THE USE OF WOOD FOR WIND TURBINE BLADE CONSTRUCTION

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Historical Problems With Wood and a Modern Solution

With the development of modern engineering materials, such as steel, aluminum and fiber reinforced plastic composites, the use of wood as a serious engineering material for sophisticated structures has greatly diminished. The reasons for this are generally well known; wood can deteriorate from rot, and be dimensionally unstable. Then the fact that the consistency of wood can vary within a single tree together with fluctuation in physical properties because of moisture level change provides for difficult quality control problems.

We feel that the demise of wood as a serious engineering material is both unfortunate and premature. With the help of modern technology, most of the problems with wood can be solved in a practical manner. For the past 10 years, we have used wood in composite with plastic resins to build high-performance sailing craft; specifically, iceboats and multihull craft that must be built at high strength-to-weight ratios to be successful. In part, our success has been due to the fact that wood itself is an excellent engineering material, and in some applications has capabilities that are unavailable with any other material (which we will explain later on in this paper). Our ability to solve the moisture problem with wood, however, was the key to the development of wood as a practical engineering material even for use in a hostile marine environment.

To better understand what we have done to achieve our solution, a discussion of the interrelationships between moisture and wood is needed.

Moisture is a major ingredient of all wood in the living tree. Even wood that is properly dried or cured will have a significant percentage of its content by weight being moisture. This will typically range from 8% to 15% of the oven dry weight of the wood, depending upon the atmospheric conditions in which the wood exists. Figure 1 shows the ultimate moisture content of wood when subjected to various relative humidities at a temperature of 70°F. Unfortunately, the subject is a little more complicated than the chart portrays because 50% relative humidity is much different at 40°F. than at 70°F. (warm air holds more moisture than cold air), but every area will have an average year around moisture and temperature level that will determine the average wood moisture content level. In our Great Lakes area, wood seems to equalize at about a 10% to 12% moisture content when dried in a sheltered but unheated area. The real problem with wood, is that its moisture level is rather quickly influenced by short term changes in atmospheric conditions. In the Great Lakes area, we continually have extremes of dry and humid climate conditions that are compounded by temperature extremes of 100°F. between winter and summer.

Wood cells are quite resistant to the invasion of moisture in a liquid form, but moisture vapor as a gas has a sudden and dramatic effect on wood by being able to easily and quickly pass through the cell wall structure. Responding to the changes in atmospheric conditions, unprotected wood may undergo many moisture changes in a short period of time, and the repeated dimensional expansion and contraction of the wood under these conditions is thought to be the leading cause of wood to age prematurely.[1] Conversely, wood in its natural state as a living organism will remain at a relatively constant moisture level during its entire lifetime until it is harvested.

This sponge-like capacity to take on and give off moisture at the whim of the surrounding environment in which it exists, is the root cause of all of the problems with wood. Specifically, varying moisture levels in wood are responsible for: (1) dimensional instability; (2) internal stressing that can lead to checking and cracking of the wood; (3) potential loss of strength and stiffness of the wood, (4) wood decay due to dry rot activity.

Dimensional instability has always been a limiting factor for the use of wood in many engineering applications where reasonable tolerances must be maintained. To complicate matters, the dimensional instability of wood has never been constant and varies widely between species of wood, with radial grain wood (cut perpendicular to grain) in most species being more stable than is tangential wood (cut parallel to grain). The dimensional change of wood due to moisture change always occurs first on the outer surface causing differing moisture levels to occur within the same piece of wood. This can lead to internal stressing that often is the cause of checking and cracking on the wood surface.

Moisture has a significant effect on the strength of wood. Dry wood is much stronger and stiffer than is wet wood. The reason for this is the actual strengthening and stiffening of the wood cell walls as they dry out. If wood is taken at its fiber saturation point of 20% and allowed to dry to 5% moisture, its end crushing strength and bending strength may easily be doubled and in some woods tripled. The result, is that wood has the potential to be an excellent engineering material when dry, but only a mediocre material when wet. This causes a vexing problem for the engineer who may not be able to determine the level of moisture content that can be maintained in the structure he is designing, and must assume a worst case situation.

Of all of the problems with wood, dry rot decay is the most known and feared. Dry rot is a misleading term since dry wood does not rot, there

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[1] Wood has been taken out of the tombs of Egypt that has been over 3,000 years old. Because of the constant temperature and humidity in which it was stored, the wood has lost none of its original physical properties.

in fact must be rather exact conditions in order for dry rot spore activity to occur: (1) The moisture content of wood must be at or near the fiber saturation point of 20%. (Rot is unknown in wood with a moisture content less than 20%.), (2) There must be an adequate supply of oxygen available to the rot spore fungi, i.e. the wood must not get too wet, (3) The temperature must be warm, 76° to 86°F. is ideal, although fungi have been known to be active at temperatures as low as 50°F. (4) There must be the proper kind of food. Some woods such as western red cedar are resistant to rot because of the tannic acid in their cellular makeup.

Although there are many types of rot fungi that can destroy wood, in North America there are two species of the brown rot family that predominate. They are very hardy creatures that seem to survive the worst large temperature extremes in a dormant state waiting only for the right conditions to occur to become active. Efforts to control the brown rot family have had only limited success and generally center around poisoning the food supply with various commercial wood preservatives. Our approach to solve this problem is quite different as will be explained.

The Wood Resin Composite

As we have discussed, most of the problems that we have with wood are moisture related. Therefore, a primary goal of incorporating wood into a composite with a resin is to provide maximum protection against moisture to the wood fiber. Our basic approach is to seal all wood surfaces with our proprietary resin system. This same resin system is used as the bonding adhesive to make all joints and laminates with the goal that they too will be secured from moisture. The lamination itself, can usually be counted upon to offer further moisture protection. To build our structures, we usually laminate thin veneers together and the glue line between each veneer serves as a significant moisture barrier. For instance, when using 1/16 inch thick veneers in a 1 inch thick laminate would provide 15 glue lines that must each be penetrated to increase or decrease the moisture content of the entire laminate.

The success of the wood resin composite method depends on the ability of the resin to resist moisture passage. Our resin system is the most effective moisture barrier that we know of and has proven itself through actual useage over many years in marine construction. We cannot claim that our resin system forms a perfect moisture barrier, but it does slow the passage of moisture into the wood to such a great extent that any moisture change within the wood itself is minimal. If dry wood encapsulated in our resin were put in a steam bath and left there for several months, the moisture in the wood would eventually rise. However, the rate of moisture change in a wood-resin composite is so slow under normal changing atmospheric conditions that the wood inside remains at a virtually constant moisture level that is in exact equilibrium with the average annual humidity and is able to easily resist violent seasonal moisture fluctuations. With the moisture content of the wood stabilized at lower levels, we are able to maintain good physical properties together with excellent dimensional stability. Dry rot is eliminated as a problem by keeping the moisture content below that required for dry rot activity and also by completely sealing the wood from an oxygen source that is a necessary ingredient for the rot spores to survive. Our testing has shown that even if wood should reach a moisture level high enough to support rot spore activity, the rot spores still cannot exist without adequate oxygen.

Structural and Economic Considerations

We, of course, did not invent the principle of laminating wood; this process had been commonly used for a number of years. There are, however, some significant differences with our method. First, a wood-resin composite laminate as we would build it is composed of a very high resin content by weight, considerably higher than what is considered normal in the general wood laminating industry. This high percentage of resin-to-wood ratio is desireable for several reasons. Enough high-density plastic is available in the composite to provide sufficient moisture protection to all of the wood fiber. Our resin also has excellent physical properties with the potential to improve the composite structurally. Wood is considerably stronger in tension than it is in compression. The resin that we have developed is just the opposite, being much stronger in compression than it is in tension. By properly mating the two materials, one compliments the weakness of the other with the potential for more strength than either would be capable of on its own.

Wood laminating is usually accomplished at pressures of 75 to 100 psi to make effective bonds. Achieving these high pressures, can be very expensive especially in overhead and capital expense for tooling. High pressures also severely limit the size of the laminated part that can be made. With our resin, we are able to make perfect bonds at low pressures. In many cases, only contact pressure is needed between wood pieces because our resin has sufficient physical properties to easily span small gaps if they should occur. Lowering the pressure needed for laminating has the positive effect of lowering the cost of wood bonding. Pressures of up to 12 psi are easily and cheaply developed with the use of the vacuum bag system and are sufficient to manufacture all of the laminated parts for the 60' wood composite wind turbine blade. Thus, the cost of molds and mixtures are quite inexpensive allowing both low or high unit production to occur at low per unit costs.

Quality Control

Using a high-strength adhesive for bonding reduces significantly quality control problems from those normally associated with the wood laminating industry. The physical properties of our resin are considerably higher than the grain strength or the shear properties of the wood. This excess structural capacity of the resin adhesive provides a wide safety margin that has proved extremely important to our success in the manufacture of lightweight boats. We have been able to produce on a regular basis, highly reliable bonded joints between wood members with only contact pressure. Even significant voids that might develop between wood laminates do not present a problem provided that there is sufficient resin adhesive to span the void.

Using a single piece of wood in a critical application has always posed a difficult quality control problem. An experienced individual had to carefully inspect each piece used for hidden flaws that might compromise strength. The multipiece lamination solved this problem by using the "safety in numbers" principle. In our turbine blade application, there will be up to 40 laminations of 1/16 inch thick veneer to form the main load-bearing "D" section. Even if several of these laminations were flawed and slipped by inspection, it would have little effect on structural capability of the entire lamination.

Wood as an Engineering Material

In considering wood as an engineering material, it is pertinent to note that "wood" is not a single material with one fixed set of mechanical properties, but rather includes many species which possess a wide range of properties, which depend upon both the species and the density selected. The range of properties is considerably wider than what is generally available with most other types of materials, where some variation of properties can be attained by means such as alloying or tempering, but where little variation of material density is possible. Wood, on the other hand, can be selected over somewhat more than a full order of magnitude in density, from 6 lbs/cuft or even less for selected grades of balsa, to over 60 lbs/cuft for certain species of hardwood. The flexibility this can provide the wood structure designer is obvious; since low-density species can be selected for efficient use as core materials, or for panels or beams where stiffness or buckling resistance is of primary importance. High-density species can be selected where there is a need for high strength and modulus per unit volume, such as in panel skins or in structural members which must occupy constrained geometric volumes. The full range of intermediate densities provide a match for requirements anywhere between these extremes. In this regard, it is worth noting that the physical properties of wood are roughly proportional to its density, regardless of species, since the basic organic material is the same in all species, and thus changing density is rather like compressing or expanding the net strength and elastic stiffness into different cross-sectional areas, with little net variation of total properties per unit mass (table I).

Given that the strength and modulus of wood vary approximately in proportion to its density, it is easily shown that the length of a solid wooden panel which is stable against buckling will vary inversely with its density, while the length of a solid wooden column stable against buckling will vary inversely with the square root of its density. Therefore, approximately a factor of ten in unsupported panel length, or a factor of three in unsupported column length, is readily available to the designer of wooden structures. Designers of structures using other materials can perhaps best appreciate what this means by imagining that a factor of 10 of density variation were somehow readily available for the steel, or aluminum, or composite, with which they regularly work.

Granted that the density variation of wood can be of advantage to the wooden structure designer, one must also inquire how good are its net properties per unit mass relative to other structural materials. There are, after all, other light variable density materials available, such as the expanded foams. For modern structures where weight is an important issue, the strength-to-density ratio (specific strength) and modulus-to-density ratio (specific modulus) are two very important numbers to consider, since they determine how much strength and stiffness you can get for a given mass of material.

A typical grade of Douglas fir, a moderate density species, will possess approximately the following properties:

	Fir
Density	.52 (32.5 lbs/cuft)
Compressive Strength	7500 psi
Tensile Strength	15,000 psi
Modulus	2 x 10^6 psi

To easily compare this to other materials, the table below indicates the strength and modulus required of the other materials to achieve exactly the same strength-to-weight, and modulus-to-weight, possessed by Douglas fir.

Equivalents of Fir

	Steel	Aluminum	Fiberglass Composite
Density	7.8(487 lbs/cuft)	2.7(169 lbs/cuft)	1.9 (119 lbs/cuft)
Compressive	112,500 psi	38,942 psi	27,403 psi
Tensile	225,000 psi	77,885 psi	54,807 psi
Modulus	30 x 10^6 psi	10.38 x 10^6 psi	7.3 x 10^6 psi

Those familiar with the typical properties of steel, aluminum, or figerglass composite, will recognize that these numbers indicate Douglas fir to be a competitive structural material on a per unit weight basis. It might also be noted that the number cited for the fir do not represent unusually good samples or unusually dry samples, and typical shop laminates we have produced, in fact, exceed the strength and modulus numbers cited.

It should be pointed out at this time that the preceding considered the properties of wood along its grain direction. The same piece of fir which displays 15,000 psi tensile strength along its grain direction will have something like 300 psi maximum tensile strength across its grain. That is a 50 to 1 variation in tensile strength depending on the load direction. The other physical properties of wood are also distinctly anisotropic, although not to as great a degree. What this means is that the wooden structure designer may have to take explicit measures to deal with cross-grain or shearing forces within the wooden structure which could safely be regarded as negligible by the designer who uses a conventional material with isotropic properties, such as steel or aluminum. It also means that in cases where large loads flow in more than one direction, that wood fiber will have to be arranged to align with all of these loads. For cases where the large loads are confined to a single plane, a structure such as laminated veneer or plywood can meet the requirements. Where loads in all three axis exist, the designer must use more sophisticated approaches tailored to the loads and geometry. All these factors are the other side of the wooden structures coin, and dealing with them is the price which the wooden structure designer pays in order to gain the advantages of this easily fabricated, high-performance, low-density structural material.

A final factor which must be considered when evaluating wood as a structural material concerns its performance in fatigue. By its very nature as a fibrous material, wood is not given to the kind of fatigue crack propagation that is familiar with metals. The literature of the fatigue properties of wood is not as well developed as that of other materials, but in round numbers, one can expect essentially infinite fatigue life for wood with loads at 30% of ultimate. For some kinds of loading, even higher percentages are acceptable. When one considers that nature has spent millions of years in the serious business of competitive survival to develop good strong trees, which must stand repeated and highly variable loads from winds and other load sources, it should not be too surprising to find that wood is an efficient structural material with very respectable fatigue properties. In fact, one should note that a tree is basically a cantilever type structure subjected primarily to variable wind loads, and that it grows in such a way that the major forces do flow along the grain direction within the tree. Since it happens that modern wind turbine blades are also cantilever type structures subjected to variable wind loads, it is not surprising that wood should be considered potentially advantageous for such an application.

Wood Wind Turbine Blade Feasibility

In order to investigate the feasibility of a wooden wind turbine blade, NASA/DOE awarded a small contract to the Gougeon Brothers, Inc., in November of 1977. Several construction concepts were considered and evaluated. A monocoque "D" section forming the leading edge, and a built-up trailing edge section was the selected method of construction. The required thickness to achieve the necessary structural properties in the "D" was examined for both a laminated veneer and bonded sawn stock fabrication technique. Both of these techniques were ultimately judged to be feasible, with the comparative fabrication advantages determined by blade size and special epoxy and wood stock handling techniques, rather than by the resultant physical properties of the finished nose.

In attempting to achieve a practical tail construction with a center of gravity for the blade at the quarter chord point, a number of tail panel construction techniques were considered. These included: (1) simple ply supported by stringers; (2) fiberglass/foam/fiberglass; (3) plywood/honeycomb/plywood; (4) plywood/honeycomb/plywood with aft web and slotting to relieve tail buckling. The final results of detailed strength and stiffness calculations for the last tail panel configuration showed that it was indeed feasible to use wood to meet the Mod OA blade structural requirements. This work is presented in detail in the final report for NASA contract No. DEN3-9. A summary of the basic blade parameters is given in figures 2 through 7.

The projected blade weight and center of gravity location which resulted from this feasibility study were quite encouraging, indicating that a blade under 2,000 lbs, with a center of gravity location reasonably near 25% chord, could be produced using wooden construction techniques.

As part of the wooden blade design, a somewhat unusual but very simple method was proposed to attach the root end of the blade to the hub. The proposal was simply to epoxy bond 24 steel studs into the 3-inch thick wood buildup which exists at the root end (see Figure 8). While the potential economic advantage of such a simple construction was clear, its engineering viability was perhaps not so clear, (even though similar techniques had been successful in a wide range of sailing craft already built and tested), and therefore test samples of these wood to steel stud bonded joints were fabricated by Gougeon Brothers and tested by NASA-Lewis. The results of these tests are available in our final report under contract No. DEN3-9 and show the engineering viability of the direct bonding technique both for withstanding maximum onetime loads, and also for withstanding repeated cyclic fatigue loads. A onetime load in excess of 40 tons was achieved for one of the samples using a 15-inch long, 1-inch diameter stud, to give you a feel for the load transfer which is possible. In the fatigue testing, the 1-inch diameter steel stud often failed before the wood or epoxy bond. This stud bonding is considered to be a very good example of the simplifications which are possible using advanced wood/epoxy construction techniques.

As a final test of wood/epoxy construction for MOD OA wind turbine blades, a 20-foot root end sample was built to the dimensions indicated in the feasibility study, complete with 24 bonded-in studs. This sample has been successfully subjected to large onetime loads in both the flatwise and edgewise directions in tests performed at NASA Lewis. It has also been subjected to fatigue testing at the Fort Eustis Applied Technology Laboratory USARTL (AVARCOM) test facility in Virginia.

Photographs of various phases of the construction of the test blade sample are shown in figure 9.

The results to date indicate that wood is both a viable and advantageous material for use in wind turbine blades. Its low density simplifies the provision of adequate buckling strength for the walls of the blade structure. Both its natural fibrous composition and its ability to be readily bonded into a virtually monolithic structure contribute to the prospect of excellent fatigue life. The quite good physical properties on a per unit weight basis allow a reasonably light blade which is still strong and stiff enough to meet operational requirements. In addition, the basic material is reasonably priced, domestically available, ecologically sound and, most important, easily fabricated.

The Cost of Wood

Douglas fir is the chosen material to manufacture the "D" section which makes up approximately 70% of the blade weight. This species of wood was initially considered due to its excellent physical properties, but became the favored material because of availability and low price. With modern reforesting programs, the Douglas fir species is being replanted at a rate that exceeds the annual harvest. Thus, this species is a renewable resource that is indigenous to our country with a significant percentage of the supply growing on federal lands. Over the past 5 year period, the price increases on top quality (clear) Douglas fir have been considerably less than the inflationary rate. This in part is due to the fact that very low levels of energy are needed to turn the wood log into usable stock (veneer or dimensional boards). In comparison, many materials requiring high levels of energy to produce have increased at a much higher rate by percentage (table II).

At present, we are able to purchase select, clear, vertical grain 1/16 inch thick Douglas fir veneers for about 80¢ per pound ready to use (trimmed) in the mold, which is competitive with most of the other materials being considered for turbine blades. It is thought that the price of wood will look even more favorable in the near future as energy costs continue to increase.

Fabrication is, of course, the major cost factor when building wind turbine blades of any material. We feel that our costs to fabricate wood blades on a production basis can be very low. We have not yet worked out all of the details, but within the next two months we will be finalizing a manufacturing plan which will be discussed in a final report under our present NASA/DOE contract No. DEN3-101.

TABLE I. - RELATIVE EFFICIENCY OF VARIOUS MATERIALS IN DIFFERENT ROLES

Material	Young's modulus, E, MN/m^2	Specific gravity, ρ, g/cc	Simple tension & compr.	Column buckling	Panel buckling
Steel	210,000	7.8	25,000	190	7.5
Titanium	120,000	4.5	25,000	240	11.0
Aluminum	73,000	2.8	25,000	310	15.0
Magnesium	42,000	1.7	24,000	380	20.5
Glass	73,000	2.4	25,000	360	17.5
Brick	21,000	3.0	7,000	150	9.0
Concrete	15,000	2.5	6,000	160	10.0
Carbon-fibre composite	200,000	2.0	100,000	700	29.0
Wood (spruce)	14,000	.5	25,000	750	48.0

Taken from the book "Structures" by J. E. Gordon.

TABLE II. - ENERGY CONSIDERATIONS FOR WOOD AND OTHER MATERIALS

[Taken from the book "Structures" by J. E. Gordon.]

(a) Approximate energies required for production

Material	Energy to manufacture, Joulesx10^9 per ton	Oil equivalent, tons
Steel(mild)	60	1.5
Titanium	800	20
Aluminium	250	6
Glass	24	0.6
Brick	6	0.15
Concrete	4.0	0.1
Carbon-fibre composite	4,000	100
Wood(spruce)	1.0	0.025
Polyethylene	45	1.1

Note: All these values are very rough and no doubt controversial, but I think that they are in the right region. The value given for carbon-fibre composities is admittedly a guess, but it is a guess founded upon many years of experience in developing similar fibres.

(b) Structural efficiency in terms of energy need

Material	Energy needed to ensure a given stiffness in the structure as a whole	Energy needed to produce a panel of given compressive strength
Steel	1	1
Titanium	13	9
Aluminium	4	2
Brick	0.4	0.1
Concrete	0.3	0.05
Wood	0.02	0.002
Carbon-fibre composite	17	17.0

(These figures are based on mild steel as unity. They are only very approximate.

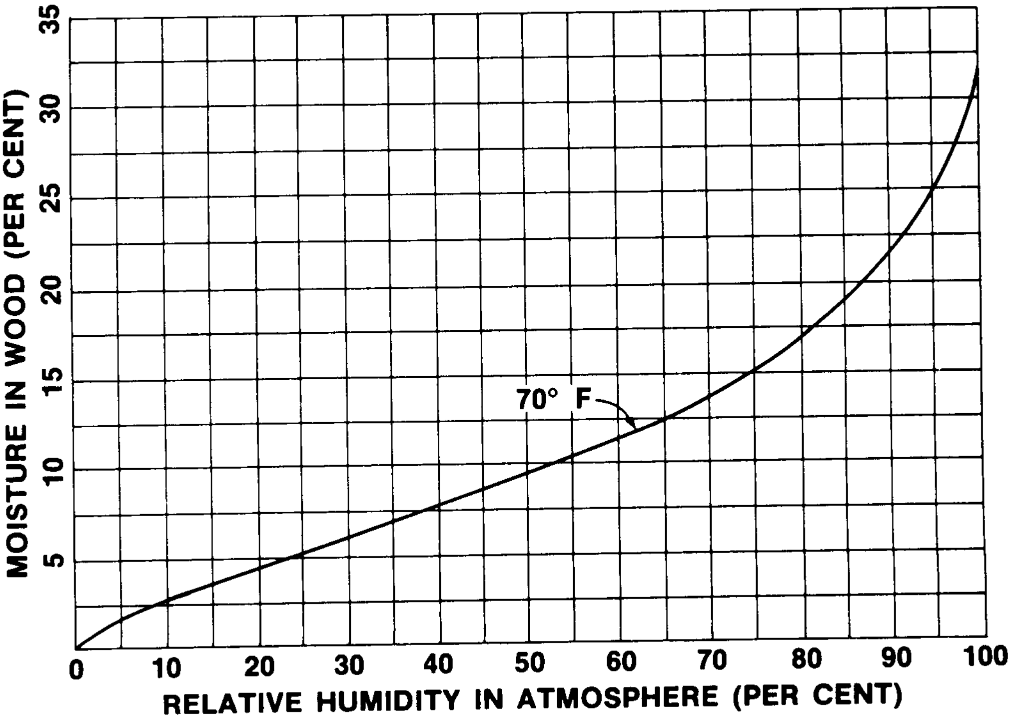


Figure 1. - Humidity chart.

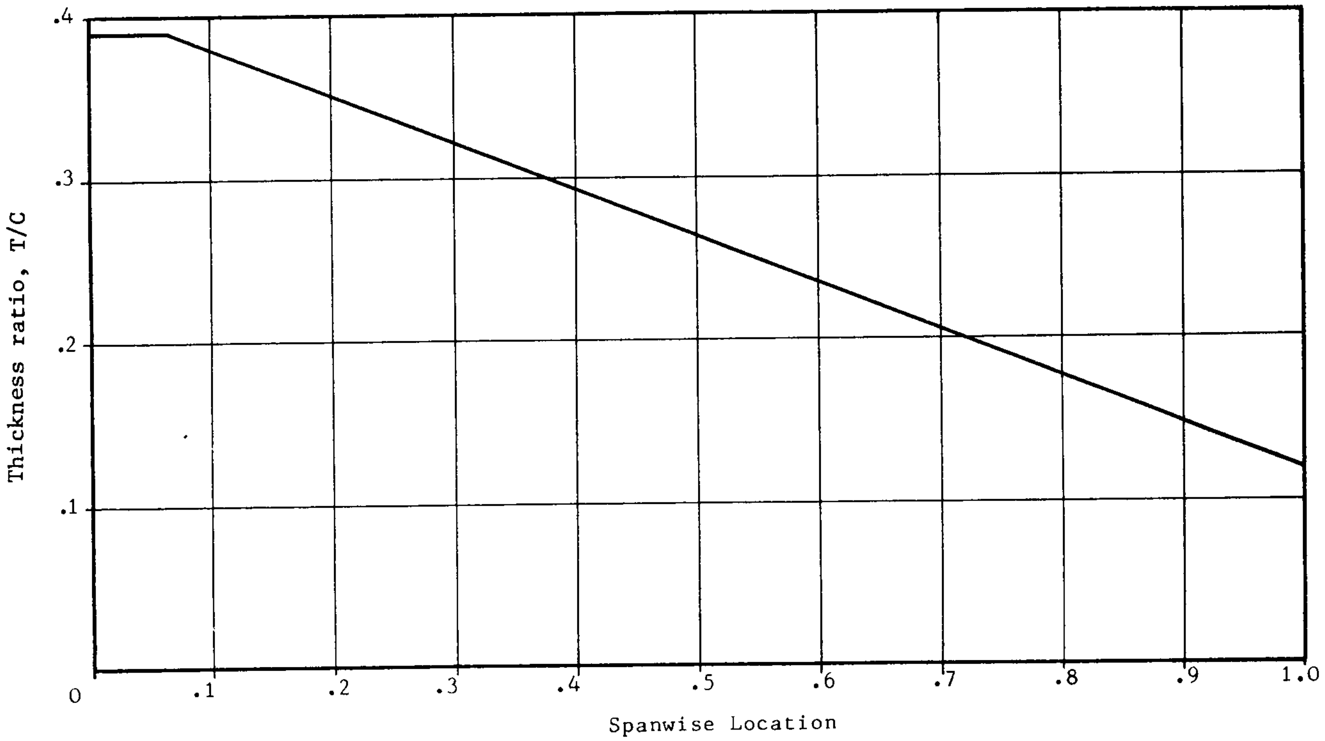


Figure 2. - Blade thickness variation.

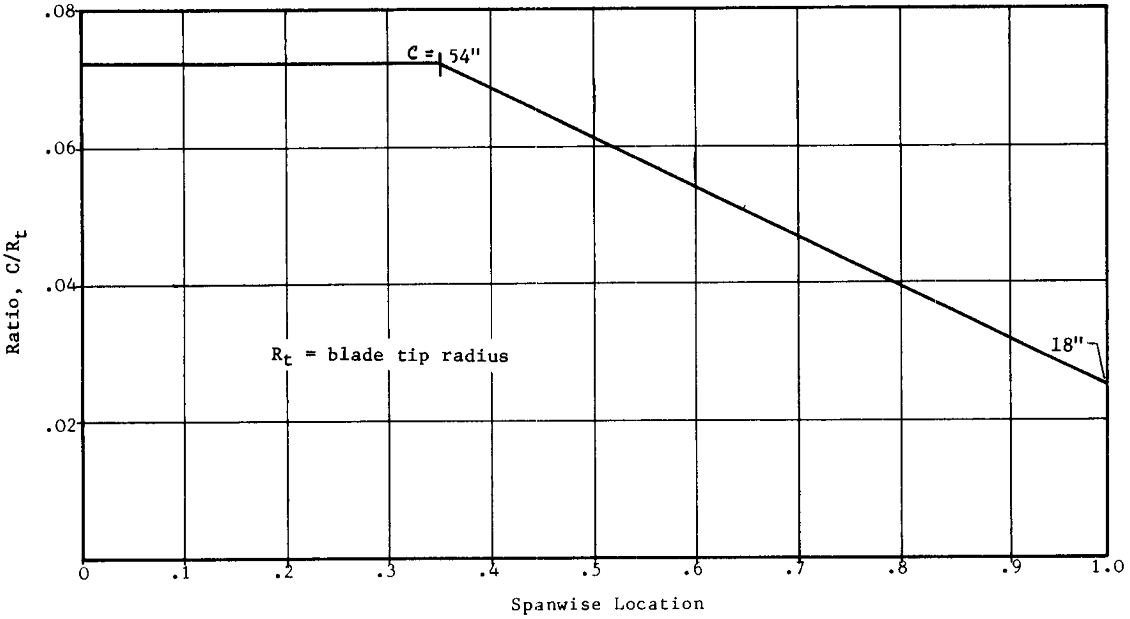


Figure 3. - Blade chord variation (plan form).

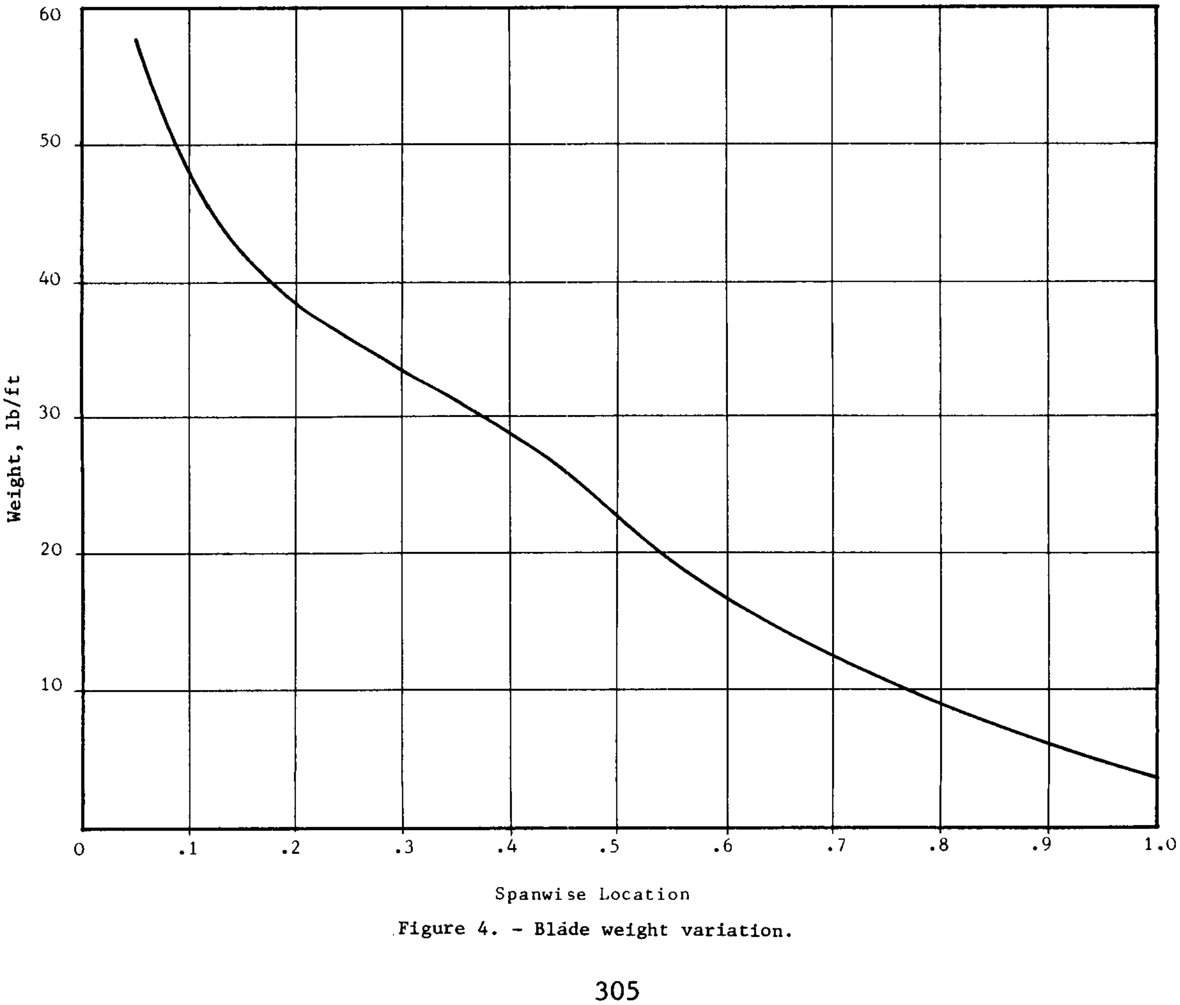


Figure 4. - Blade weight variation.

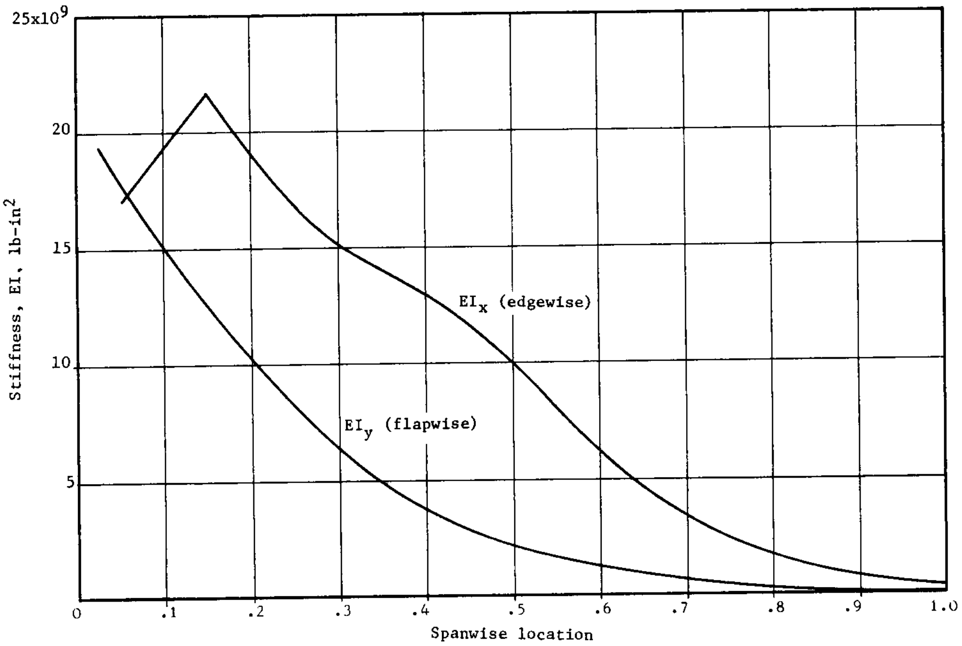


Figure 5. - Blade stiffness variation.

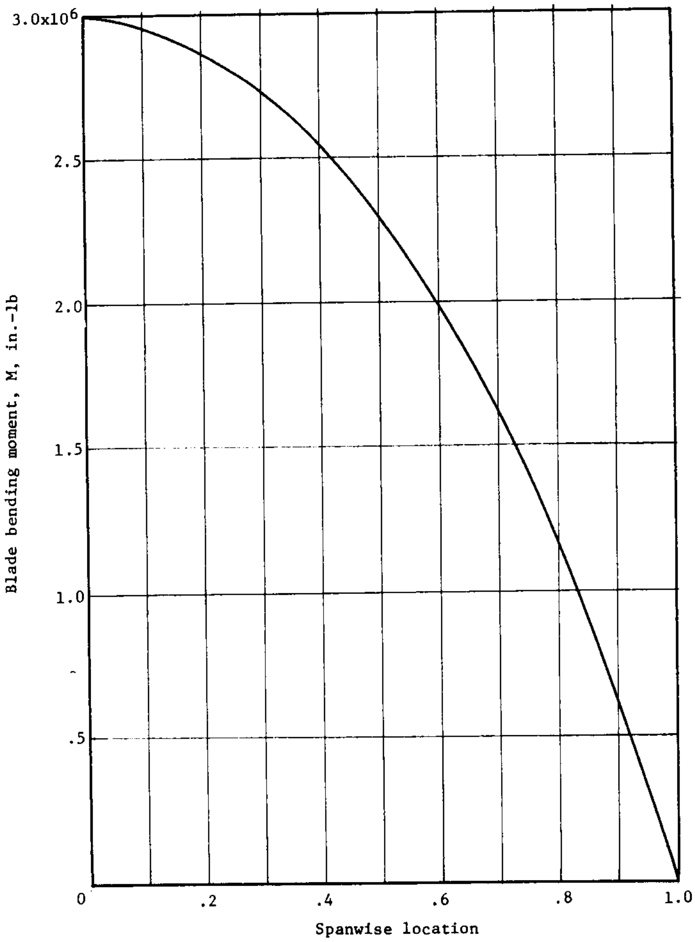


Figure 6. - Hurricane gust specification.

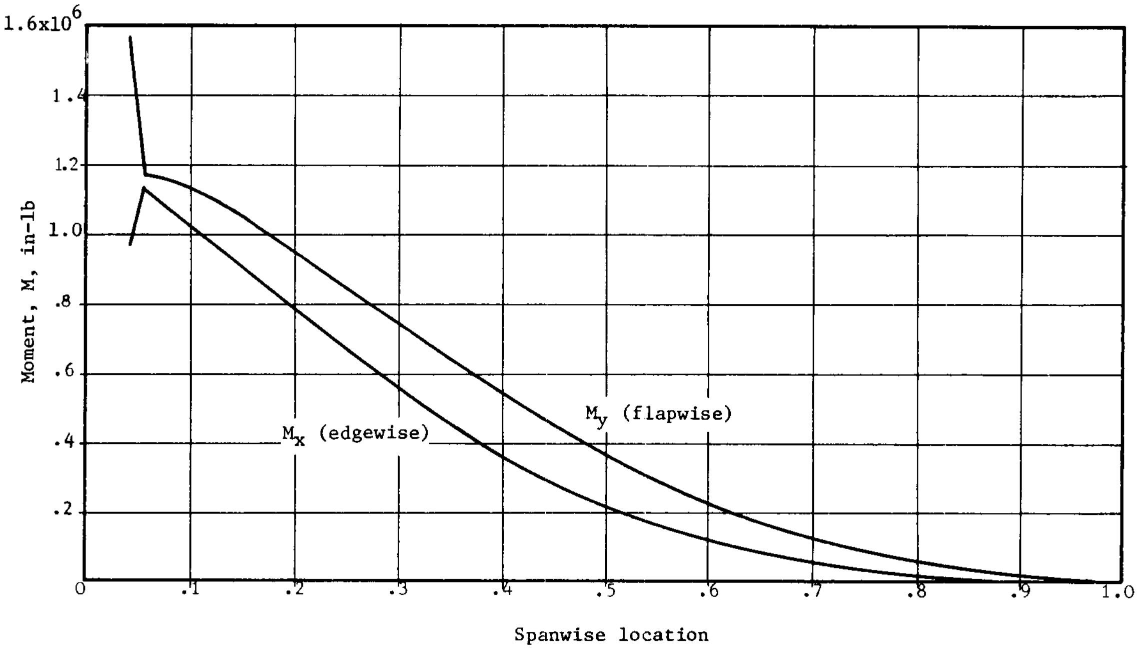


Figure 7. - Working load specification.

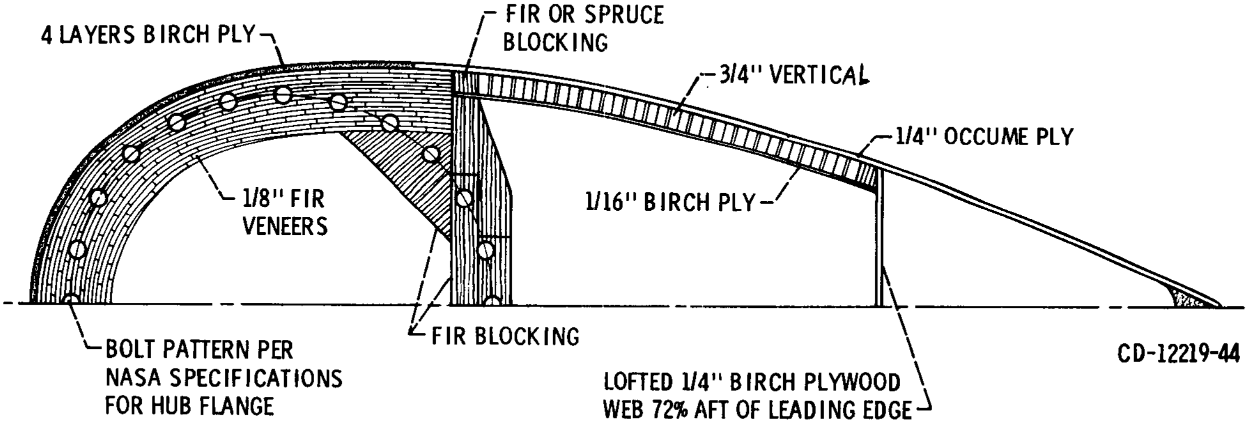
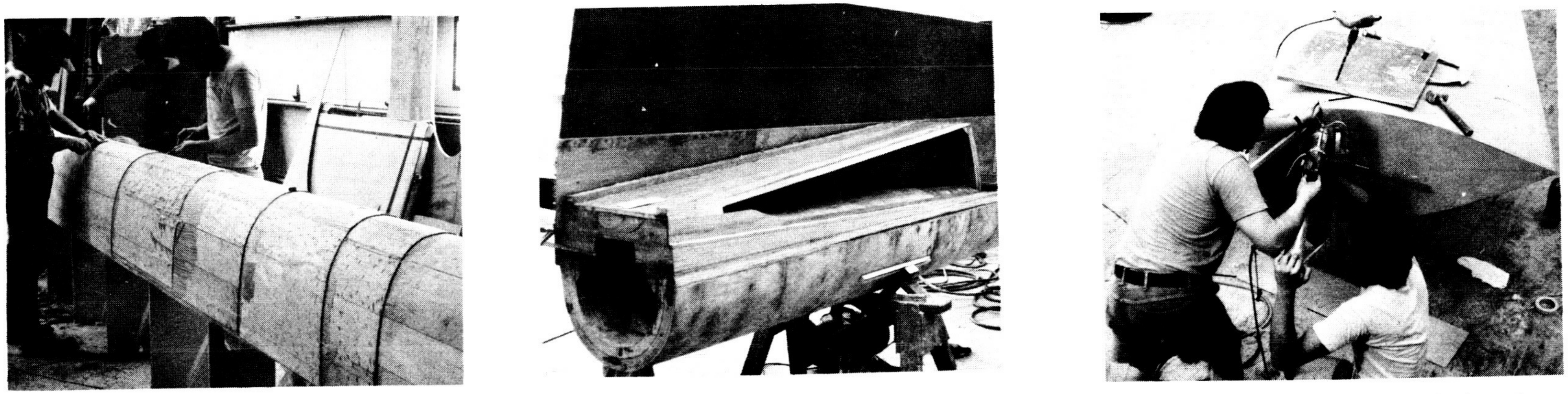


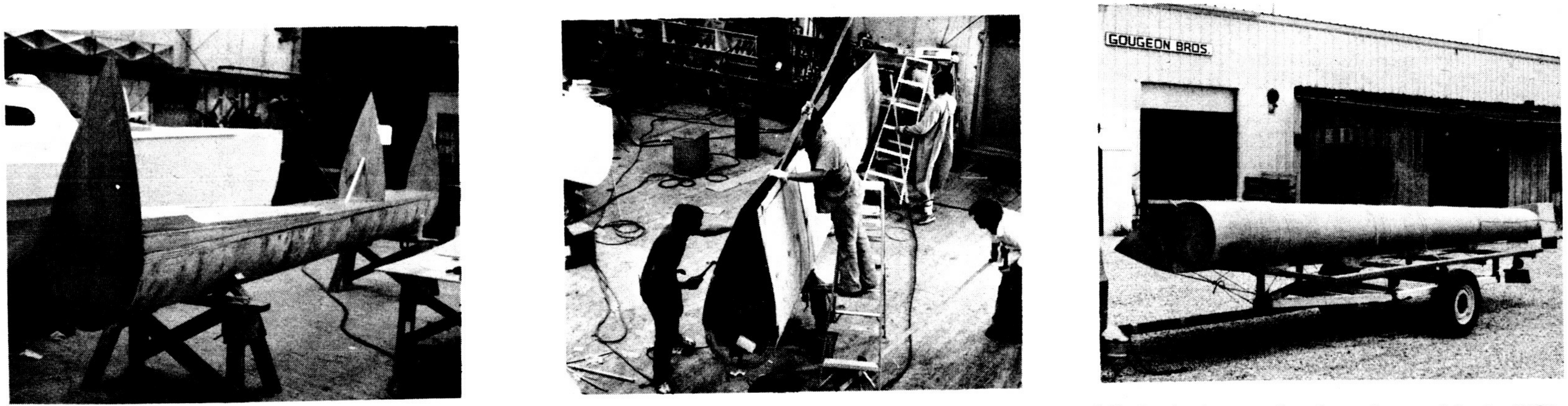
Figure 8. - Root end construction concept.



(a) Laminating the "D" section.

(c) Installation of compression strut and tail section on one side.

(e) Drilling pilot holes which will be enlarged to insert steel studs.



(b) Installation of sheer web and blocking at root end.

(d) Installation of opposing tail section and joining at aft tip.

(f) Studs inserted and ready to ship to NASA-LeRC for testing.

Figure 9. - Construction of 20-foot test specimen.