DESIGN, FABRICATION, AND TEST OF A STEEL SPAR WIND TURBINE BLADE

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INTRODUCTION

One potential means for reducing the costs of wind turbine blades is to use a mass produced structure as the primary structural member of the blade. Tapered beams such as those used for utility poles are the type of mass produced structure envisaged. The airfoil shape could be formed by light-weight foam or light-weight ribs overwrapped with fiberglass cloth. In order to determine the feasibility of this concept, a 60 ft. steel spar blade was designed. Using this design, two blades were fabricated at the Lewis Research Center and tested on the Mod-0 wind turbine (ref. 1).

This paper describes the design and fabrication of the blades. Performance and blade load information is given and compared to analytical prediction. In addition, performance is compared to that of the original Mod-0 aluminum blades. Costs for building the two blades is given, and a projection is made for the cost in mass production. Finally, design improvements to reduce weight and improve fatigue life are suggested.

BLADE DESIGN AND ANALYSIS

The purpose of this program was to show that a wind turbine blade based on a steel spar could be fabricated in a satisfactory manner. Once fabricated it was necessary to show that the blades performed adequately on Mod-0. A 30-year blade life was a secondary consideration in this program.

Design Concept

A schematic of the steel spar blade design is shown in figure 1. Figure 1(a) shows the steel spar. Because of the constraints placed on the design by the Mod-0 hub flange dimensions and the availability of steel spar material, the steel spar extended from station (sta.) 148 in. to sta. 750. The space between the hub flange (sta. 32) and the steel spar flange was filled with a high strength steel tubular extension section. To reduce the blade loads it was necessary to reduce the precone angle from the 7° built into the Mod-0 hub to 3°. The steel spar is at a 4° angle to the extension section. The steel spar is made in two sections which are welded together at sta. 558.

This was done to allow the use of lighter wall material on the outboard section of the blade.

The blade planform and a typical cross section are shown in figure 1. The leading edge airfoil shape is formed with foam while the trailing edge shape is formed with wooden ribs. The skin is fiberglass cloth. Details of the design are given in a subsequent section.

Design Specifications

Blade design requirements and additional rotor information are given in table I. For comparison purposes, the same information for the original Mod-0 aluminum blades is given in the table. The steel spar blade is a much simpler blade with no twist and a constant thickness ratio. The rotor operating speeds were chosen to optimize annual energy capture.

The spar design was based on a single load case. That was the 120 mph wind case which was taken to be equivalent to a uniform pressure of 50 $lb./ft.^2$ on the surface of the blade. Because of the short term nature of the operation of this blade on Mod-0, no fatigue load cases were required.

Design Allowables

The critical area of this design is the spar to flange weld area. Initially it was assumed that the flange material would have a yield strength of 60,000 psi. However, the actual material had a yield strength of only half this. Table II gives the measured material properties for the various spar components. The allowable strength was taken as the minimum measured strength.

Because of the reduced allowable in the flange material, additional analysis was done with the high wind load case. In addition, a rotor overspeed to 48 rpm load case was investigated. The high wind case showed that the spar flange yield strength allowable could be exceeded in winds as low as 87 mph. However, the stress was well below the ultimate strength in winds up to 120 mph. The overspeed case also showed the yield allowable was exceeded but again the stress was well below ultimate.

Predicted Fatigue Life

The cyclic blade loads associated with operation at the cut out wind speed (40 mph) were used in predicting a fatigue life for these blades. These loads would provide a conservative estimate of fatigue life. The MOSTAB-WTE code (ref. 2) was used to calculate spar loads and stresses. Cyclic and maximum spar stresses are plotted in figure 2 for operation at 40 mph wind speed. The critical portion of the blade is the spar to flange weld at sta. 153. Using the stress amplitude at this station, both the Structural Welding Code and the AISC Code were used to estimate fatigue life. Fatigue life predictions are shown in figure 3. The Structural Welding Code predicted a life of 2.9×10^5 cycles, while the AISC Code predicted a life of 6×10^5 cycles. Based on these predictions, it was determined that the blades could be safely operated for 100 hours (about 2 x 10^5 cycles) before reinspection of the welds is required.

BLADE FABRICATION PROCEDURE

The first step in the blade fabrication procedure was preparation of the steel spar. The spar-to-spar and spar-to-flange welds were made. The welds were inspected by dye penetrant and x-ray. The outer surface of the completed spar was then sandblasted and coated with an epoxy resin.

The remaining steps in the fabrication procedure are illustrated in figure 4. The wood leading edge ribs, spaced 12 in. apart, were bonded into place. A fiberglass tube for holding balance weights was inserted through holes in the ribs and bonded into place. Foam pieces, previously cut to shape, were inserted between the ribs and bonded to the spar. This assembly was then overwrapped with three layers of fiberglass cloth/epoxy and cured.

Next, the wood trailing edge ribs were bonded into place, again at 12 in. intervals. A wood trailing edge piece was bonded to these ribs. To provide additional support for the ribs, pieces of foam overwrapped with fiberglass were inserted between the ribs and bonded to them.

The last major process in the fabrication procedure was the installation of Razorback cloth. Razorback is a specially treated fiberglass cloth which shrinks when a cellulose acetate butyrate (CAB) dope is applied. This material is used in general aviation and provides a very strong and smooth surface. The assembly shown in figure 4 (e) was overwrapped with two layers of Razorback and doped with CAB.

The final step in the procedure was painting. Photographs taken during blade construction are shown in figure 5.

BLADE TESTS

The steel spar blades were mounted on the Mod-0 hub in late September of 1978. They were removed from the hub in late February of 1979. During that time they operated for about 75 hours during a variety of tests. After dismount the blades were inspected. The Razorback skins showed no sign of deterioration and dye penetrant check of the spar-to-flange weld revealed no cracks. This section presents blade weight, balance and natural frequency information obtained before the blades were operated, and blade performance and loads during operation on Mod-0.

Weight, Balance and Natural Frequency

Blade weight and balance data are summarized in table III. As fabricated, the weights of the two blades were within 28 lbs. (approximately 1 percent) of each other. The total weight was 3617 lbs. compared to 2000 lbs. for the Mod-0 aluminum blades.

For analysis purposes the blade natural frequency and mode shape were calculated using a finite element model. This model considered the mass and stiffness of the steel spar and extension piece, but only the mass of the wood, foam and fiberglass. The frequency and mode shape obtained from the model were used in the MOSTAB-WT (ref. 2) code for predicting blade loads.

The first flatwise and edgewise cantilever bending frequency predicted by the model was 1.88 Hz. The actual blade frequencies were obtained with the blades mounted on the Mod-0 hub. The first flatwise frequency was measured at about 1.75 Hz. and the first edgewise was measured at about 1.85 Hz. The small difference between the flatwise and edgewise frequencies indicated that the wood and fiberglass contributed only slightly to the blade stiffness.

Blade Performance and Loads

During the tests of the steel spar blades, Mod-0 was operated with the tower in two distinct modes. The first was the hard tower mode where the tower had a first bending frequency of about 2 Hz.; the second was the soft tower mode where the tower had a first bending frequency of about 0.8 Hz. This frequency change was achieved using a fixture that was placed between the Mod-0 tower and its foundation (ref. 3). The measured performance and loads described in this section were for both the hard and soft towers. In general, the tower natural frequency had very little effect on performance and blade loads.

The measured blade performance is compared to that predicted by the PROP code (ref. 4) in figure 6. The blades performed slightly better than predicted. Their performance is compared to that of the Mod-0 aluminum blades in figure 7. The performance is nearly equivalent which was unexpected because of the steel spar blades having a larger root cutout and no twist. These aspects detrimental to performance must have been offset by the better surface smoothness achieved with the type of fabrication used for the steel spar blades and by their larger chord length.

A comparison of measured and predicted flatwise steady and cyclic blade root loads is shown in figure 8. The predicted loads were obtained from the MOSTAB-WT code (ref. 2). There is good agreement with the cyclic loads. At the higher wind speeds the code overestimates the wind shear resulting in higher predicted cyclic loads. The difference between the predicted and measured steady component of the flatwise loads is probably due to some error in the mass distribution of the model used in the code. In addition, the actual rotor speed was slightly less than that used in the code.

Measured and predicted chordwise steady and cyclic blade root loads are compared in figure 9. The predicted cyclic load is slightly greater than that measured. This is probably due to a slight error in the total mass and mass distribution in the model. The steady component of the chordwise load is the torque producing component. At least part of the difference between measured and predicted chordwise steady load can again be attributed to the difference between the actual rotor speed and that used in the code.

Based on the operation of the steel spar blades on Mod-0, two general observations can be made. First, inasmuch as the measured blade loads (figure 9) were less than those used to predict blade fatigue life, the predicted life is very conservative. Secondly, even though these blades had vastly different mass and frequency characteristics compared to the Mod-0 aluminum blades, they behaved very well on Mod-0. In fact, they appeared to run more smoothly than the aluminum blades even when the tower was in its soft mode.

BLADE COSTS

The actual cost of the two steel spar blades is given in table IV. The costs are divided up into three main categories: steel spar and extension piece; wood, foam, fiberglass, etc. material costs; and labor costs for assembly of the airfoil on the spar. These three categories were selected to enable one to project the costs for high rate production.

The actual cost of blades 1 and 2 was $57,465 and $49,065, respectively. The major reason for the reduced cost of blade 2 was a one third decrease in the labor required to apply the wood, foam and fiberglass.

The cost of these blades in limited production is estimated to be $35,000. This estimate is based on a single vendor quote. In high production it is estimated that a blade using this concept could be produced for $12,500. This includes $4500 for spar material and labor, $3000 for airfoil material, and $5000 for airfoil fabrication.

The above reduction of the spar cost is achieved by assuming the spars are mass produced specifically for wind turbine blades. This eliminates the need for the expensive extension piece and the spar-to-spar weld. Possible means for improving the fatigue life and reducing the weight of the spar are discussed in the next section. The reduction in the wood, foam, etc. cost was achieved primarily by increasing the rib spacing and reducing the Razorback covering from two layers to one layer. Additional cost savings were assumed to accrue from quantity purchases. The labor costs for assembling the airfoil on the spar were reduced substantially based on the assumption that the blades would be mass produced in a highly automated factory.

POTENTIAL DESIGN IMPROVEMENTS

The design presented here requires modification because of its limited fatigue life. In addition no attempt was made to optimize the design of the spar. Two potential design improvements are discussed in this section.

Double Wall Spar

The fatigue life of steel spar blade could be increased by increasing the thickness of the spar wall where it is welded to the flange. One means of doing this with low cost spar material is illustrated in figure 10. In the highly loaded root area of the blade, the main spar is reinforced by a second concentric spar. This procedure is used routinely by utility pole manufacturers. The additional thickness of material at the weld should reduce the stress to below the endurance limit. A fatigue test of a double walled spar is planned.

Roll Formed Spar

With the roll forming process it is possible to tailor the spar diameter and wall thickness exactly to the load carrying requirements of the spar. A spar formed by this process for a 60-ft. wind turbine blade is shown in figure 11. The spar has a linear taper in diameter and a linear taper in wall thickness except at the weld lands. The spar was designed so that a stress allowable of 30,000 psi not be exceeded for the 120 mph wind case and a stress amplitude of 6000 psi not be exceeded for the 40 mph operating case. It is estimated that a 60-ft. blade using a roll formed spar would weigh less than 3000 lbs.

CONCLUDING REMARKS

A 60-ft. wind turbine blade based on a low-cost steel spar as the primary structural member was designed. Two blades were fabricated and operated successfully on the Mod-0 wind turbine. Blade loads were close to those predicted, and rotor performance exceeded predictions. Because of the limited fatigue life of the present design, minor design modifications are required to improve the fatigue life. It is estimated that in mass production a blade of this design can be produced for less than $20,000.

REFERENCES

1. Thomas, R. L. and Richards, T. R.: ERDA/NASA 100-Kilowatt Mod-0 Wind Turbine Operations and Performance. NASA TM-73825, 1977.

2. Spera, D. A.: Comparison of Computer Codes for Calculating Dynamic Loads in Wind Turbines. NASA TM-73773, 1977.

3. Winemiller, J. R., Sullivan, T. L., Sizemore, R. L., and Yee, S. T.: Design, Fabrication and Initial Test of a Fixture for Reducing the Natural Frequency of the Mod-0 Wind Turbine Tower. NASA TM-79200, 1979.

4. Wilson, R. E. and Lissaman, P. B. S.: Applied Aerodynamics of Wind Power Machines. Oregon State University, 1974.

TABLE I. COMPARISON OF ROTOR CHARACTERISTICS
(NACA 23000 Series Airfoil)

Characteristic	NASA-Steel Spar Blade	Lockheed-Aluminum Blade
Rotor diameter, ft.	126	125
Root cutout, percent	23.0	6.4
Root chord, ft.	6.3	4.5
Tip chord, ft.	2.1	1.5
Root thickness ratio	0.24	0.40
Tip thickness ratio	.24	.12
Solidity	.033	.031
Precone angle, deg.	3.8 (effective)	7.0
Total twist, deg.	0	34 (nonlinear)
Airfoil surface	rib stitched fiber-glass cloth	riveted aluminum
Operating speed, rpm	32	40

TABLE II. MATERIAL PROPERTY DATA

Part		Test no.	Yield stress (0.2%), psi	Ultimate tensile stress, psi	Tensile elong., %
Spar	Flange	1	35,000	59,000 [a]	38 [a]
		2	28,400 [a]	59,600	50
	Weld, flange/pipe	1	35,900	64,600	7 [a]
		2	37,600 [a]	61,600 [a]	7
	Weld, pipe/pipe	1	54,700	79,700 [a]	16 [a]
		2	50,000 [a]	79,800	16
		3	53,900	81,000	16
Extension piece		---	80,000 [b]	107,000 [b]	

[a] Allowable value

[b] Estimated from hardness of RC 22

TABLE III. STEEL SPAR BLADE WEIGHT AND BALANCE

Item	Blade No. 1	Blade No. 2
Blade weight, lb.	2460	2488
Balance weight, lb.	68	0
Extension weight, lb.	1089	1125
Total weight, lb.	3617	3613
Spanwise c.g. station, in.	285	285
Chordwise c.g., percent chord	27	27

TABLE IV. STEEL SPAR BLADE COST

Item	Blade No. 1	Blade No. 2
Spar Material and Labor		
Main Spar	850	850
Tip Spar	215	215
Flange (forging and machining)	3000	3000
Welding and Inspection	3000	3000
Extension Piece	15000	15000
Total Spar Cost	22065	22065
Airfoil Material		
Wood, Foam, Fiberglass	3000	3000
Razorback and C.A.B. Dope	2000	2000
Total Airfoil Material Cost	5000	5000
Airfoil Fabrication (@$20/hr.)		
Assemble Wood, Foam, etc.	24000	16000
Apply Razorback, Dope, Paint	6400	6000
Total Airfoil Fabrication Cost	30400	22000
Total	$ 57465	$ 49065

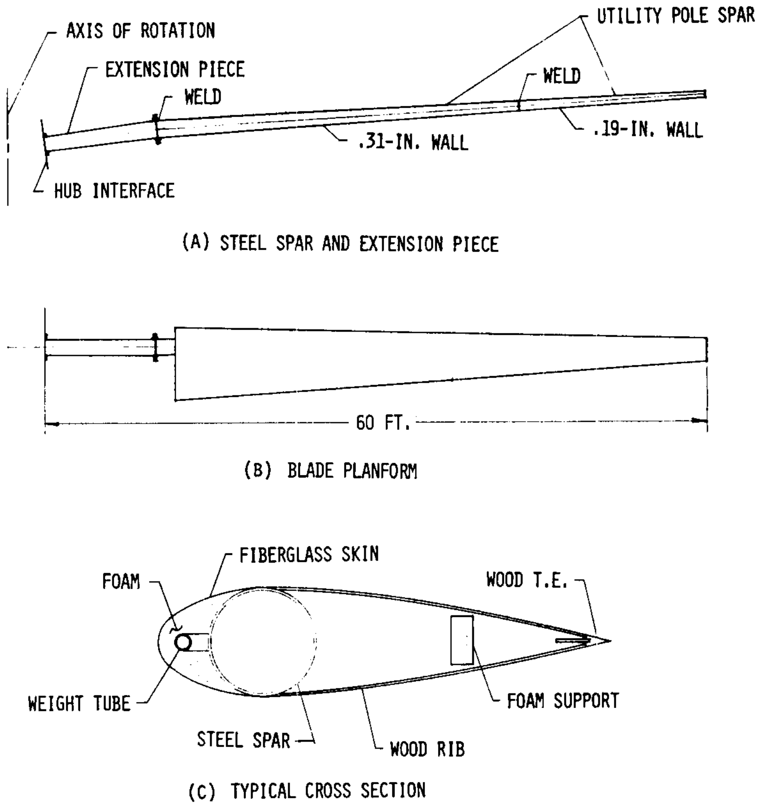

FIGURE 1 - STEEL SPAR BLADE DESIGN.

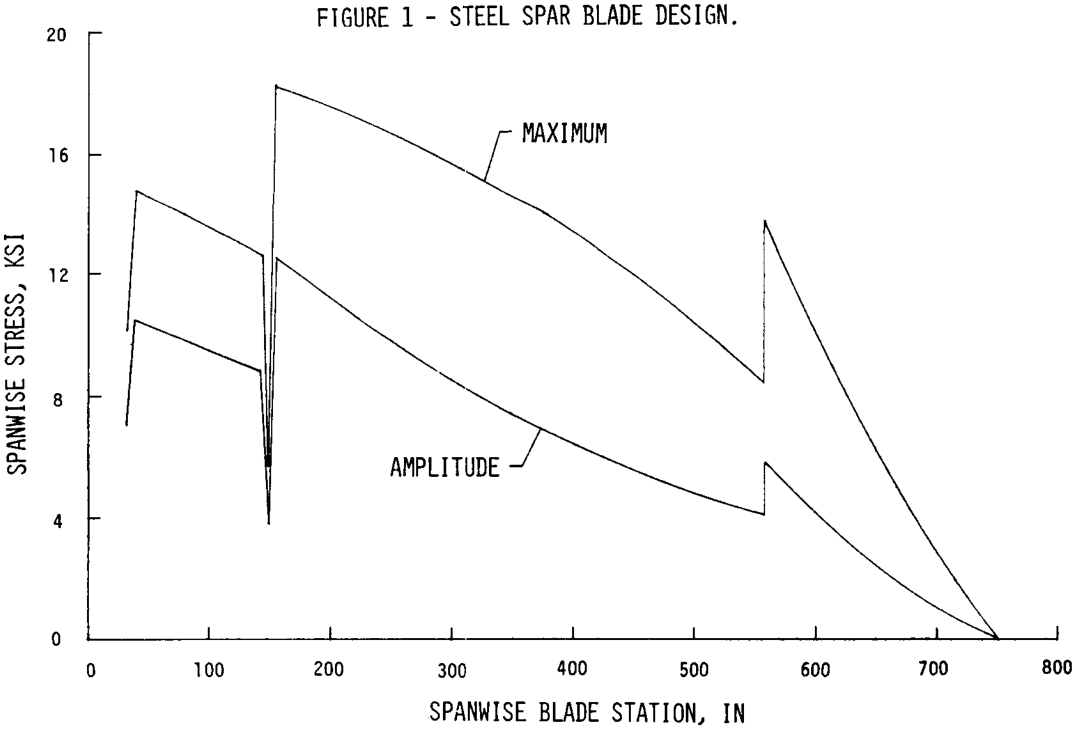

FIGURE 2 - CALCULATED STRESS IN SPAR FOR 40 MPH OPERATION

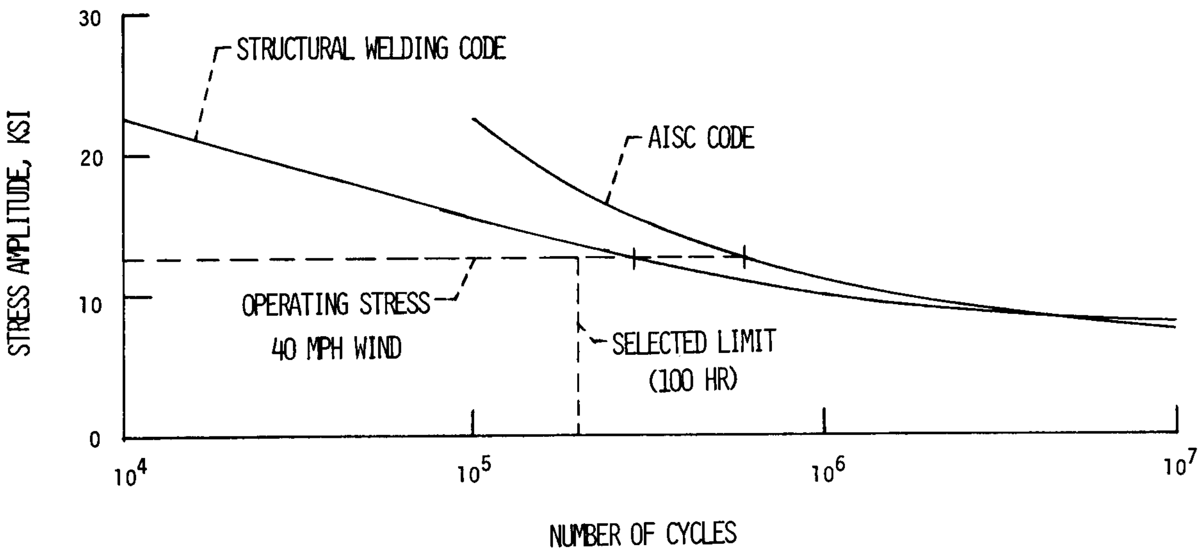

FIGURE 3 - SPAR-TO-FLANGE WELD FATIGUE LIFE ANALYSIS.

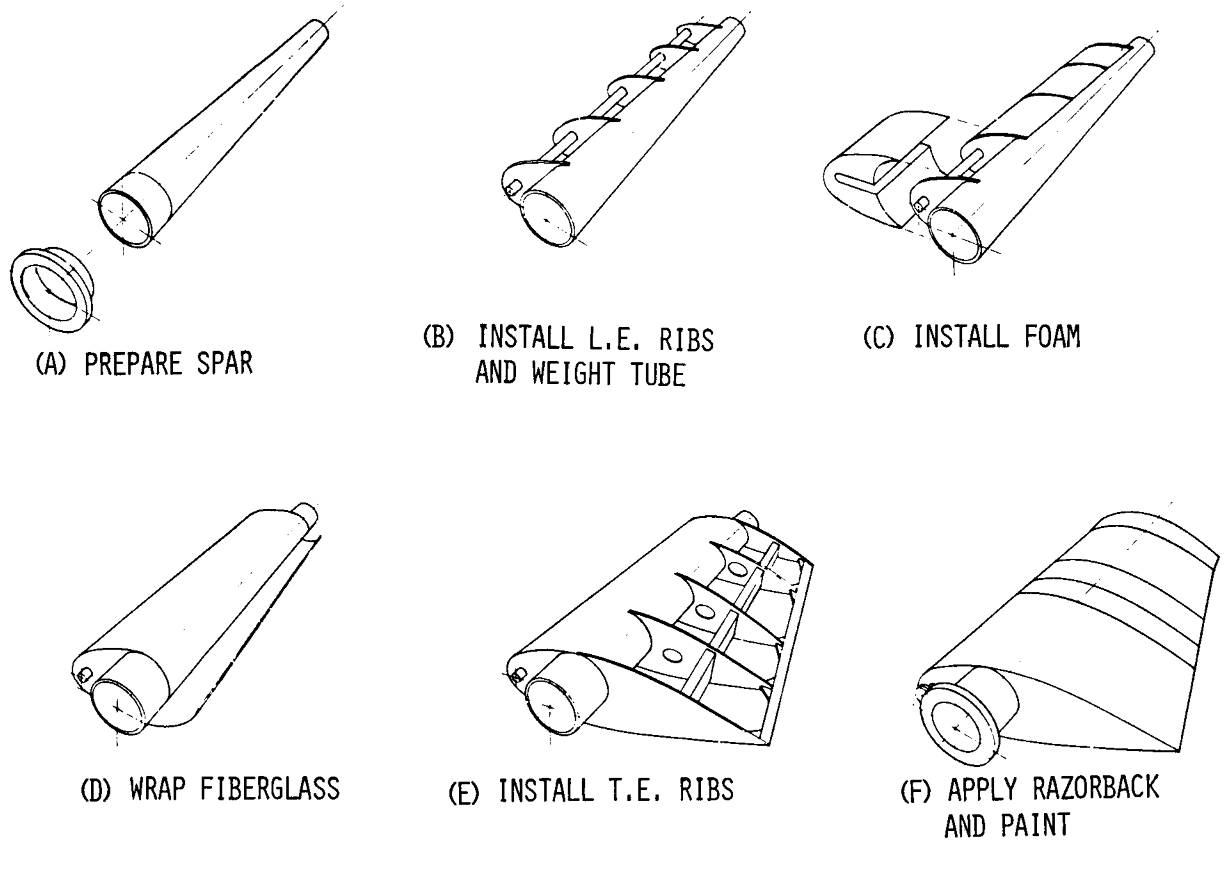

FIGURE 4 - STEEL SPAR BLADE FABRICATION PROCESS.

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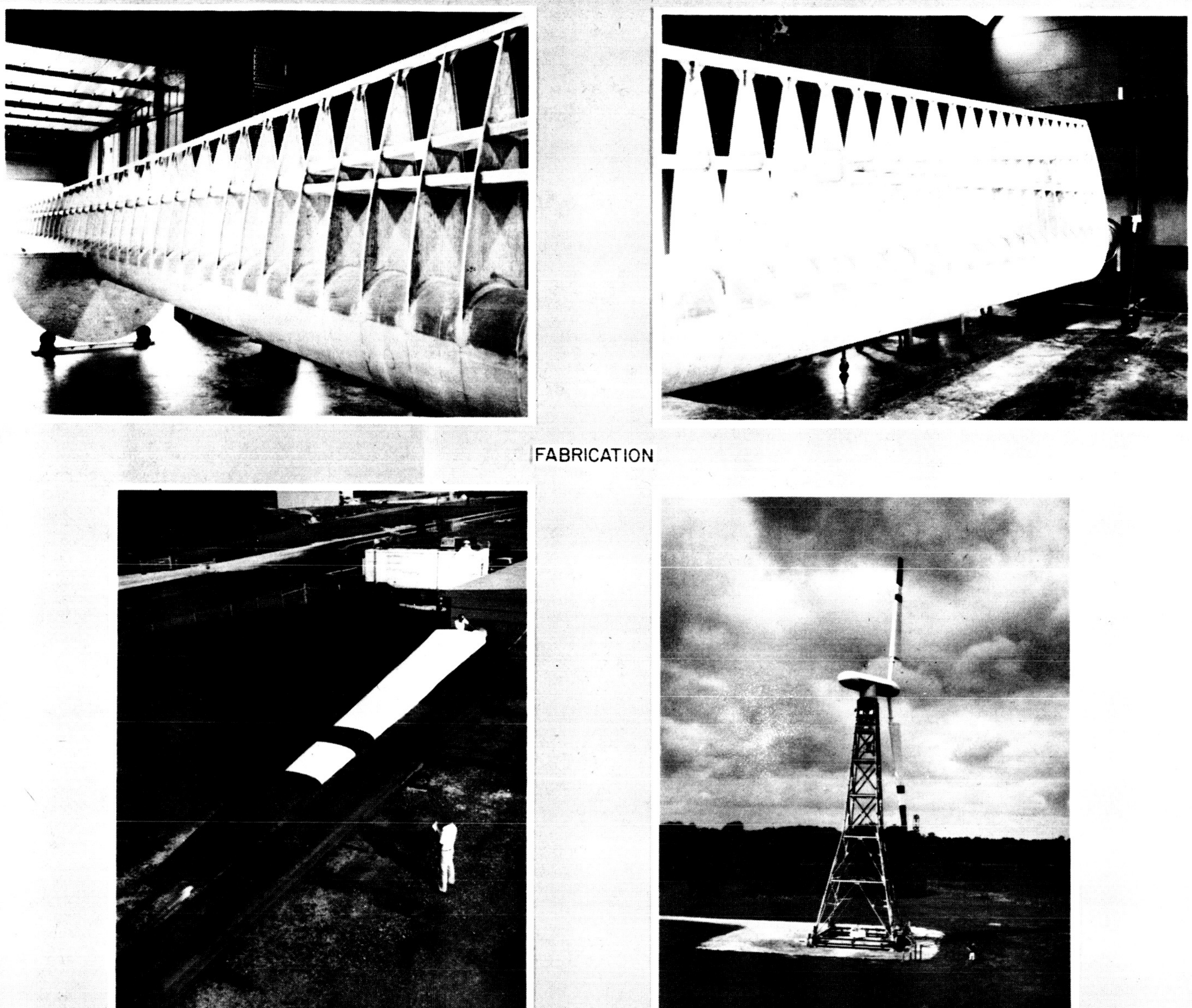


FABRICATION

LOADS APPLICATION

INSTALLATION ON MOD-O

FIGURE 5 - PHASES OF CONSTRUCTION OF UTILITY POLE BLADES.

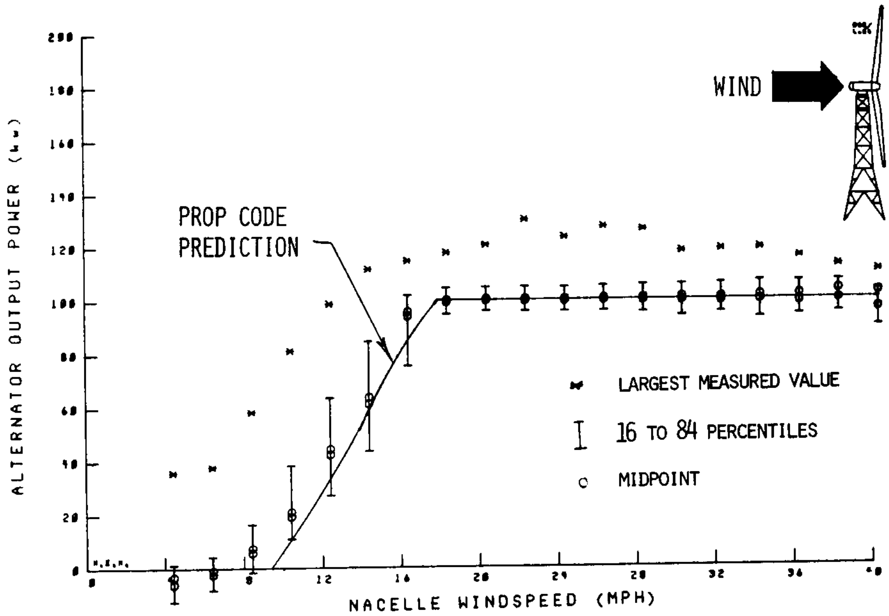


FIGURE 6 - COMPARISON OF PREDICTED AND MEASURED STEEL SPAR BLADE PERFORMANCE (SOFT TOWER).

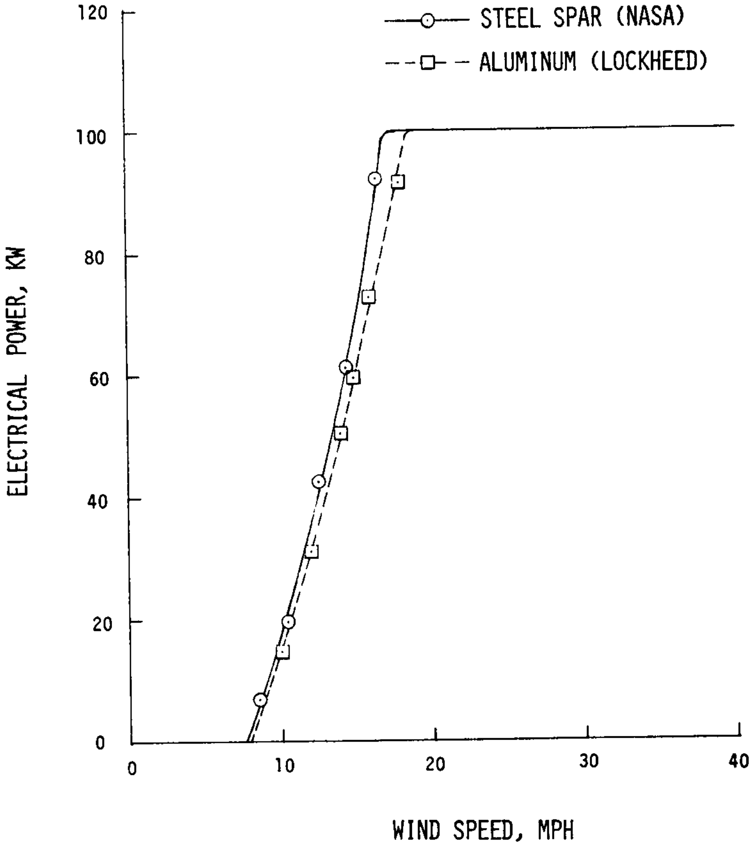
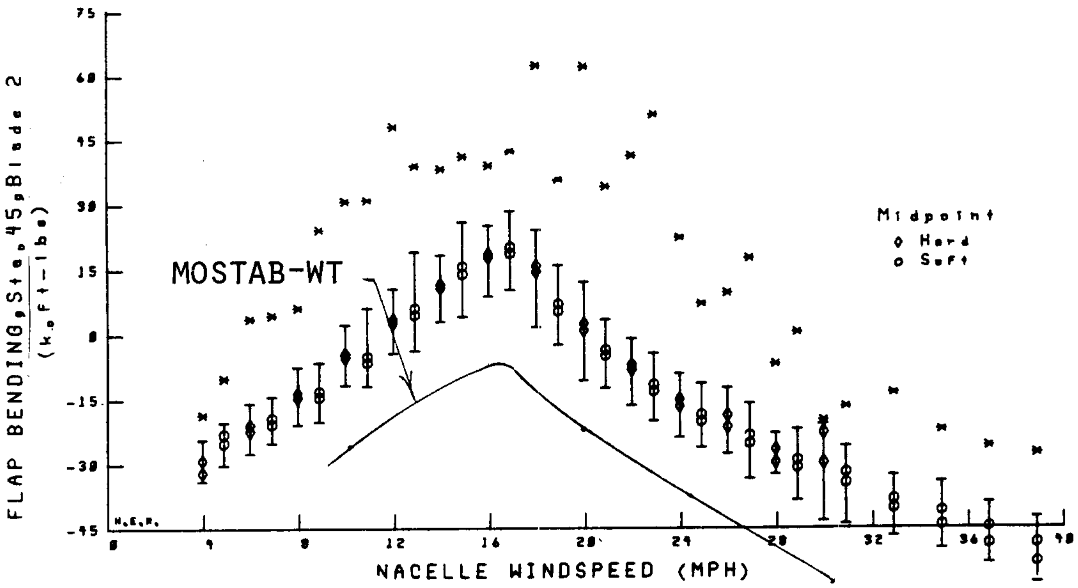
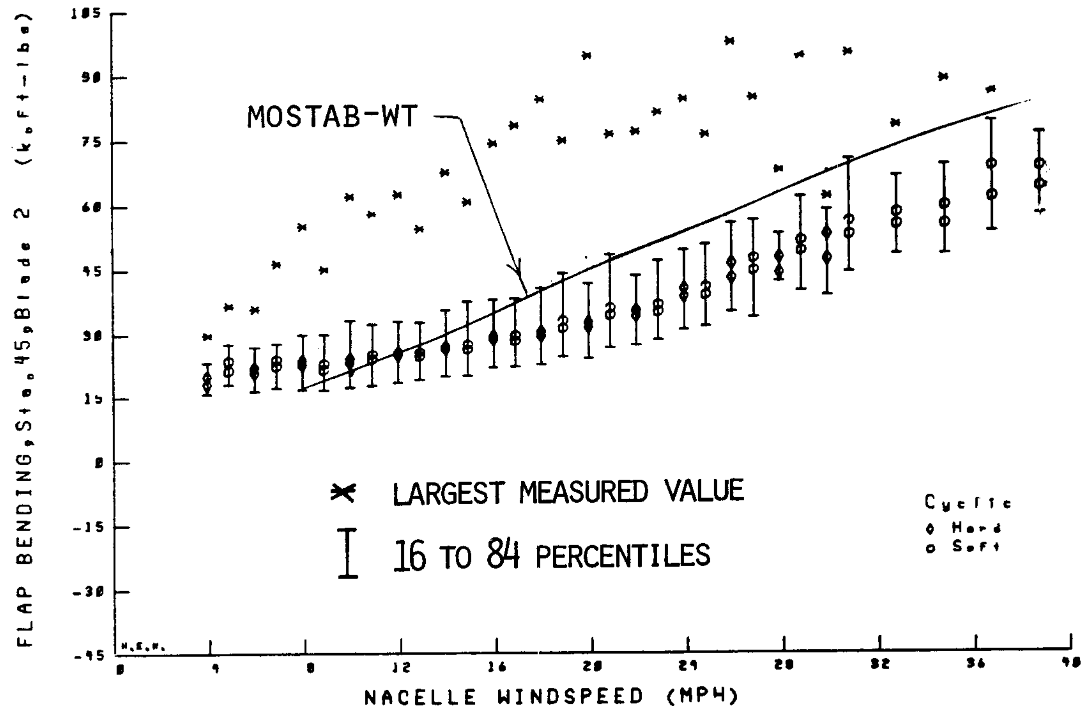


FIGURE 7 - COMPARISON OF PERFORMANCE OF TWO SETS OF MOD-0 BLADES.

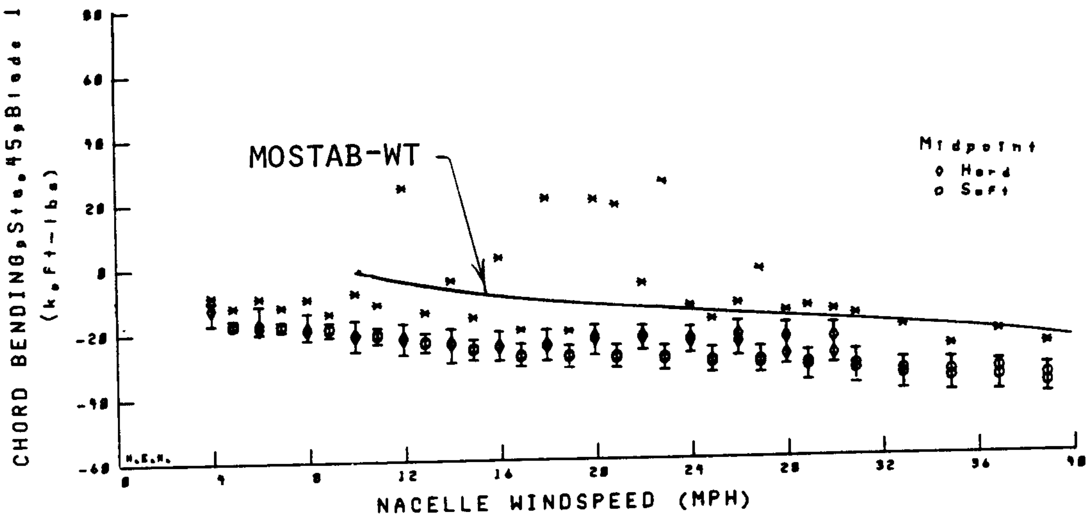


(A) STEADY LOAD

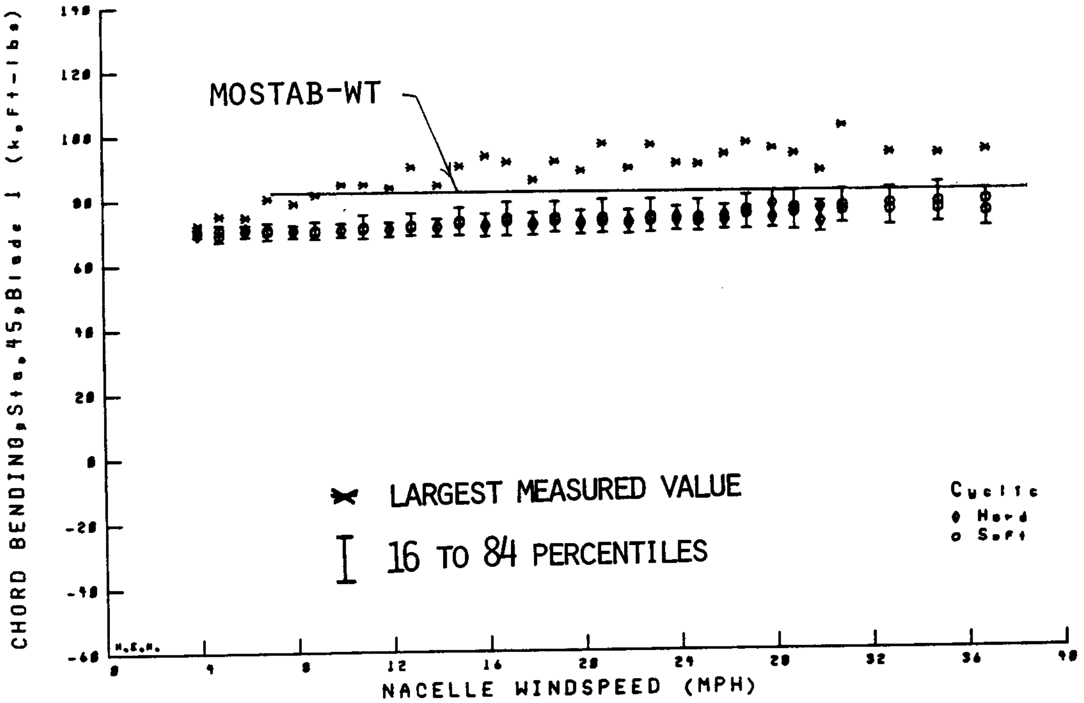


(B) CYCLIC LOAD

FIGURE 8 - COMPARISON OF MEASURED AND PREDICTED STEEL SPAR BLADE FLATWISE ROOT LOADS (HARD AND SOFT TOWERS).



(A) STEADY LOAD



(B) CYCLIC LOAD

FIGURE 9 - COMPARISON OF MEASURED AND PREDICTED STEEL SPAR BLADE EDGEWISE ROOT LOADS (HARD AND SOFT TOWERS).

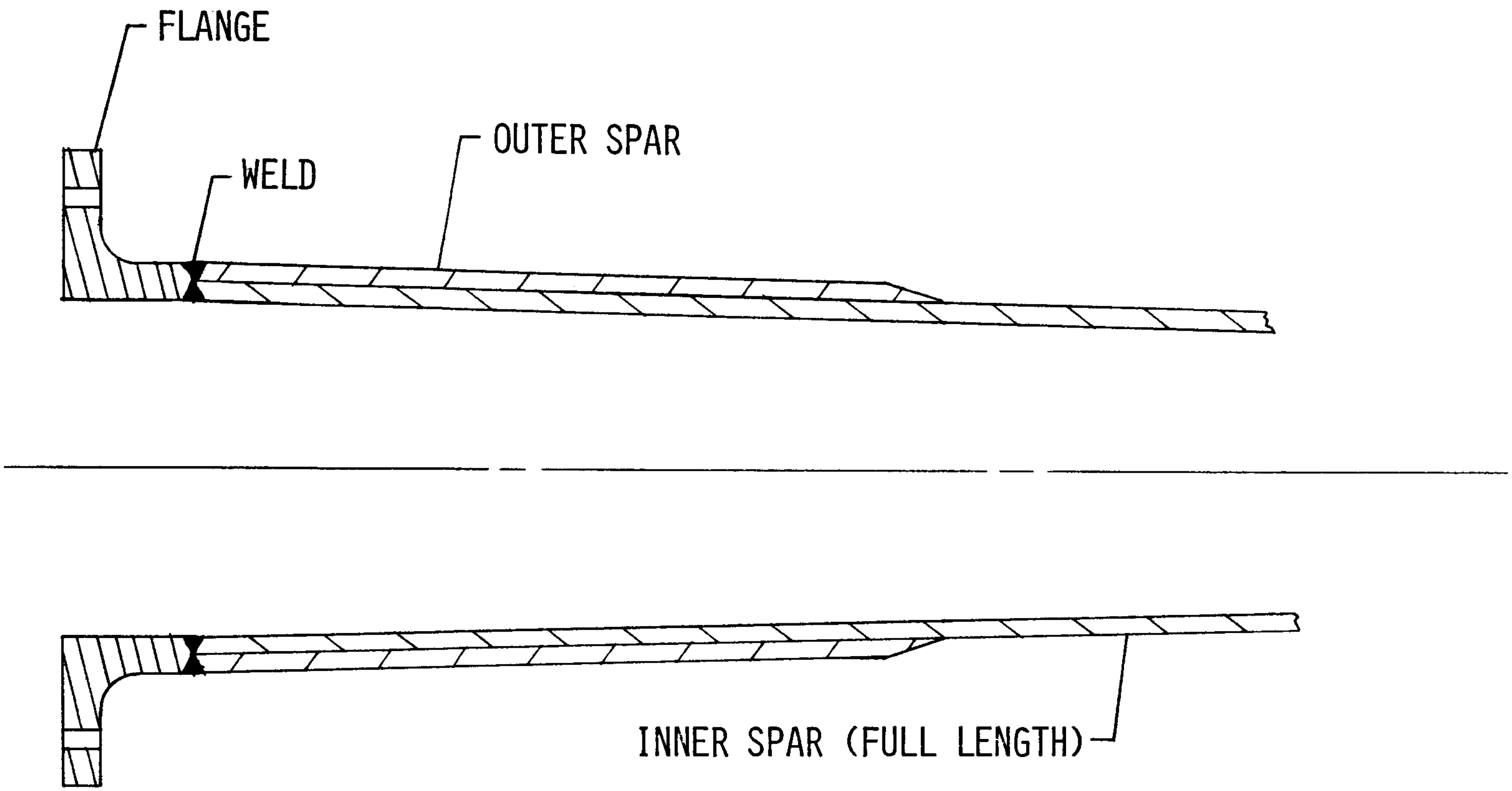


FIGURE 10 - DOUBLE WALL ROOT END SPAR

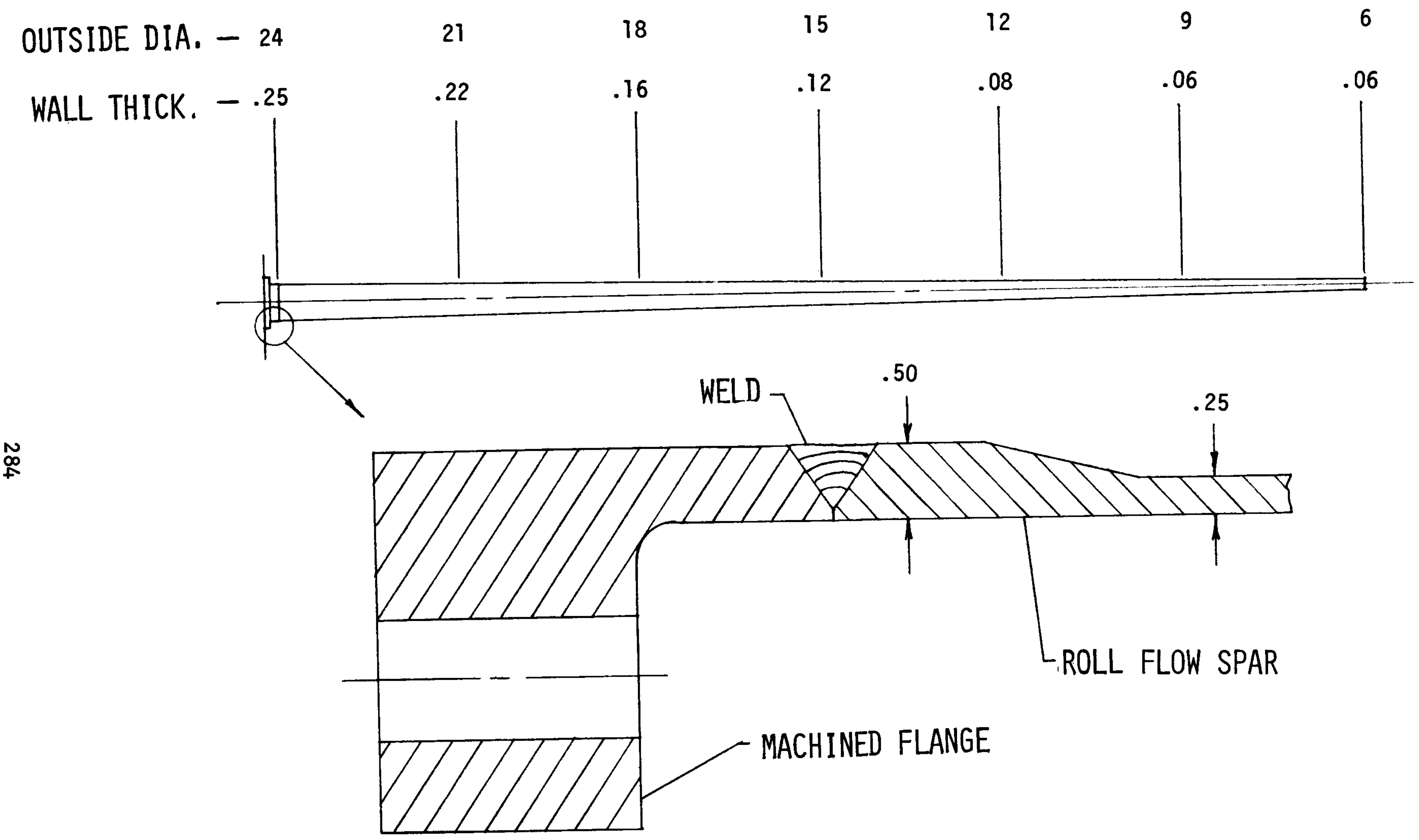


FIGURE 11 - ROLL FLOW SPAR (ALL DIMENSIONS IN INCHES)