^2 (15¢/ft^2	1305
24 steel studs	55 (120)	24	\$40 each	960
Epoxy	202 (445)	223 kg (490#)	\$3.00/kg	662
Birch aircraft plywood 3.2 mm thick (1/8")	121 (266)	65 m^2 700 ft^2	\$6.90/m^2 \$64¢/ft^2	448
Birch aircraft plywood 1.6 mm thick (1/16")	28.5 (63)	30.5 m^2 330 ft^2	\$6.00/m^2 (56¢ ft^2)	185
Lightning protection and ice detector	4.5 (10)			125
Miscellaneous Paint, nose strip, etc.	7.3 (16)			100
Douglas fir sawn stock	64.5 (142)	91 bd ft	74¢/bd ft	67
Fiberglass, 10-ounce 60" wide	13.6 (30)	32 m 35 yds	1.64/m (1.50/yd)	53
Birch aircraft plywood 6.4 mm thick (1/4")	24 (53)	6.4 m^2 (69 ft^2)	8.00/m (75¢/ft^2)	52
Verticel honeycomb	12.7 28	33.5 m^2 (360 ft^2)	1.45/m (13.3¢/ft^2)	48
TOTAL	1047 2304	-----	-----	4005

of man hours and materials was approximately 24 hours and $100.) Since the time of that in-field repair, those blades have seen over 6000 hours of sync time with no indication whatever of distress in the area of the repairs. Several interesting observations can be made based on this experience. It has demonstrated that the structural integrity of these laminated blades is such that they are perfectly airtight structures - there are no significant breaks in the structure proper or its many bond lines. Pressure equalization for shipping or for a possible hurricane environment must be explicitly provided if desired. All subsequent blades are now vented at the tip for moisture removal as well as pressure equalization. It has also shown that the wood/epoxy construction system is suited to rapid and relatively simple in-field repair, and that such repairs to date have not had an adverse effect on service life. This is not a surprising result to those familiar with this construction system, as it is known that the resin system is several times stonger than the cross grain strength of the wood which it bonds; however, those unfamiliar with the system may want to consider the implication of this as it relates to the ease of in-field repairs and overall maintenance costs.

Emergency Shutdown

Early in the operation of the Kahuku MOD OA machine, a true overspeed emergency shutdown was encountered. This condition was the design driver for both the flatwise strength and stiffness of the wood/epoxy blade structure. It constitutes the most severe one time load test for which the blade design was qualified. The test result was negative: no visible damage was observed, and the blades still fly.

Periodic Inspections

The blades have been subjected to periodic inspection of a detailed nature by hoisting an inspector right up to the blade for close, hands on inspection. A summary of those inspection observations is given in the wind turbine project report prepared by Hawaiian Electric [3]:

> "The most significant improvement affecting reliability and availability of Makani Huila has been the wood-resin composite blades. The three other machines have required major blade repair or replacement within the first 2000 hours of synchronous operation. Makani Huila has passed that milestone with no sign of blade deterioration.
>
> The composite blades have proven particularly suited to Hawaii's moderate climate. The salt laden ocean breezes have had no apparent negative effect on the blades. The resin protected blades are impervious to water and unattractive to termites. The natural resiliency of the wood has eliminated premature fatigue failure. The resin glue has eliminated the rivet problems that have plagued the aluminum blades of previous machines. The blades are performing admirably.

The first scheduled 1000-hour inspection (actually performed at 640 sync. hours) showed only minor separation near an unloaded section of the blade root. Some paint touch-up was done. The 2000-hour inspection revealed no significant changes in blade condition. If the separations noticed during the first inspection have propagated at all, the change has been too small to warrant corrective action. No special operational precautions have resulted from the inspections. The blades are in excellent condition."

It should be noted that the aluminum MOD OA blades were designed and build using standard accepted aircraft design and fabrication techniques. But they were the trailblazers, and could not draw on previous experience regarding the actual severity of the wind turbine blade fatigue environment. Viewed in that light, their performance was not unreasonable, and a lot of knowledge was gained. It is encouraging that the emerging wood/epoxy technology was able to draw on that experience base and provide a working blade at comparable blade weight (without spool piece).

Power Output

The Hawaiian MOD OA machine at Kahuku Hills was formally dedicated on July 3, 1980. By July 16, 1981, just over 1 year later it had achieved over 6000 hours of sync time, and had delivered more total power to the utility grid than any of the other MOD OA machines, including the Clayton, New Mexico machine, which began operation in late November of 1977. The Kahuku machine has averaged nearly 100 kw over this first year which is a power factor of about .5, even though some down time for inspections and minor repairs is also included. Taken against actual hours on line, the machine has averaged about 150 kw. This is in large measure a direct result of the excellent wind regime at Kahuku Hills, and is also a tribute to the energy and dedication of the wind power team of Hawaiian Electric. However, the consistent and troublefree performance of the wood/epoxy blades has also been an important element in that success. For a more detailed report of the operating experience of the MOD OA machines from the standpoint of quantity and quality of power delivered, the reader is directed to another of the papers in this proceedings [4].

Long Term Durability - Fatigue

The MOD OA machines are oriented with the blades downwind of the tower. This causes each blade to experience a significant region of sharply depleted wind velocity once each revolution. The result of this can be seen in many ways. Most obvious is an audible low level thump as each blade passes behind the tower. This is due to the rapid unloading and restoration of the dynamic pressure distribution around the blade. This presents a significant fatigue environment to the blade structure, particularly near the tip where dynamic pressures are highest. In particular the honeycomb cored tail would be the part of the structure most susceptible to this pulsating pressure distribution. However, the design calculations showed large margin against this fatigue mechanism, and so far experience has not shown any problem in that area.

The wind shadow effect also causes a transient vibration of the entire blade. The flatwise vibration damps out quickly due to aerodynamic damping but its effect is visible in the traces of flatwise root loads [2] and also is visible to the eye if carefully observed. The edgewise vibration is not visible to the eye. However, it is visible on the data traces [2], both as a 5 per rev, edgewise load variation at the root and as a fluctuation in generator power output.

The overall set of loads seen at the blade root constitute a real design challenge at the root stud load takeoff of the MOD OA blades for long term fatigue. It was in recognition of this fact that NASA performed extensive fatigue testing of both individual studs and entire inner blade sections. The performance of these specimens indicates that the blade root should be able to sustain the long term fatigue loading environment, but the design margin there is certainly not as large as it is elsewhere in the blade. It should be pointed out that significant advances in stud performance were made during early design and testing work, and that further advances in performance almost certainly still remain. Even at the present level of development, this wood to steel load takeoff method has been demonstrated to be reasonably efficient both for one time loads and for long term fatigue loads.

The primary wood/epoxy blade structure has large margin against fatigue both from the airloads which load the structure flatwise and the gravity moment which loads it edgewise. The fatigue margins are typically in excess of 100% throughout all of the major structural elements. For bonds and joints which act in crossgrain loading, margins on the order of 300% to 500% were typically provided largely because the low density of wood allowed generous bonding area and made such margins easy and practical to attain. If these margins in fatigue seem large, one must remember that it was the one time loads of overspeed emergency shutdown which drove much of the design of the current MOD OA blades, and that wood is a material with very good fatigue properties relative to its weight. One should consider that nature has spent millions of years in the serious business of competitive survival in order to develop good strong trees, which must stand repeated and highly variable loads from winds and other load sources, and it is therefore not too surprising to find that wood is an efficient structural material with very respectable fatigue properties. The current design acknowledges and benefits from those properties.

Environmental

Nature determined long ago that its structures must be biodegradable and recycleable. It could not afford to have its forests cluttered up with indestructable fallen trees. Man is also beginning to realize the necessity of this approach. The ability of wood to decay is a positive necessity in the overall scheme of things, but has been an inconvenience and limitation in mankind's structural use of wood. It is important to point out that this decay is not a simple function of the passage of time. Healthy trees can stand for centuries with no apparent loss of properties. Samples of wood entombed in the pyramids for thousands of years have been found to be as sound structurally as recently cut wood. Time alone has very little effect.

The decay process of wood requires an elevated moisture content and a supply of oxygen. There is no "dry" rot. The fiberglass/epoxy outer blade sheath provides not only a tough physical skin, but also an effective barrier to the passage of moisture and oxygen. All of the bond lines and lamination glue lines provide additional and redundant barriers. The net effect is to provide the wood with a moisture stable environment without free oxygen. Both of the requirements for decay are absent - the wood is more effectively isolated than either living trees (elevated moisture) or pyramid entombed (some free oxygen) wood. It can be pointed out that lightweight wood/epoxy boats protected with this technique have now survived over 12 years in the relatively severe marine environment with no evidence of degeneration. Thus there is no a priori reason to expect that suitable longevity would not be possible in the wind turbine environment. Only time and experience will finally give proof, but the prospects are good in view of our present knowledge.

THE FUTURE FOR WOOD/EPOXY WIND TURBINE BLADES

To date the wood/epoxy construction technique has been applied to the construction of blades as large as the 19 m (62.5 ft) MOD OA, and as small as 6.7 m (22 ft). By the time this is printed and distributed, blades of 3 m (10 ft) length will be in production. In the NASA/DOE sponsored MOD 5A effort, a wood/epoxy rotor was selected at the conceptual design level. That rotor would be 122 m (400 ft) in diameter, which is a single blade length of 61 m (200 ft). It therefore appears at this time that the wood/epoxy construction technique is a viable choice over the whole size range of power generating wind turbines. The primary advantages of the material which appear to suit it particularly well to the wind turbine blade application are several;

1) low basic material cost
2) relatively low resin use as a percent of overall weight
3) high per unit weight strength and stiffness
4) exceptionally high per unit weight fatigue capability
5) thick shells for simple, buckling resistant design
6) resin stronger than base material gives easy bonding and repair
7) high corrosion and weather resistance
8) smooth accurate airfoils
9) totally bonded monolithic structure

Overall, it appears that the basic technical capability of the laminated wood/epoxy material in the wind turbine blade application is reasonably well established, even though there are a number of areas where further development and better experimental characterization would allow more efficient design.

The economics of blade production are also becoming reasonably well defined. It took about ten men and two months to build the molds and first pair of MOD OA blades. This does not include building the plug from which the molds were taken, and some long hours were admittedly involved, but this still gives a feel for the time and effort involved in pursuing this method of construction. Also bear in mind that this was a first time production run, with lots of first time bugs and problems to be worked out. Given all of the above, this overall performance seems a good argument that the basic technology must be reasonably efficient in terms of time and manpower. Using the present tooling as is (no tooling/setup costs), and including no costs associated with subsequent shipping and the like, a MOD OA blade can now be produced for about $40,000. By setting up for a production run of 100 blades per year or more, and making a few blade design changes to improve costs and producibility, it is felt that the blade costs could be cut roughly in half. There are many avenues left to explore in the realm of cost effective production, but the initial results are encouraging. Aggressive work is in progress to improve the basic knowledge and techniques associated with the laminated wood/epoxy material, and it appears that this material now warrants serious consideration at all size levels of the modern electric power generating wind turbine.

Acknowledgements

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