EVALUATION OF AN OPERATING MOD-OA 200 kW WIND TURBINE BLADE

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The Mod-OA wind turbine blades, manufactured by Lockheed Aircraft Service Company (LAS), Ontario, California, are now operating in Clayton, New Mexico. These blades, rotated for the first time on November 30, 1977, establish the Mod-OA as the first wind-driven generator in 35 years to be continually tied into an electrical power system that services a community. Two additional sets of Mod-OA blades have become operational on the Island of Culebra, Puerto Rico, and Block Island, Rhode Island.

Blade design follows that of the Mod-O wind turbine built for NASA. The Mod-OA wind turbine blades are geometrically the same as the Mod-O blades. Structural modifications recommended by Lockheed to extend the fatigue life of the Mod-O blades and NASA's experience with the Mod-O unit influenced the design of the Mod-OA turbine blade structure; so did cost and schedule constraints.

Operating limits were determined from analyses and Mod-O experience. No tests were made to corroborate the many assumptions necessary for fatigue analyses (the behavior of structural details). It is generally the practice in fatigue analysis of aircraft structures (both fixed and rotary wing) to corroborate analysis assumptions with tests. Fatigue damage of the Mod-OA blade structure during normal operation might accumulate at an unexpected rate. Appropriate caution in the form of frequent inspections and corresponding repairs (if necessary) was therefore recommended.

DESCRIPTION OF THE 200-kW WIND TURBINE SYSTEM

The 200-kW wind turbine is a two-bladed, horizontal-axis, rotor system driving a synchronous electric generator through a step-up gear box located within a nacelle. The nacelle is mounted on top of a 100-foot tower as shown in Figure 1 with the rotor located downwind from the tower. The 200-kilowatts rated power output of the wind turbine is achieved at a turbine rotor speed of 40 rpm and a rated wind speed of 18.3 mph. The rated wind speed is defined as the lowest wind speed at which full power is achieved. The wind turbine power output, as a function of wind speed, is regulated by varying the pitch angle of the blades. At wind speed below cut-in and above cut-out the rotor blades are placed in a feathered position and no power is produced. The cut-in wind speed, defined as the lowest wind speed at which power can be generated, is 6.9 mph. The cut-out wind speed, defined as the lowest wind speed at which wind turbine operation would result in excessive blade stress, is 34.2 mph. All of these wind speeds are measured at a 30-foot elevation.

In the gear box, the shaft rpm is increased from 40 to 1800 rpm. A high-speed shaft connects the gear box to the 200 kW alternator. The drive train assembly is enclosed in a fiberglass nacelle for environmental protection. The nacelle and rotor assembly are positioned at the top of a tower to provide the necessary blade tip to ground clearance. A hoist provides access to the tower. The onsite controls and electrical switchgear are housed in the control building at the base of the tower.

The yaw drive permits rotation of nacelle/blades to maintain proper alignment with the wind. Rotation is achieved by driving a large bull gear with two pinion gears. The two pinion gears, which are preloaded against each other to increase torsional stiffness, are driven by separate motors and yaw drives. If necessary, yaw control can be achieved by using only one unit. The yaw rate, 1/6 rpm, is operational whenever the wind speed exceeds the cut-in wind speed of the wind turbine.

The torsional stiffness of the tower-nacelle interface is further increased by activating three yaw disk brakes. Even during the yawing motion, some brake pressure is applied to damp out any torsional oscillations by maintaining a drag force. Once the machine has aligned itself to the wind, this brake pressure is increased to the maximum.

The function of a fluid coupling on the high-speed shaft is to damp out the power oscillations resulting from the continuously varying wind velocity that the blades must withstand due to the tower shadow and the wind shear effects.

BLADE DESCRIPTION

In many aspects, the blades are similar to an airplane wing: they contain leading and trailing edge structure, formers, stringers, ribs, webs, and skin. However, the length of each blade (62.5 feet), the taper, twist, and contour parameters it must maintain coupled with the balance, weight, and flex requirements for symmetrical blades, make them unique. All components were tested for chemical and physical properties to ensure against impurities. In addition to the required test certifications, a copy of the actual test results accompanied each certification.

Before assembly was started, the blade fixture was boresighted and adjusted to ensure contour, taper, and rigidity at all stations. The same check was performed at least three times a week during actual blade assembly.

The brake-formed leading edge, assembled in sections, serves as the base for installation of the D-spars, formers, stringers and ribs. Once installed in the blade assembly fixture, the leading edge is drawn tight against aluminum sheets fastened to the jig frame on one side and ribs on the other. Stability is ensured by use of turnbuckles and a strap that is secured to the concrete floor.

Before any adjustment of the leading edge skin is attempted, each skin segment is aligned to chord lines marked on the jig and then boresighted adjustments are made as required and the first skin segment of the leading edge is trimmed and spliced together with the second skin segment, etc., until the leading edge is one complete assembly. D-spars and ribs are added and secured to the leading edge by Hi Loc fasteners. Formers over D-spars, and stringers on both sides of the leading edge and the formers, give additional support to the blade. Thick aluminum skins, varying from 3/16-inch just aft of the blade root to 3/64-inch at bladetip, are attached to the ribs which run the length of the blade. Except for the steel blade root fitting, all components are constructed of heat-treated 2024T3 aluminum.

All structural components are wet-sealed at assembly, and frequent inspections are made to ensure an airtight condition exists. Five hollow tubes, one in the apex of the leading edge at the blade root, one centered on ribs at the root segment; and three attached at the blade tip, permit weights to be added or removed to balance each set of blades. In addition, throughout the entire length of the blade (approximately every 22 inches) weighted tubes and solid bars are installed in the leading edge to maintain section and segment structural balance.

Strain gages, installed in the blade root and in the blade midsection, enable monitoring of flap bending, in-plane bending, and torsion moments during operation. The gages are epoxy-sealed and all wires secured to a terminal board and then, by clamps, to the ribs and blade root.

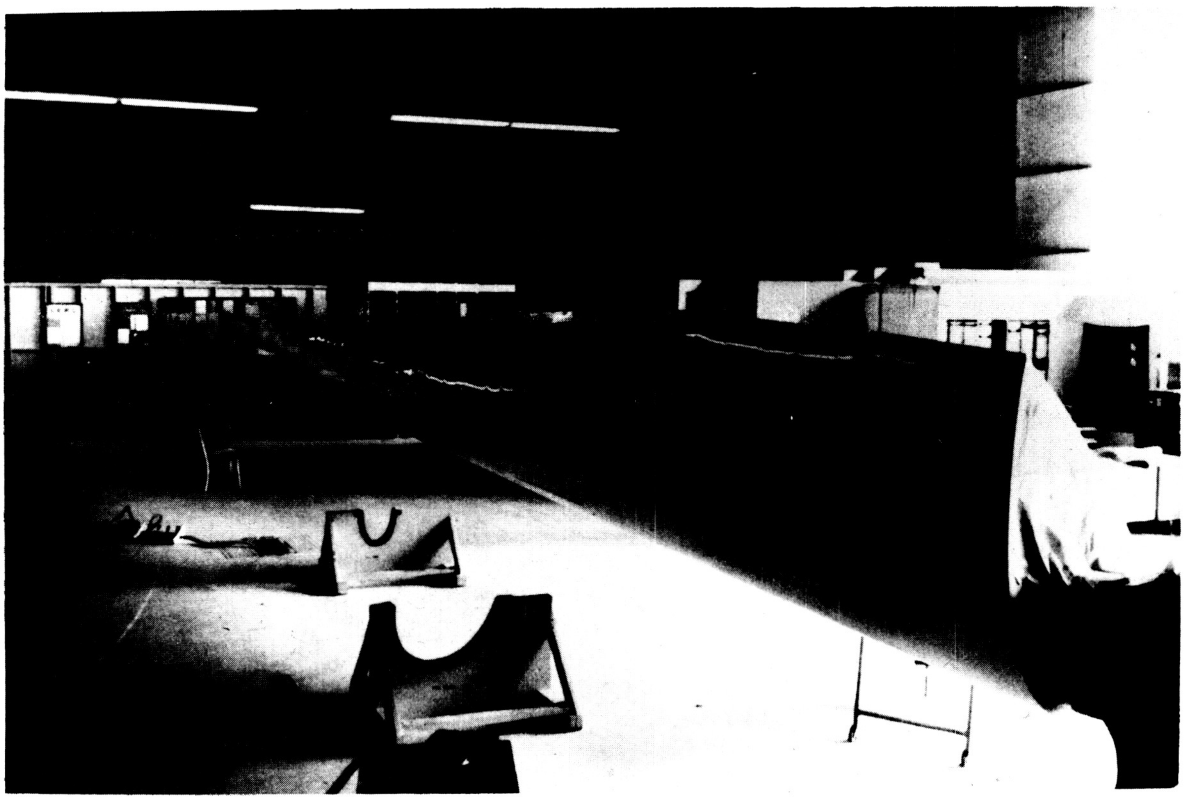
Each blade (see photo) was tested for (a) deflection and vibration, (b) weight and balance, (c) strain gage accuracy, and (d) X-rayed for defects. Each set of blades was given deflection and vibration, weight and balance, and symmetry checks.

MOD-O TEST/ANALYSIS EXPERIENCE

NASA LeRC selected a 100-kW WTG as being large enough to assess technology and solve engineering problems of large (1 - 3 megawatts) WTG's and yet maintain costs within the available project budget. The test program provides engineering data needed to determine whether the technology for wind energy can be used to create machines that will help meet the nation's energy needs at costs that are competitive with other systems.

Experimental test data have been correlated with analyses of turbine loads and complete system behavior of the ERDA-NASA 100 kW Mod-O wind turbine generator over a broad range of steady state conditions, as well as during transient conditions.

MOD-0A Turbine Blade - LAS Ontario, Calif.



The Lockheed California Company, designer and fabricator of the Mod-0 metal blades, was funded under Contract NAS 3-20036 by the NASA-Lewis Research Center to evaluate the test data and conduct structural analyses of the wind turbine rotor blade to provide:

Task I - Fatigue Analysis

Task II - Analysis of Wind Velocity Measurement Test Data

Task III - Correlation of Analytical with Actual Loads Data

Task IV - Potential Structural Blade Modification

Lockheed applied two different analytic computer programs to determine loads for correlation with measured data supplied by NASA: Lockheed's WINTUR (WINd TURbine) program, a quasi-steady fully-coupled analysis method (a brief description of the method is included in reference 3); and an adaptation of Lockheed's REXOR-WT (Revised and Extended rotOR-Wind Turbine) program.

Loads computed by the WINTUR program were used to calculate stresses used in the fatigue analysis, Task I. The test conditions for which correlation was shown were:

- 40 rpm and 100 kW
- 40 rpm and zero power
- 30 rpm and zero power
- 20 rpm and zero power
- Emergency feathering

MOD-O CONFIGURATION EFFECTS ON ROTOR BLADE LOADS

Three sequential configuration evolutions have resulted in the current Mod-O wind turbine. For each of the three configurations, the wind turbine was operationally tested in a similar wind environment. The purpose of the tests was primarily to compare rotor blade loads as a function of structural configuration, while attempting to maintain an identical wind environment.

- Configuration I - The wind turbine tower was configured with stairs and rails. A single yaw drive is installed between the tower and the nacelle as described in reference 1.
- Configuration II - The wind turbine tower stairs and rails are removed. The single yaw drive between the tower and nacelle is retained.
- Configuration III - The wind turbine tower stairs and rails are removed. A mechanical lock (yaw keeper) is installed between the nacelle and tower structure. The yaw keeper provides much higher torsional stiffness in yaw rotation than the single yaw drive. This was mechanically incorporated by design and installation of a dual yaw actuation drive combined with a brake system.

Synoptically, the results that these configuration changes achieved on the wind turbine blade root bending moments (measured at 40 inches from the shaft center line) are summarized on table 1.

TABLE 1. BLADE BENDING MOMENTS MEASURED DURING OPERATION IN CONFIGURATIONS I, II AND III COMPARED WITH THE DESIGN LOADS

MOD 0 OPERATIONAL CONFIGURATION	BLADE BENDING MOMENT (FT-LBS) AT STATION 40					
	FLAPWISE			INPLANE		
	PEAK TO PEAK	MEAN	CYCLIC	PEAK TO PEAK	MEAN	CYCLIC
Config. I	130,000	-65,000	±65,000	108,000	-18,000	±54,000
Config. II	70,000	-17,850	±35,000	102,850	-10,280	±51,420
Config. III	64,500	- 7,750	±32,250	80,000	-18,000	±40,000
Design	58,000	-23,400	±29,000	75,000	-11,200	±37,500

The supporting tests and correlations with analytical methods which lead to the understanding and solution of these engineering problems is the primary subject of reference 2. To facilitate a more detailed examination of the structural dynamics of the Mod-0 wind turbine system Appendix A has been included in reference 2 which provides basic Mod-0 geometry, mass and stiffness distributions, blade frequency spectra, and tower wake test results by NASA LeRC and Lockheed, also see references 3, 4 and 5.

The blade loading measurements taken for configurations I, II and III, presented in Table 1, were obtained with power loadings into a resistive load. Mod-0 synchronous operation with emphasis on the power/drive train dynamics is also reported in reference 2.

COMPARISON OF BLADE LOADS DURING OPERATION IN CONFIGURATION I, II AND III

The average peak to peak, mean and cyclic bending moments experienced during operation in configuration II were smaller than those measured during operation in configuration I. The results indicate that removal of the tower stairs and rails has a pronounced effect in reducing the flapwise bending moments in the rotor blades but little effect in reducing the inplane bending moments.

In comparing inplane blade bending moments for configuration II and III, the following observations are noted:

1. The average cyclic inplane bending moment was reduced by 22 percent during operation in configuration III.

2. The mean inplane bending moment increased by 75 percent during operation in configuration III.

The average peak to peak, mean and cyclic flapwise bending moments experienced during operation in configuration III are smaller than the loads measured during operation in configuration II.

The results indicate that by increasing the yaw stiffness of the structure between the nacelle and tower, the cyclic inplane blade bending moments can be significantly reduced. However, configuration III had little effect in reducing the cyclic flapwise blade bending moments, when compared to the blade loads encountered during operation in configuration II.

CONCLUSIONS AND RECOMMENDATIONS BASED ON MOD-O TEST/ANALYSIS

- Accurate prediction of blade loads, particularly at higher frequency, requires an accurate description of tower, nacelle, and drive train dynamics.

- Blade high frequency mode tuning can be significantly affected by the structural dynamics of the tower and nacelle. Chord bending must be monitored if nacelle yaw system characteristics are changed to assure that blade loads don't become excessive.

- Good agreement between calculated and measured loads was obtained in an analysis that included only two blade dynamic modes, first flap and first inplane, and a blade quasi-steady torsion mode.

- Operation of the WTG, in its present configuration, should avoid power and rpm combinations that result in generator-armature resonance.

- To eliminate the armature resonance problem, use of either an increased stiffness coupling or an across-coupler damper appears feasible. Further analyses would aid in making a choice and are required to ensure an adequate design.

MOD-OA DESIGN CRITERIA AND LOADS

Strength and stiffness criteria were developed by NASA. Although the adequacy of these criteria to define ultimate strength has been shown to some degree during operation of the Mod-O wind generator, the Mod-OA is located at a different site, in a different environment, probably will be operated by personnel who have no experience with the Mod-0 unit, and is intended to be operated for long periods of time, continuously integrated into an electrical power supply (varying loading). The Mod-0A unit will test the fatigue endurance of a wind turbine of this type long before comparable data are accumulated on the Mod-0 unit. It is expected, however, that ultimate strength and stiffness criteria as applied to the Mod-0A unit are probably adequate. The major concern is the assurance of longevity under the total operating environment.

Differences in structural design between the Mod-0 and Mod-0A wind turbine blades were simply the result of recommendations made by Lockheed during an analytical appraisal of Mod-0 operational load measurements in the interest of increasing longevity and the results of recommendations of a NASA safety group. In the interest of expediency, all recommendations were not followed in the final design of the Mod-0A blade structure. For example, the skin thickness was reduced to comply with an existing manufacturing capability, and a cable-type blade retention system (which has been recommended by the NASA safety group) was deleted for expediency of cost/schedule.

The structural integrity of the Mod-0 wind turbine blades is based on the four loading cases stipulated by Contract No. NAS3-19235. Airload distributions for each case were specified. However, it is conceivable that structural design criteria do not properly account for terrain or climatic differences from the Plumbrook site (site-specific criteria) nor, large fluctuations of loads which might occur as the result of being electrically tied into a power system different from the one the Mod-0 unit has been tied to.

Design of Mod-0A blades was based on loads distributions for the four specified cases plus the upgrading recommendations. Recommended changes which were directed at the Mod-0 design, assumed 50,000 hours of use at 40 rpm generating 100 kW in a 26 mph wind and that flow through the tower can be completely blocked (e.g., after a severe ice storm). These recommendations were used to aid the design of the Mod-0A blades. New design loads were calculated for the four cases and were adjusted to reflect data which was measured on the Mod-0 unit.

MOD-OA FATIGUE

Fatigue life prediction entails many uncertainties. For example there are many situations that might cause the blade loads spectrum to exceed that which was established for design; and untested structural details can cause concern regarding blade life prediction even under known load conditions.

The curve of figure 2 is the result of a fatigue analysis, reference 7, made for the Mod-OA blade structure. The analysis assumed:

- Blade station 637.5 is probably most critical.
- Airload distributions which had been specified for the Mod-0 blades apply to the Mod-OA.
- Allowable stresses have a 99% probability of occurring.
- The wind turbine will operate at speeds up to the cut-off wind speed for 50% of the time.
- The quality of structure (design and manufacture) is comparable to that of an airplane wing; i.e., stress concentrations exist at some local structural details.

The prediction precludes effects of fretting, corrosion, or other unpredictable damage. The figure shows that a life of 30 years is attainable with a cut-off wind speed of 41 mph (initially specified as 26 mph). However, even when a high quality is sought in a development unit it is possible that a lesser quality will exist at some local details.

Results of the fatigue analysis were also plotted (figure 3) to show what might be expected if:

- loads or stresses are different from those calculated.
- the quality of the structure is different from expected.

Interpretation of figure 3 introduces the need to define two symbols which are common to fatigue analysis, S/S_o and K_T. S represents stress, and the subscript, o, merely signifies "original"; so $S/S_o = 1.0$ represents the values used in the analysis whereas a ratio above 1.0 would indicate that actual stresses will be greater than those used in the analysis. The K_T value is a measure of the quality of the structure; it reflects holes, scratches, cut-outs, etc. A value of $K_T = 4.5$ is representative of the quality of aircraft structure generally sought during design, but as implied earlier, it's not unusual for K_T values to be as high as 6 or 7 at some structural details.

It's noteworthy from both figures (2 and 3) that a change of a few mph of cut-off wind speed, or a small change in either K_T or S/S_o, can mean a change of very many years of life. Had cost/schedule permitted, tests of structural details could have significantly reduced the uncertainty of fatigue life prediction.

INSPECTIONS

It must be realistically assumed that cracks, corrosion, and fretting will appear during the operation of any new engineering equipment. Even in aircraft, where structural analyses are usually backed by many tests, the most damaging fatigue loading on an aircraft wing structure occurs during the takeoff-fly-land cycle, which on a high-time commercial airplane might occur around 100,000 times. A helicopter rotor blade has a finite replacement life of 2000 hours and is generally subjected to load cycles of the order of 20,000 per hour. The wind turbine blades, which are expected to operate for 30 years, will experience millions of cycles (approximately 12 million cycles/year).

The high number of load cycles per unit time is of concern with respect to rates of crack propagation. If a small crack exists due to a material flaw or a seemingly inconsequential scratch or crack, the high frequency of load reversals can cause the crack to grow rapidly to a critical size. To circumvent this possibility most of the structure was designed to be fail safe, i.e., consisting of multiple elements. However, fail safety requires that growing damage be found before it grows to a critical length. Thus, regular inspections are necessary.

The flange root tubular steel fitting and the hub structure are monolithic (not fail safe).

The wind turbine is expected to be in service (operating) about 50 percent of the time, and will be out of service (but possibly in a violent environment) the rest of the time.

Fretting is known to accompany a high frequency of load reversals, so appropriate inspections must be established to permit early detection of cracks due to fretting.

The installation is subject to exposure to weather which can become a corrosion problem. The recommended inspection interval must also take this phenomenon into account.

INSPECTION PERIODS

Start inspections after the first 500 hours of operation. All inspections which are recommended for the root area and basic blade should be performed every 500 hours of operation (10^6 cycles). After five inspections without cracks, severe corrosion, or fretting, increase the inspection period to 1000 hours. After five inspections beyond the 1000 hour period, a further extension should be considered. A careful review of the loads experience, inspection reports, and other pertinent results should be made before extending the inspection period.

X-ray the entire blade once per year.

It is important to derive similar inspection periods for hardware other than the blade.

It is difficult to establish an inspection interval for fretting and corrosion because there exists no experience with wind turbines on which to base such an interval; except the NASA experimental operations with the Mod-0 wind turbine. It would be expected that the inspection interval will increase as operating experience accrues.

MOD-OA 200 kW OPERATIONAL EXPERIENCE

The MOD-OA wind turbine entered service January 1978 in Clayton, N.M., following several years of development by NASA-Lewis on a similar machine, the MOD-O (of the same external geometry as the MOD-OA), at Plum Brook, Ohio.

Operating loads were monitored continuously during the first three months of operation. There was no indication that operating limits would ever be exceeded, so the monitoring operation was relaxed. The new monitoring procedure was to record and erase at 45-minute intervals (of operation) and to examine operating loads occasionally.

At some time following initial checkout, structural damage did accrue. An automatic shutdown device did not prevent high loads. The first sign of difficulty was a discoloration of some fasteners; rivets began to loosen; and a crack in the skin was found. Because excessive loads were not at first apparent, the initial assumption was that faulty workmanship during blade manufacture caused the structural damage. However, reexamination of some records showed that loads in excess of operating limits were encountered. They occurred during nacelle yawing and, according to NASA sources, the total time spent in nacelle yawing during the lightly monitored 3-month period was 58 hours, reference 12.

These excessive loads could have caused the damage; however, it's probable that other loads, as high or even higher, were encountered at some time when no record was made. This documented situation indicates that the design of the blade structure is very forgiving; even though operating limits were exceeded, damage was minimal and repairable.

Prior experience on the MOD-O and subsequent investigations of the MOD-OA system strongly suggest that these loadings were caused by massive yaw stiffness degradation that led to a 2P resonance of the nacelle/tower system in the yaw axis. This is thought to have occurred only during nacelle yawing operation.

MOD-OA MEASURED BLADE LOADS

Results of an analysis of the data of reference 8 (NASA PIR 44), the variation of cyclic and mean flapwise and chordwise bending moment at Blade Sta 40 with wind speed, are superimposed on the graphs of reference 9 (NASA PIR 58) in figures 4, 5, 6, and 7. There is approximate agreement of most of the data, especially mean bending moments, where the data of PIR 58 are believed to be for normal operation. The cyclic flapping bending moments, however, are significantly larger and the chordwise loads somewhat larger than reached earlier. (Data are from tests at Clayton, New Mexico.)

Lockheed's calculated blade loads are shown in figures 4, 5, 6, and 7. These were calculated for steady winds with zero yaw. The steady wind loads represent average loads (0σ) presuming that positive and negative gusts and yaw errors do not affect the average. These loads were used for structural evaluation of the MOD-OA wind turbine blades.

3σ curves were predicted by assuming 30° yaw error and gusts. With mean and 3σ curves available, the 2σ curve is approximated for a Gaussian distribution and compared with measured data for high winds (PIR 44). The low wind speed 2σ curve is obtained, similarly, by extrapolating the data of PIR 58 from 0σ (mean) and 1σ to 2σ.

An interesting note is that the variations of flapwise and chordwise loads that were calculated based on a stiff yaw system were slightly conservative when compared with the loads recorded during the high winds of January 7, 1978 (PIR 44). This does not necessarily mean that safe loads were not exceeded, however, since the variations shown above were used for blade evaluation only to the cutoff wind speed (40 mph). Loads due to higher wind speeds were not considered in the fatigue spectrum since no such loadings (in routine service) were expected, reference 11.

The 2σ loads are shown for comparative purposes only. In defining the fatigue load spectrum, all levels of loads must be considered.

LOADS DUE TO DEGRADED YAW SYSTEM OPERATION

The magnitudes of the loads measured indicate that the system suffered deterioration prior to May 18, 1978. Furthermore, the postulation that at least part of this behavior was due to nacelle yaw stiffness deterioration appears to be correct by reference to the wave form of the inplane Blade Sta 40 bending moment history shown in figure 8. It displays a dominant 3P harmonic that has been seen, in the analyses of reference 10, only with a tower of low torsional and lateral bending stiffness.

The chordwise and flapwise bending moment histories calculated for Case 2 of reference 10 are also shown in figure 8. Aside from chordwise oscillation amplitudes being about half those of the Clayton data of 5/18/78, they agree very closely in wave form. The flapping bending moment also shows good agreement, even in magnitude, with that measured.

In Case 2 of reference 10, a MOD-0 tower with an arbitrarily low stiffness in lateral bending and torsion was employed. A review of the data showed tower resonance at about 1.4 Hz or approximately at 2P. The 3P blade inplane bending oscillation appears to be due to the tower 2P resonance. In the case of the MOD-OA system, this would roughly be equivalent to operating with yaw drive stiffness somewhat less than occurs with a single-drive unit (or approximately a 90 percent stiffness reduction). But here the agreement between the two situations ends. In Case 2, the blade inplane cantilever frequency was 3.80P (in MOD-OA it is supposed to be 4.80P) the wind speed was 40 mph (instead of the reported 25 mph) and the tower shadow employed in Case 2 was that with the stairs in (instead of the much lower MOD-OA tower shadow). The power output at the shaft was 133 kW instead of the 242 kW of MOD-OA.

Since the measured flapping loads would agree much better with calculated loads at a higher wind speed, the wind speed during the loads measurement may be in error.

STRUCTURAL REPAIR OF CLAYTON, N.M. BLADES (004 AND 005) AND SERIAL UPGRADE OF MOD-OA PRODUCTION BLADES

Mod-OA blades 004 and 005 were taken to NASA Lewis Research Center, Cleveland, Ohio, in June 1978 after approximately 1200 hours of service at Clayton, New Mexico. The complete blade was inspected for structural defects using nondestructive testing methods. The steel root fitting was removed and the root end of the blade inspected further. The damage found (after 2.8 million rotations) was localized between stations 48 and 125. The blade span is

750 inches with the first rib located at Sta 48. This work was supported by Lockheed both at Clayton, N.M. and Cleveland, Ohio. Following inspection, preliminary designs were made of reinforcement doublers for repair of the distressed areas. Fretting of the rib interface at Sta 48 was also found and various conceptual designs were examined by Lockheed and NASA engineers, but resolution of this subject presently is dependent on development testing in the NASA laboratories.

The NASA modifications were installed at Cleveland on blades 004 and 005. Similar designs are documented on Lockheed Drawings 1900031 and 1900032 to provide Lockheed Aircraft Service Company, Ontario, California, the means to incorporate these modifications into the current production blades 008 and 009. The root details at the rib station 48 will be supplied by NASA Lewis Research Center directly to LAS upon completion of their laboratory test program. It is expected that the additional blades 010 and 011 will be similarly modified during assembly and that blades 006 and 007 will eventually be retrofitted to this same configuration.

The rationale for the incorporation of the repair modifications into production blades is that hot spots have been identified by the abnormally high loadings. These loadings can be considered as an accelerated fatigue test that has pointed out areas in which increased loads margins can provide added protection.

Since blades 004 and 005 structural repairs were made on an inspect-and-repair-as-necessary basis rather than through an ongoing analysis/design effort, it is recommended that the operational limitations recommended in LR 28395, 10 January 1978, for continuous loads monitoring and frequency of inspections be followed.

Other MOD-OA blades that are modified in the same manner as 004 and 005 should also adhere to the operating limitations recommended in LR 28395.

OPERATION OF MOD-O BLADE AT CLAYTON, N.M. DURING STRUCTURAL REPAIR OF MOD-OA BLADES

The MOD-O blades were installed on the Clayton, N.M. wind turbine in June 1978 as an interim means to continue operation of the system. The 200 kW capability of the wind turbine was retained even though these blades were designed for the 100 kW experimental unit and had been through the early development phases of wind tower shadow, emergency feather and nacelle/tower yaw stiffness. Following approximately 800 hours of this added service and return of the repaired MOD-OA blades these MOD-O blades were returned to Cleveland, Ohio for inspection and overhaul. The fretting at rib station 48 was at this time quite measurable by feeler gage. The shell structure, as in the case of the MOD-OA blades outboard of station 100 to the tip station 750, was in excellent condition. Upon removal of the steel root-end fitting it was found that the rib at station 81 was cracked in several locations and that the safety attachment between the steel tube and the blade web had some elongated holes. This indicates that centrifugal loads were being partially carried by this backup load path. Although the fretting might be cured by elastomeric bearing or aluminum bronze bushing applications, it seemed the rib replacement repairs at blade station 81 warranted a more direct method consistent with tooling requirements. Therefore, the repair method proposed addresses the repair, fretting and tooling as one problem. The proposed modification to the MOD-O blades as shown on figure 9 and figure 10 has been adapted and will be implemented in the near future.

CONCLUSIONS

The MOD-OA wind turbine which entered service in January 1978 in Clayton, N.M. was found to be damaged locally between stations 48 and 125 after 2.8 million rotations. Loads due to degraded yaw stiffness and fretting at rib station 48 were the factors which have been identified as primary to this distress. The repaired blades have now operated an additional 2000 hours (4.8 million rotations) without further problem.

It is noteworthy that the fatigue analysis predicts that station 637.5 is the most critical and these sections have 7.6 million rotation cycles.

The shell structure of the MOD-OA and MOD-0 blades outboard of station 125 are both in excellent condition. The latter unit now has a total of 1300 hours (3.1 million rotations).

The correlation between test and analysis has been good and currently no unexplained problem areas exist.

Refinement of the emergency or safety shutdown feathering rates and procedures are desirable to minimize the large load transients which can occur.

Since this aluminum blade structure has been shown to be forgiving, the primary focus of additional safety features should be the monolithic hub which might lend itself to the cable-type retention previously mentioned as a NASA safety group consideration.

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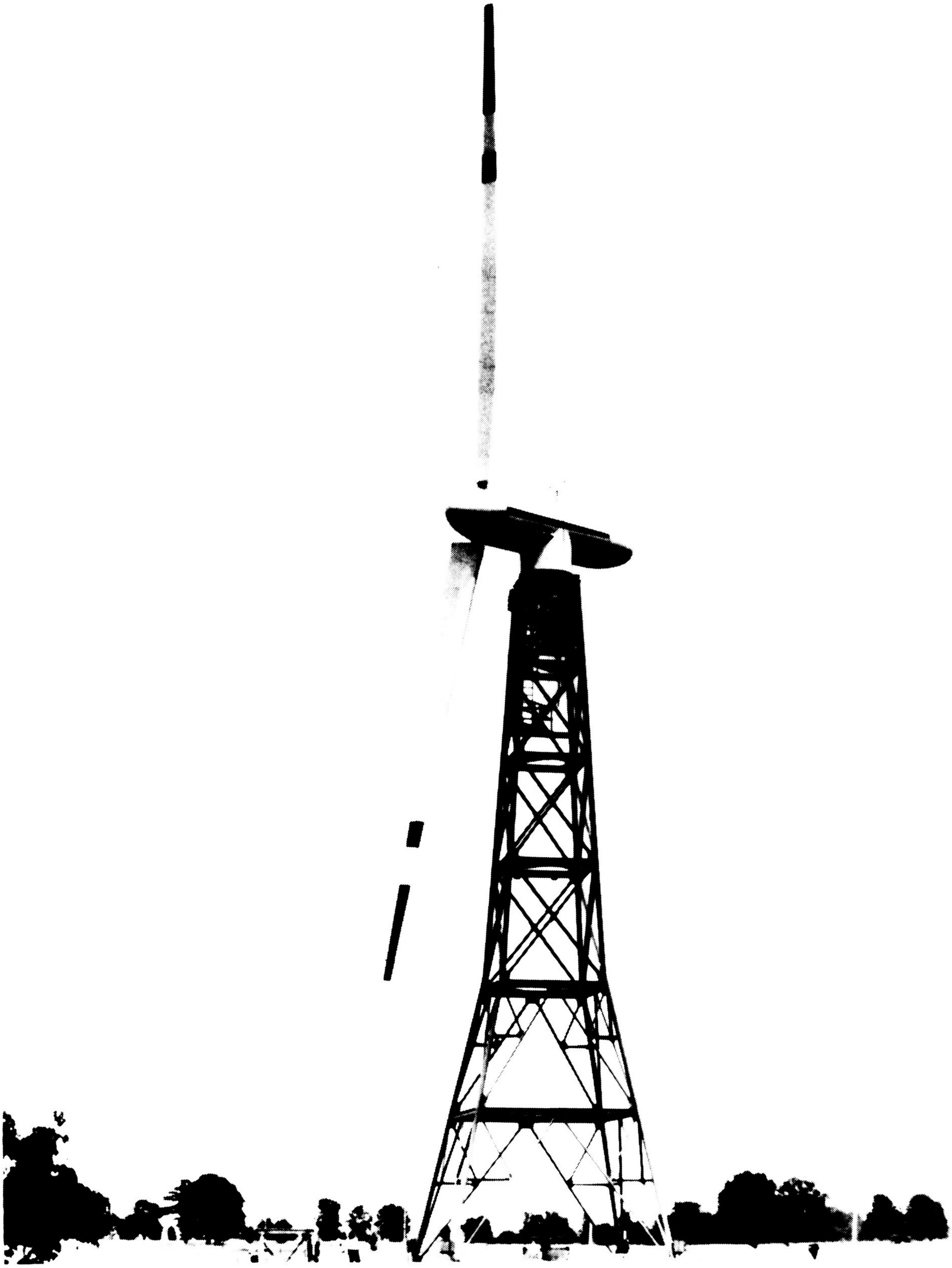

Figure 1. Mod-0 Wind Turbine - Current Configuration (Mod-0 and Mod-0A) Without Stairs or Rails.

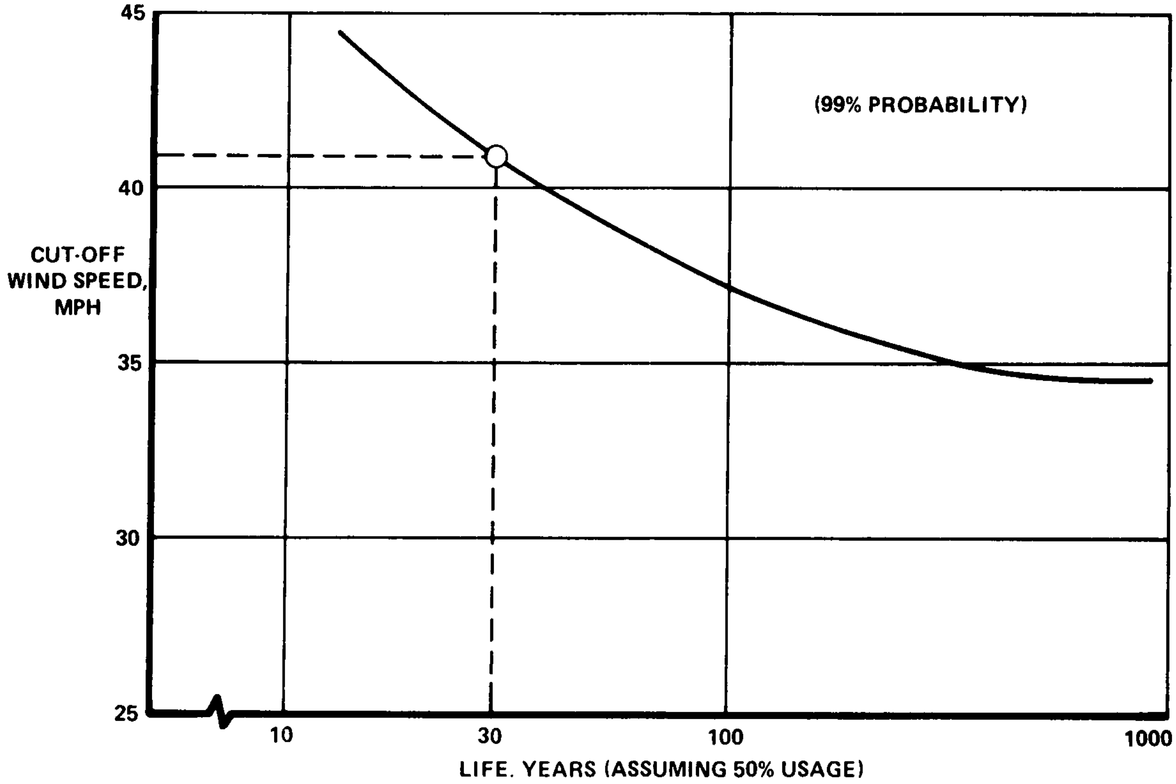

Figure 2. Result or Fatigue Analysis of Mod-OA Blade (at Station 637.5) Assuming Structure Quality Comparable to that of a Typical Airplane Wing Structure.

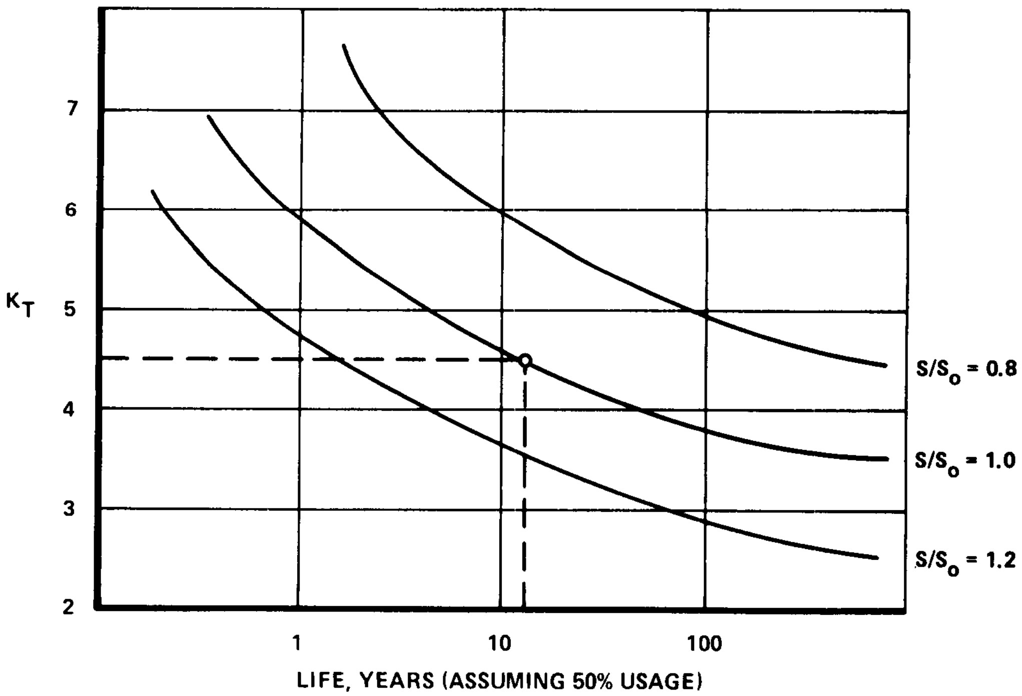

Figure 3. Result of Fatigue Analysis of Mod-OA Blade (at Station 637.5) Indicating What Might Happen to Life as S/S_o and K_T Vary.

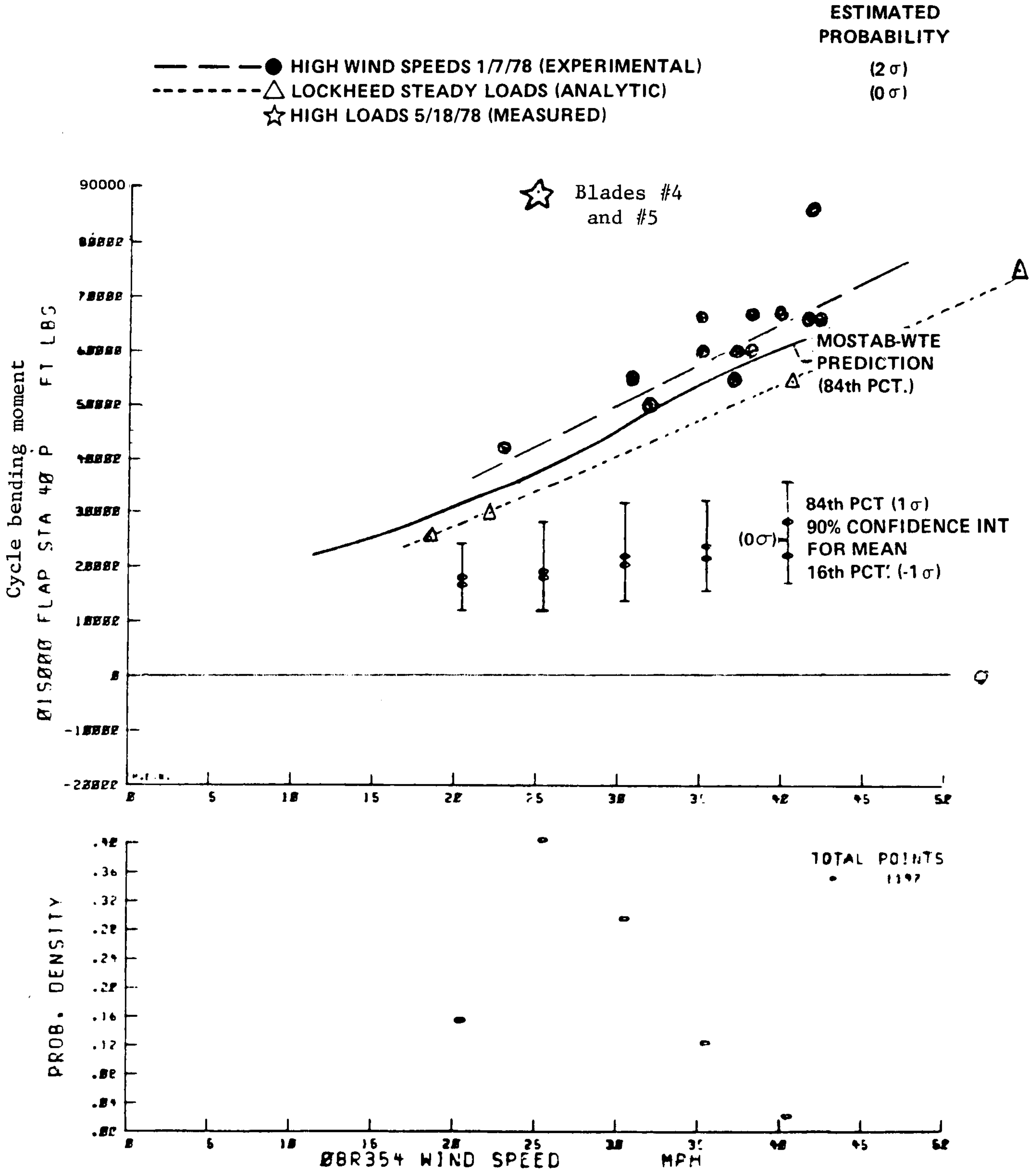

Figure 4. Cyclic Flapwise Moment at Sta 40.

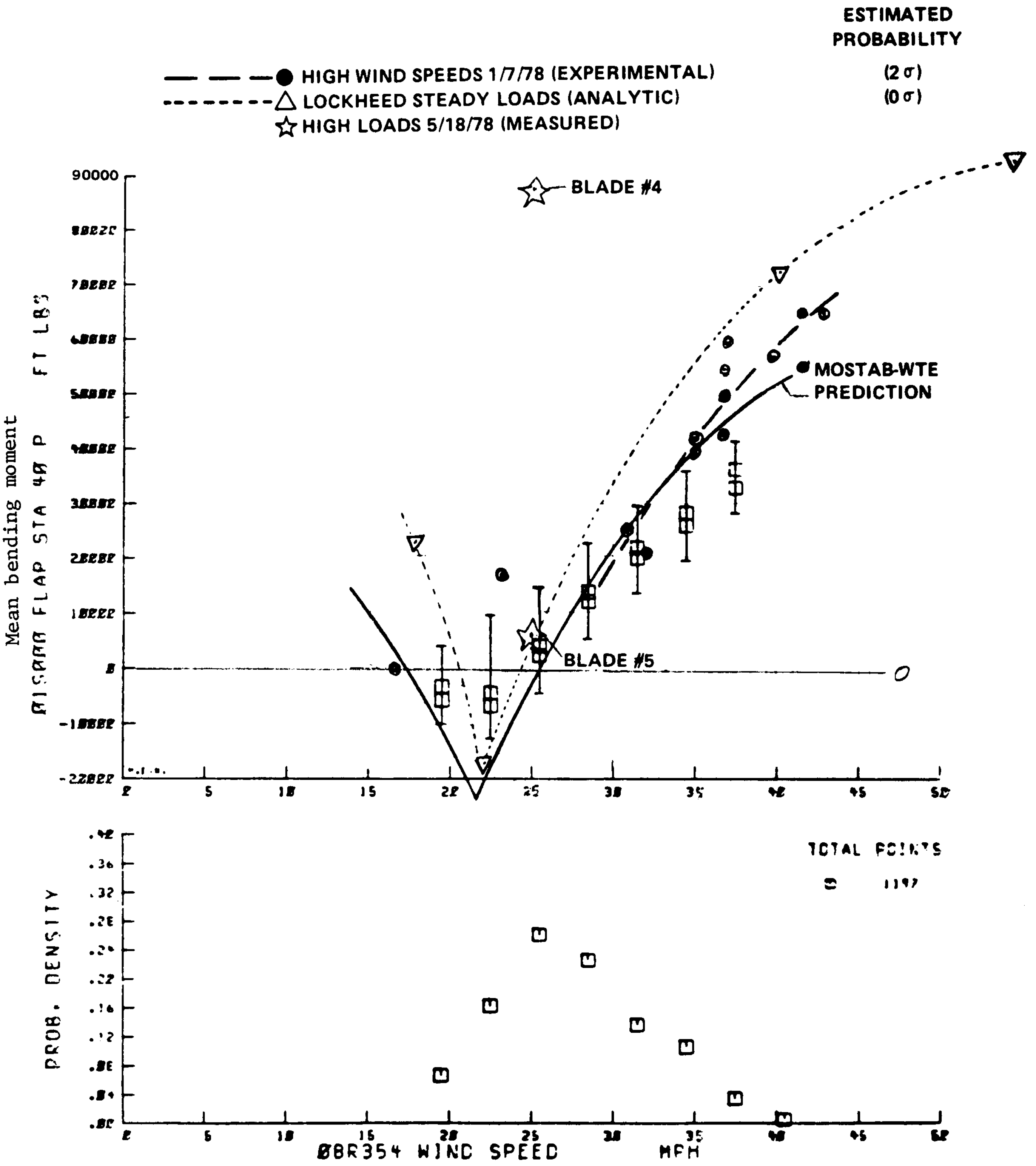

Figure 5. Mean Flapwise Bending at Sta 40.

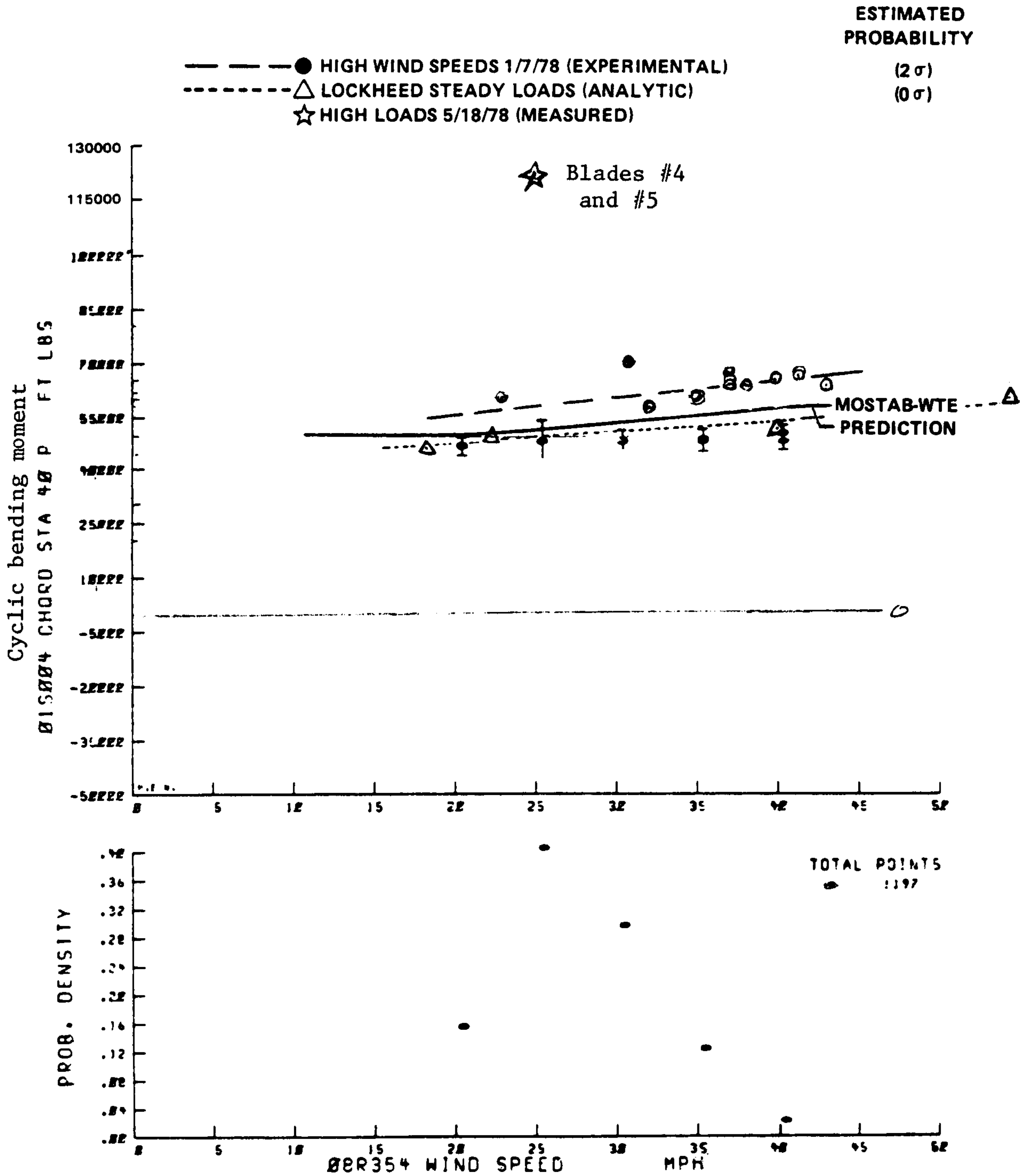

Figure 6. Cyclic Chordwise moment at Sta 40.

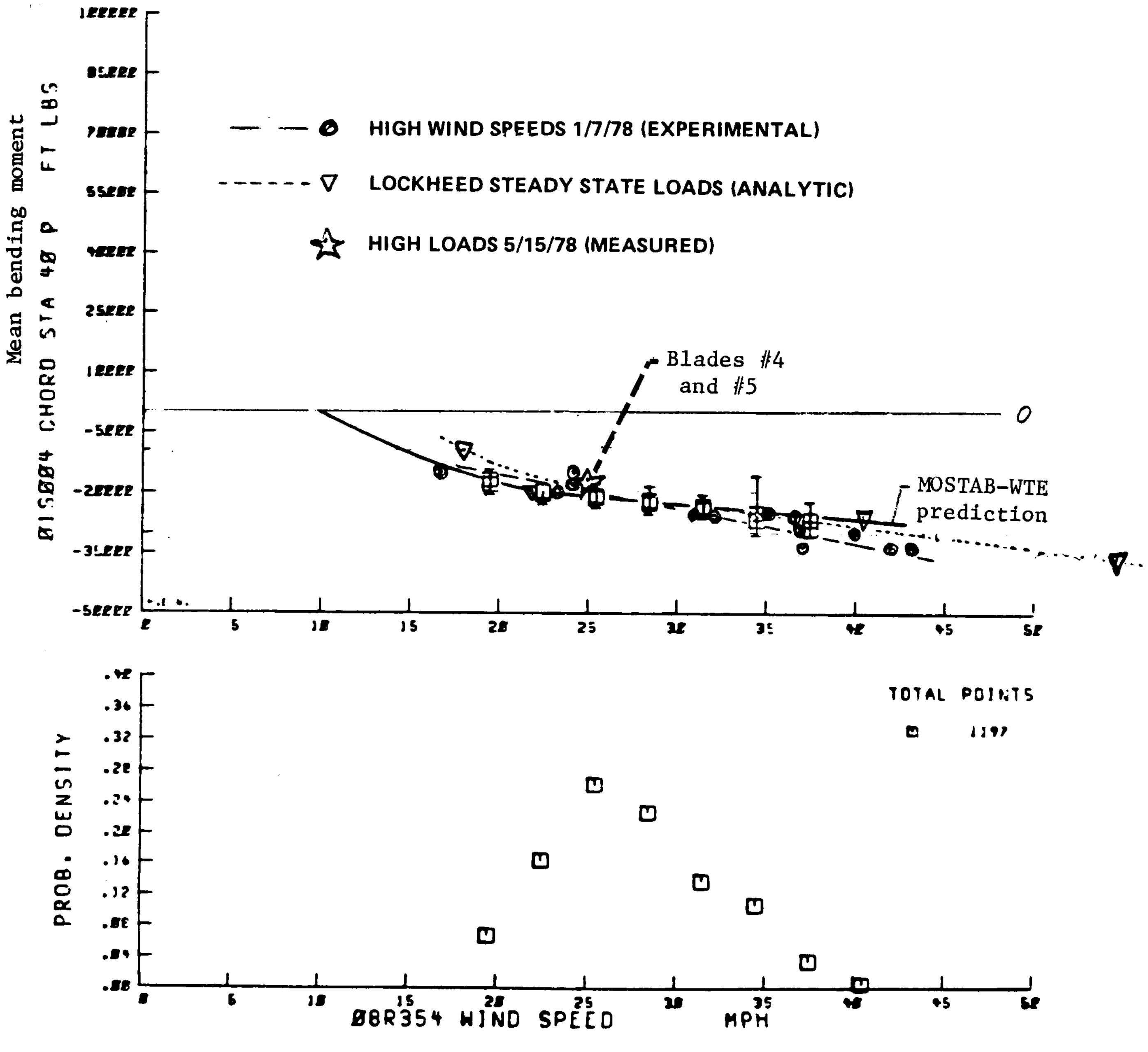

Figure 7. Mean Chordwise Bending at Sta 40.

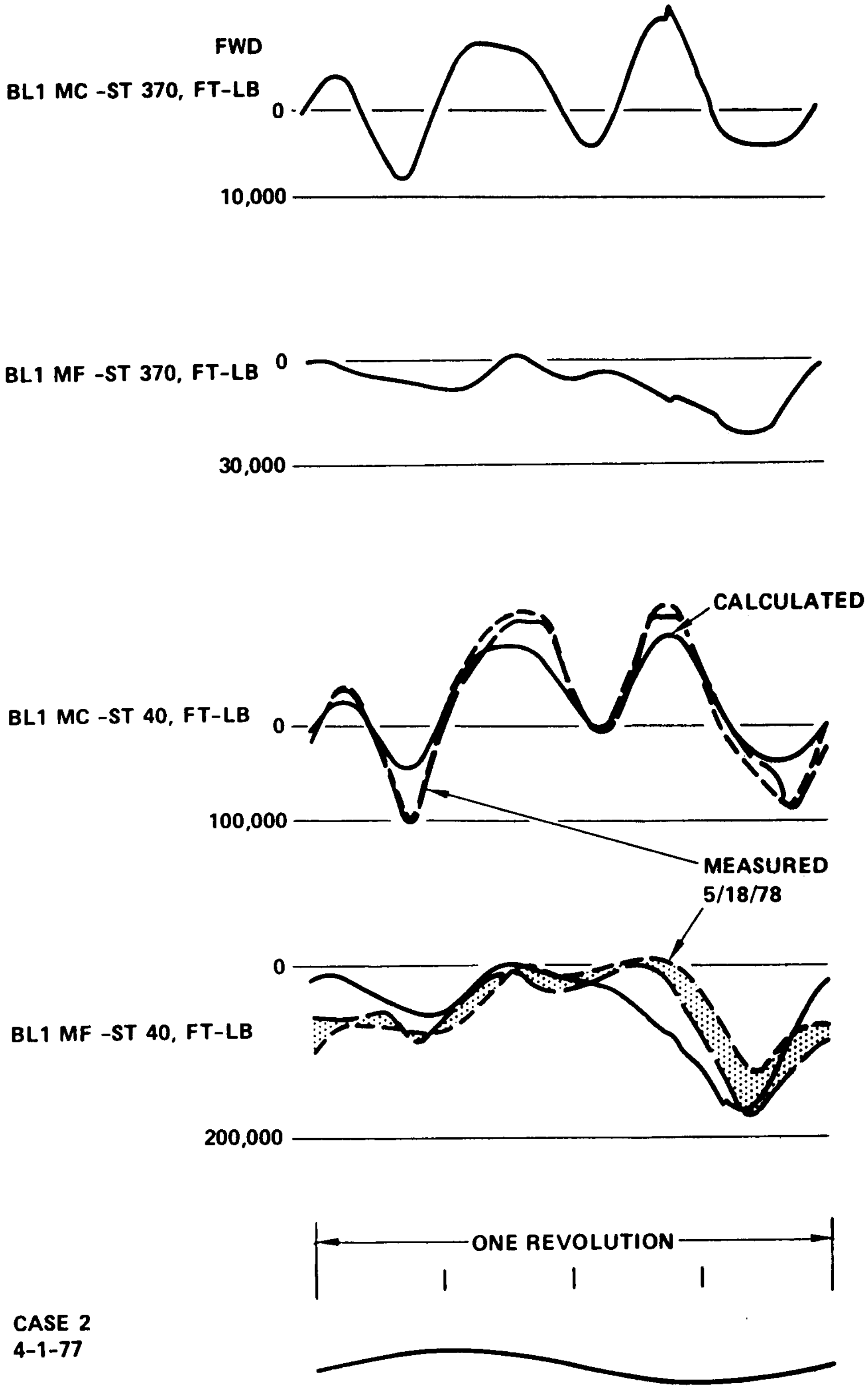

Figure 8. Calculated and Measured Blade Loads With Reduced Tower Stiffness.

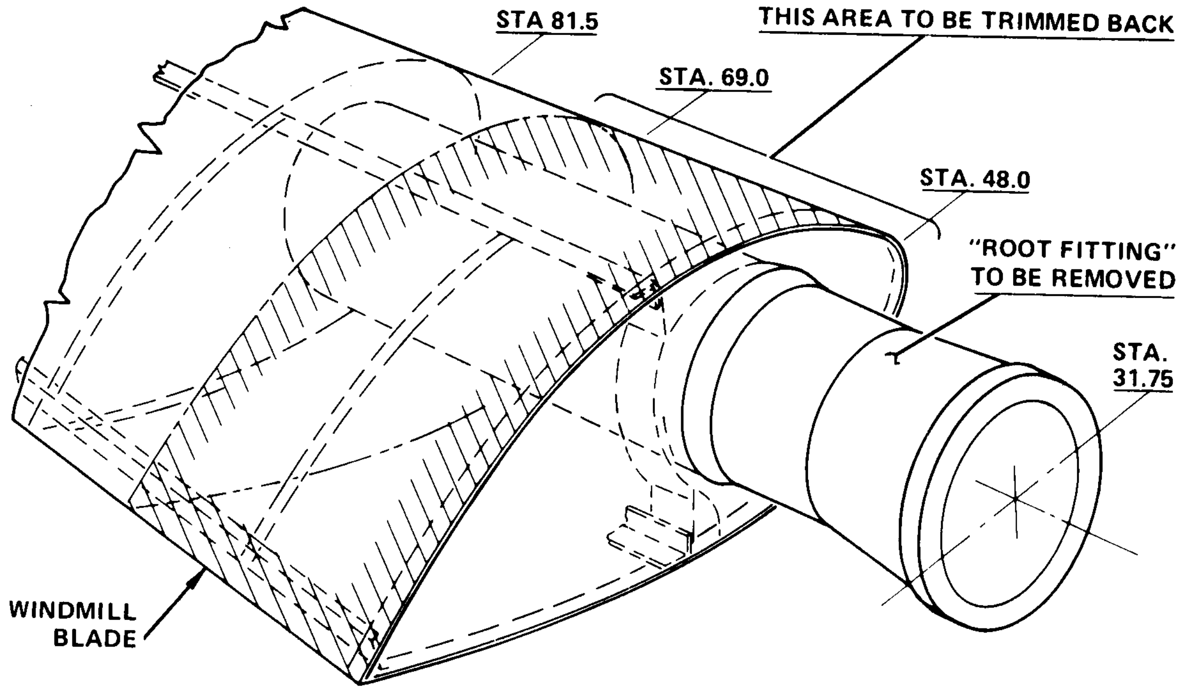

Figure 9. Blade Root End Before Modification (Existing).

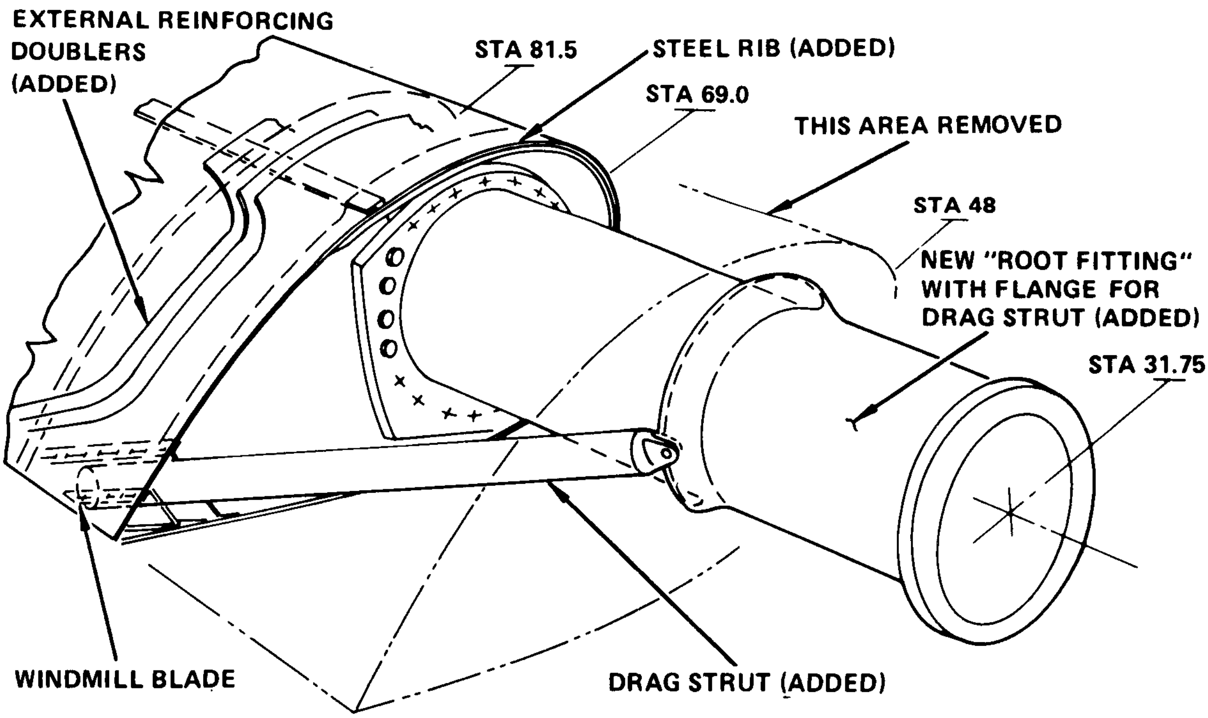

Figure 10. Blade Root End After Modification.