LARGE, LOW COST COMPOSITE WIND TURBINE BLADES

Herbert W. Gewehr
Kaman Aerospace Corporation
Bloomfield, Connecticut 06002

INTRODUCTION

Various studies have shown that the cost of energy decreases with increasing rotor size in Wind Turbine Generator systems, and that the cost of the rotor is a major contributor to initial procurement and annual operating costs (References 1 and 2). In an effort to reduce rotor cost, NASA Lewis Research Center, with Department of Energy funding, initiated a program to develop a large, low cost wind turbine blade representative of a design for a 300 ft-diameter wind generator system. This paper describes the design, analysis, and test results of that program, and its extension to the follow-on program, fabrication of two composite blades for the Mod-1 200 ft-diameter wind turbine. Structural Composites Industries, Inc., Azusa, California, fabricated the spar for the 150 ft blade.

150 FT BLADE

Since the primary objective was fabrication of a large, low cost blade, the task was approached from the standpoint of selecting a commercially available low cost process and adapting the design to it. Among the several processes considered, including both metal and composite constructions, Kaman selected a composite design which employed a new application of a commercially available glass fiber material, recommended by SCI, which we named Transverse Filament Tape (TFT). TFT is a woven roving E-glass tape having all of its structural fibers oriented across the tape width. Use of TFT in the manufacturing process for the spar involved winding TFT onto a mandrel, with overlap, and simultaneously overwinding a layer of continuous filament rovings for compaction. Ninety percent of the material deposited was TFT, oriented along the spanwise axis of the spar. The overwound rovings (hoops) comprised the other 10 percent of material. Patent applications have been filed for certain aspects of this TFT process.

Special emphasis was placed on matching the design to the structural properties obtainable from the process, taking into account the anticipated commercial quality of the TFT laminate. Refinement of the process to typical aerospace standards was deliberately avoided. Determination of the material properties and structural capabilities of TFT were primary considerations in the 150 ft blade design and analysis effort.

Design Description

Figure 1 illustrates the blade configuration which is essentially that originally proposed by Kaman and reported earlier as a design concept (Reference 3). Figure 2 illustrates the completed blade positioned for static tests.

Primary components are the TFT wound E-glass/epoxy spar, an E-glass/polyester trailing edge spline made from pultrusions, sandwich panels constructed of resin impregnated kraft paper honeycomb faced with glass cloth/epoxy skins, and a steel hub adapter. These components are joined by epoxy bonding, except for the hub adapter, which is mechanically fastened to the spar and spline. The total blade weight was 36,000 pounds; 23,000 pounds of composite structure and 13,000 pounds of steel adapter and hardware.

The spar is a D-shaped monocoque shell, tapered in planform, depth, and wall thickness to achieve desired bending stiffness, mass distribution, and aerodynamic shape. It has a 15 degree linear twist and is about six feet wide by four feet deep at the root, and two feet wide by seven inches deep at the tip. The wide spar at the root provides stiffness for edgewise tuning of natural frequency without requiring an excessively large trailing edge spline. The spar tip is narrowed to reduce outboard blade weight for flatwise tuning.

Spar wall thickness is 1.5 inches from root to midspan, and it tapers down to one inch at the tip. The nominal wall thickness is measured at the corners of the aft web, where laminate compaction is greatest. Thicker spar walls are evident where compaction is less.

Local reinforcement is provided at the inboard end of the spar for about three feet, by interleaving between courses of TFT a woven roving having a ± 45 degree bias orientation. This produces a four inch wall thickness of more nearly isotropic properties where the steel hub adapter is bolted to the composite spar.

Ten afterbody panels, five upper and five lower, are honeycomb sandwich construction of kraft paper core and glass skins. The panels range in length from 15 to 30 feet, and in weight from 144 to 433 pounds. Panel thickness varies from six inches at the root to two inches at the tip. Outer skins are two plies of 1583 glass cloth and inner skins are one ply. Local reinforcement is added at panel edges for attachment to adjacent structure. The 3/8-inch core is phenolic resin impregnated, and weighs 2.3 pounds per cubic foot. Sizing of panel thickness was dictated by the requirement to carry afterbody airloads and to stabilize the trailing edge spline under edgewise bending loads.

The trailing edge spline was fabricated by laminating E-glass/polyester pultruded planks with epoxy adhesive, and shaping to the desired contour. Steel cheek plates were bonded and bolted to the inboard end of the spline to transmit axial loads to the root end truss. The spline extends from the root to mid-span. A trailing edge closure of glass cloth extends from midspan to the blade tip.

The composite subassemblies were joined by bonding with room-temperature curing paste epoxy adhesives. 35 psi bonding pressure was applied by pneumatic hoses retained in a steel framework. Prefabricated T-clips were fitted and bonded between the spar aft wall and the afterbody panel inner skins to improve the structural effectiveness of the panel inner skins.

Syntactic foam adhesive was injected into the cavity between the spar and the afterbody panel core to provide a shear connection between the afterbody panel and the spar.

The hub adapter was attached to the spar by 18 five-inch tapered bushings inserted into carefully machined holes in the composite. Each bushing was held in place with a three inch-diameter stud torqued to achieve a 400,000 pound preload which prevents the bushing from unseating on its loaded side. All machining cuts for each hole were made from a single setup at that hole, to achieve the alignment and squareness tolerances required for uniform load distribution in the composite.

Design Loads

Design of the 150 ft blade was based upon a downwind, 16 rpm rotor, and operating cases specified by NASA which provide representative critical conditions for the structure. The six cases are briefly identified as:

1. Rated power (1800 kW), rated wind (18 mph)
2. Increasing gust, 18 mph to 60 mph, plus 25 percent overspeed
3. Emergency feather in 11 seconds
4. Decreasing gust, 18 mph to zero mph
5. Hurricane wind (120 mph), non-rotating
6. Maximum yaw rate (2 deg/sec) at 50 mph wind velocity

(Wind velocities are at 30 ft reference height.)

Analysis of the five rotating cases revealed that Case 2 produced the highest fatigue loads for the spar. Although Case 2 was projected to occur only infrequently, Kaman conservatively considered Case 2 to occur continuously for design purposes, primarily because little is known about the frequency of occurrence of fatigue-producing loads in wind turbine systems operating for a number of years. Case 2, therefore, became the design driver for 30 year life requirements. Fatigue stresses in the spar associated with Case 2 loads were maintained below the estimated endurance limit of the composite material.

Case 2 was critical for both fatigue and static loads in the trailing edge outboard of Blade Station 18. Inboard of Station 18, Case 2 is critical for fatigue, and Case 6 is critical for static loads in the trailing edge spline and its attachment to the root end truss.

Case 5 produced the highest static loads in the spar, and was selected for static strength and buckling criteria. Case 5 loads were based on the conclusion that maximum aerodynamic force normal to the blade chord would be generated at the blade tip while the blades were feathered and parked horizontally. Although feathered, maximum force can be generated on the blade with only a 12 degree change in wind direction from the zero lift condition; therefore, the blade was designed for the maximum force case. The critical orientation for Case 5 loads was a downward-acting force combined with gravity, which put the lower (flat) surface of the blade into compression.

Afterbody panels and their attachments to the spar and trailing edge were designed to Case 5 airloads, plus loads imposed by spar deflections.

Material Allowables

Transverse Filament Tape (TFT) has been used for many years in the manufacture of commercial, filament wound pipe. Small quantities (about 10 percent) have been added to pipe to improve axial strength and bending stiffness. In wind turbine blades, the percentage of TFT is much greater than in pipe; TFT comprises approximately 90 percent of the spar to provide much greater bending strength and stiffness. As a consequence of this primary structural duty, laminate characterization tests were conducted to provide material allowables for design.

Static characterizations were obtained via small specimen tests of TFT laminates. Thin laminates were laid up in the laboratory for tests at room temperature and 160°F, under both wet and dry conditions. Laminates having 20% and 35% resin content were tested. Hot-wet specimens were heat-soaked at 160°F and 95 percent relative humidity for 500 to 1000 hours before being tested within 15 minutes after removal from the environmental chamber.

Static properties obtained for 35 percent resin content, under the 160°F, wet conditions are shown below, along with the values used for design allowables derived from the hot-wet tests:

	160°F, WET	DESIGN ALLOWABLES
Ultimate tensile strength, ksi	52.7	33.7
Tensile modulus, 10^6 psi	5.4	5.4
Ultimate compressive strength, ksi	44.2	41.4
Compressive modulus, 10^6 psi	4.8	4.8
In-plane shear strength, ksi	3.46	3.16
Shear modulus, 10^6 psi	0.305	0.305
Short beam shear strength (Interlaminar shear), ksi	3.32	3.12
Poisson's ratio	0.33	0.33

Strength properties of design allowables were reduced 3-sigma from the mean, whereas elastic properties were mean values.

Fatigue characterization was obtained from small specimen fatigue tests of sandwich beams having a TFT laminate on one side and a stainless steel sheet on the other, separated by aluminum honeycomb core. This configuration placed the neutral axis of the beam close to the stainless steel side, so that bending moments imposed on the beam resulted in primarily axial loads in the TFT laminate. The laminate was made with a TFT overlap in the center, fully representative of the overlap obtained in the winding pattern for the spar. The objective of the fatigue tests was to determine whether there was a significant reduction in fatigue strength in the TFT structure when compared with a continuous-filament structure. TFT depends solely upon the resin matrix for tensile load transfer from one layer of glass rovings to an adjacent layer. The effect on fatigue strength of abruptly ending a roving layer across the primary stress direction was also of interest.

Fatigue testing these specimens proved to be a difficult task, involving many invalid failures as a consequence of specimen design. Initially, the TFT specimens were machined from flat laminate plates and then bonded to the sandwich beam for the bending fatigue tests. The machining operation produced cut fibers at the edges of the specimen which became failure loci producing invalid fatigue failures. Later, TFT laminates were molded to shape to avoid the cut edges of the machining operation. The molded specimens were better, but still produced invalid failures in the vicinity of retention grips. A better solution appears to be use of wound tubular specimens which eliminate laminate edges. Company-funded fatigue testing of tubular specimens has shown this approach to produce valid failures which provide better fatigue characterization than flat panel tests of composite laminate structures.

Results of the sandwich beam fatigue tests and a tubular specimen test are shown in Figure 3. The shape of the mean curve was based upon historical data from other sources and its location was based upon the sandwich beam tests. The data point for the single tubular specimen falls close to the mean curve, tending to validate the series. It is believed that the fatigue data presented in Figure 3 can be used with reasonable confidence that additional testing will not result in large changes in the position of the curve, and that it is unlikely that any such change would be toward lower values. To the degree that small specimen data are useful for design, it is believed that these data are conservative.

The mean curve was reduced three standard deviations (3-sigma) to provide a curve to be used for design. The allowable vibratory stress is obtained by applying the Goodman Diagram correction for steady stress using the 3-sigma-reduced fatigue endurance limit of 9000 ± 7000 psi, and the 3-sigma-reduced ultimate stress of 48,900 psi for the 35% resin content, room temperature, dry condition.

In addition to the laminate characterizations described above, four quarter-scale specimens representing the blade root end attachment were fatigue tested to provide substantiation for the single-shear retention method. Double-ended specimens contained the same proportions of TFT, hoop rovings and ± 45° bias tape as in the full-scale spar. Hardware details and installation procedures were also representative of the full-scale structure.

Specimens were tested in a tension-tension mode. Two were tested to 2 million cycles at normal operating loads, and two were tested to 10 million cycles. In an attempt to produce a failure, the last of the four specimens was tested at the Case 2 gust condition for 10 million cycles. Bearing stress range in the bolt holes was 6500 - 19,400 psi during that test. No failures were produced in any of the specimens. It was concluded that the design values and interleaved laminate construction used for the root end composite structure were satisfactory for the full-scale spar.

Material allowables for the afterbody structure and its attachment in final assembly were based upon handbook data and industry practice for the well-established designs employed. As a check, several sub-element tests were run to verify the bond strengths obtained from the fabrication process proposed for the complete blade. These tests included measurement of skin strength and various bond line strengths listed below:

TEST	NUMBER OF SPECIMENS	AVERAGE STRENGTH	REQUIRED STRENGTH
Afterbody skins, tensile strength	4	51,000 psi	10,000 psi
Skin to core bond tensile strength	2	175 psi	10 psi
Afterbody skins bond adhesive lap shear	8	2,280 psi	550 psi
T-clip to spar attachment (detail) tensile strength	2	565 lb/in.	45 lb/in.
T-clip to spar attachment (subassembly) tensile strength	1	613 lb/in.	45 lb/in.
Afterbody panel to spar attachment shear strength of syntactic foam	2	117 psi (core failure)	32 psi

Blade Cost

The actual cost of fabricating the first prototype 150 ft blade was just over \$10/lb, exclusive of tooling and other non-recurring costs. That blade was made on one of a kind soft tooling, plywood forms for blade final assembly, and jury-rigged support fixtures for drilling the root end adapter holes. The 60 ft trailing edge spline was carved by hand. The blade spar was wound in four steps by SCI on a low cost steel mandrel which had a steadyrest at mid-span to minimize bending deflections and fatigue stresses.

Improvement of obvious limitations to efficiency in the above soft tooling includes a stiffer, smoother mandrel which would allow spar fabrication in one step instead of four, use of a fixture capable of machining all root end holes without repositioning the fixture support structure or the spar, fabrication of the trailing edge spline as a molded detail to eliminate hand carving, and use of a final assembly fixture that positions subassembly details with less hand-fitting. Implementation of these improvements is projected to result in an average cost of the next ten blades at around $7/pound, and the 200th blade at $3/pound. These costs include the cost of an operational hub adapter, lightning protection, erosion protection, etc., not provided on the prototype 150 ft blade.

Blade Tests

After blade fabrication was completed, the hub adapter was welded to a 30 ft long load reaction beam for static tests and natural frequency determinations. Static tests included measurement of blade edgewise and flatwise stiffness and deflections, proof-load tests to design limit load in edgewise and flatwise directions, and an ultimate failing load test in the flatwise direction.

Natural frequencies were determined by manually shaking the blade to reveal the low frequency fundamental bending modes, and by impact tests for higher bending modes and torsion.

Blade stiffness and deflection measurements were made by applying nominal loads at the blade tip, recording strain gage data along the blade, and measuring blade deflections from a reference line. Similar measurements were made during the limit load tests, and proved to yield better results with less data scatter.

The limit load test in the edgewise direction was based upon design loads under Case 6, the yaw condition, which is critical for the trailing edge structure. The limit load and ultimate failing load test in the flatwise direction was based on Case 5, the hurricane wind condition (164 mph wind at hub height), which is critical for spar buckling.

After completion of the natural frequency and stiffness determinations, and the edgewise test to design limit load, the blade was repositioned for the flatwise tests. The blade was tested to design limit load in the flatwise direction and then taken to failure at 9 percent above design limit load. Failure occurred as local crippling at a visible flaw in the spar laminate at blade station 45. Subsequent investigation revealed that the flaw was a local bulge in 60 percent of the spar wall thickness, resulting from the four step winding process and the associated soft tooling. Future blades will be made in a single step with improved tooling to eliminate such flaws.

Subsequent to the ultimate load test of the complete blade, the outboard 100 ft of blade was still structurally intact, so it was set up and tested in flatwise bending as a simply-supported overhanging beam. The test section from station 90 to 150 had none of the local flaws observed in the inboard region of the spar where the previous test had resulted in failure.

The outboard test section successfully sustained bending moments in excess of the ultimate design condition (defined as 1.5 times design limit) from blade station 106 to the tip. At blade station 130, the applied moment was 2.8 times design limit, well above the predicted buckling strength of the spar wall.

This test demonstrated that large knockdown factors from theoretical crippling strength predictions are not necessary for pure monocoque glass/epoxy structures of this type, provided no serious material defects (such as the local bulges present at the station 45 failure location) are present.

MOD-1 BLADES

Kaman will fabricate two 100 ft composite blades for the Mod-1 wind turbine. A special challenge in the Mod-1 composite blade program is the requirement that the blades be designed to meet Mod-1 interface conditions established for the steel blades presently employed on the machine. Consequently, the composite blades must match steel blade weight, stiffnesses, deflections, frequencies, etc., to be compatible with the wind turbine system.

The blades will be designed using the technology developed under the 150 ft blade program described above, but with improvements clearly indicated by the results of that program. Also, the Mod-1 blades will be provided with lightning protection, leading edge erosion protection and paint.

The program will deliver two blades in 12 months, including proof testing. A prototype spar will be built and tested to ultimate load in flatwise bending to demonstrate freedom from buckling instability before spars for the two blades are built.

Design Description

Figure 4 illustrates the configuration of the Mod-1 composite blades. The spar is wider and deeper than on the 150 ft blade to match stiffness and tuning requirements of the Mod-1 machine. Additional material is added in the lower surface of the blade spar, as shown in the mid-span section view in Figure 5, to provide buckling stability for an emergency feather condition which includes 25 percent rotor overspeed and abrupt blade pitch change, causing large flatwise bending moments which deflect the blade towards the tower. The added material is unidirectional E-glass tape in which the structural fibers are oriented in the lengthwise direction of the tape (warp direction). This tape, termed Longitudinal Filament Tape (LFT), is laid down spanwise on the spar so that its structural fibers lie parallel to the structural fibers of TFT.

The afterbody panels of the Mod-1 blades are basically the same as on the 150 ft blade, the same materials and method of construction will be used. The trailing edge spline has been eliminated to save weight and reduce cost. This has been made possible by increasing the width of the spar for edgewise natural frequency tuning. The spar shape transitions from an airfoil shape at 40 percent radius to circular at the root where a conical steel adapter, shown in Figure 6, is bolted to the composite in a manner similar to the 150 ft blade. The adapter has an internal flange and bolt circle which interfaces with the Mod-1 rotor hub. The blade will be painted with an epoxy/polyurethane paint system and a leading edge neoprene boot will be provided along the outboard one-third of the blade for erosion protection. A steel tip cap and braided wire trailing edge strap are planned for lightning protection.

Design Loads

Preliminary design loads for the Mod-1 composite blades are the bending moments predicted for the steel blades they will replace. Design loads will be updated by NASA Lewis as the composite blade design evolves. The highest flatwise and edgewise bending moments for static strength and buckling criteria are those which occur during the emergency feather condition shown in Figures 7 and 8. Peak loads during gust conditions and hurricane winds are lower than in the feathering case. It is required that the material proportional limit not be exceeded by these loads, which occur infrequently.

Bending moment distributions to be used for fatigue calculations are specified for 25 and 35 mph wind speeds, along with moment and frequency of occurrence spectra about the nominal values at those speeds. Moment distributions at 35 mph are shown in Figures 9 and 10. The blade is to be designed to withstand the cumulative effects of 435 million fatigue cycles during 30 years of operation when subjected to the 25 and 35 mph wind spectra.

Other Design Requirements

For compatibility with the existing Mod-1 wind turbine system, the composite blades must meet the following additional design requirements:

Maximum blade weight	20,000 pounds
Maximum blade tip deflection (emergency feather, overspeed condition is critical)	71 inches
Blade frequencies:	
1st Flatwise	1.17 - 1.45 Hz
1st Edgewise	2.80 - 2.98 Hz
1st Torsion	17.5 Hz

Material Allowables

The same composite material allowables developed for the 150 ft blade will be used for the Mod-1 blades, except that a 1/3 knockdown factor will be applied to elastic properties for buckling to account for fabrication variability. Therefore, the design ultimate load for buckling will be 2.25 times design limit load, whereas the design ultimate load for static strength will be 1.5 times design limit load.

Blade Tests

In addition to the ultimate load test to be performed on the prototype spar, both blades will be proof tested to design limit load in both flatwise and edgewise directions. Stiffness and deflection measurements will be made edgewise directions. Stiffness and deflection measurements will be made during the proof tests. Natural frequencies will be determined for flatwise, edgewise and torsion modes.

CONCLUSIONS

- Design, analysis, fabrication and testing of a 150 ft composite blade have been successfully accomplished.
- Transverse Filament Tape (TFT) is capable of meeting structural design requirements for wind turbine blades
- Low cost fabrication of large wind turbine blades has been demonstrated
- Fatigue design allowables should be based on tests of wound specimens instead of flat laminates to minimize test terminations which obscure the true fatigue performance of composite structures
- Composite blades can be designed for interchangeability with steel blades in the Mod-1 Wind Generator System.

REFERENCES

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2. General Electric Company, "Design Study of Wind Turbines, 50 kW to 3000 kW for Electric Utility Applications, Volume II, Analysis and Design," NASA CR134935, December 1976.

3. Sullivan, T. L., et al., "Wind Turbine Generator Rotor Blade Concepts with Low Cost Potential," NASA TM73835.

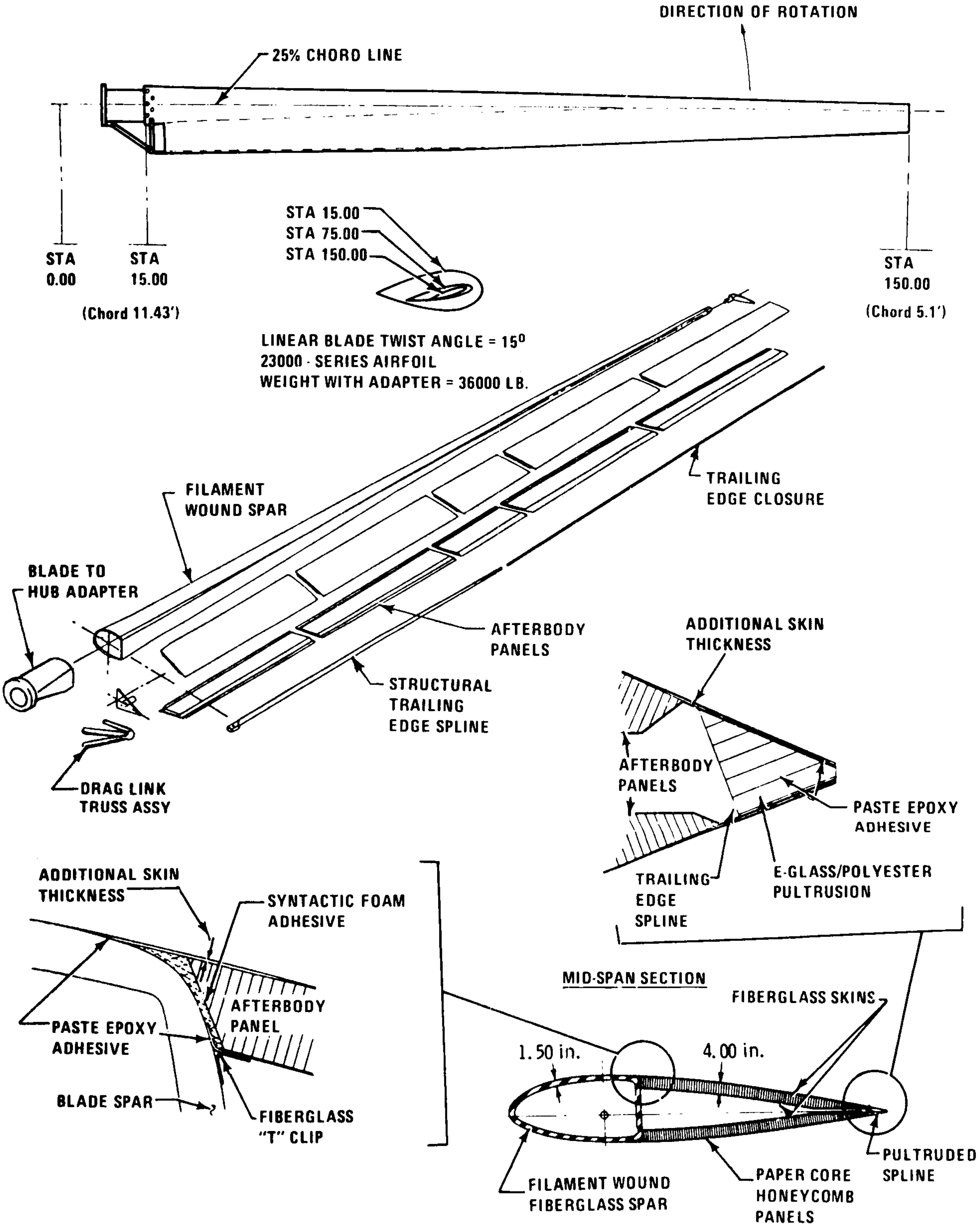

Figure 1. 150 Foot Wind Turbine Blade

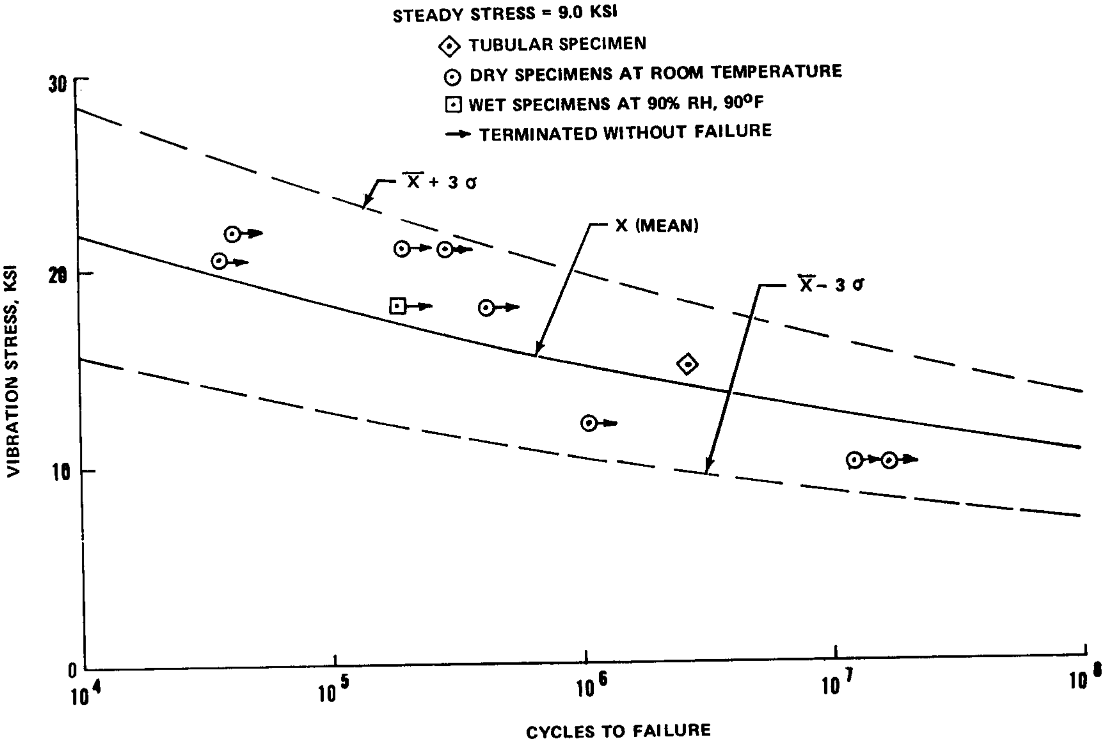

Figure 3. Spar Material Fatigue Characterization

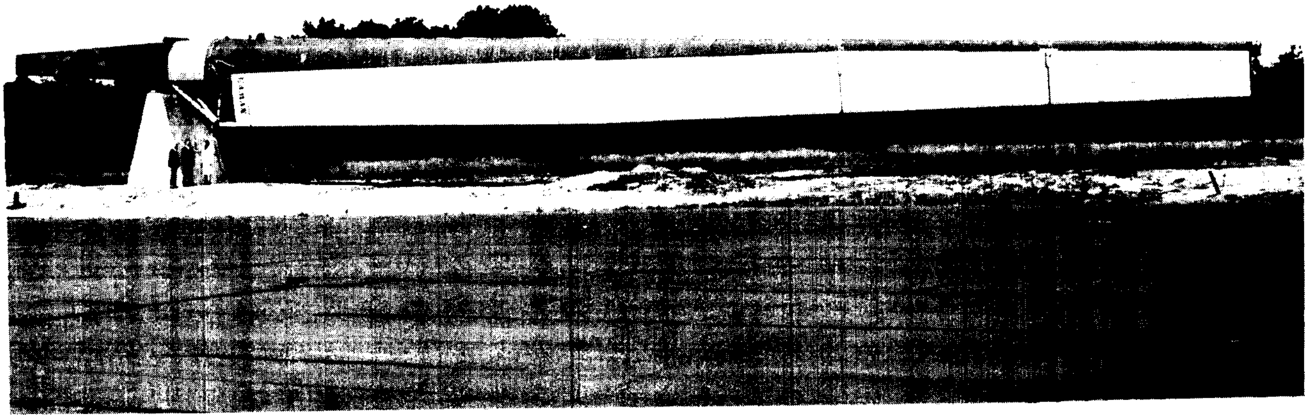

Figure 2. Completed 150 Foot Wind Turbine Blade, Positioned for Edgewise Tests.

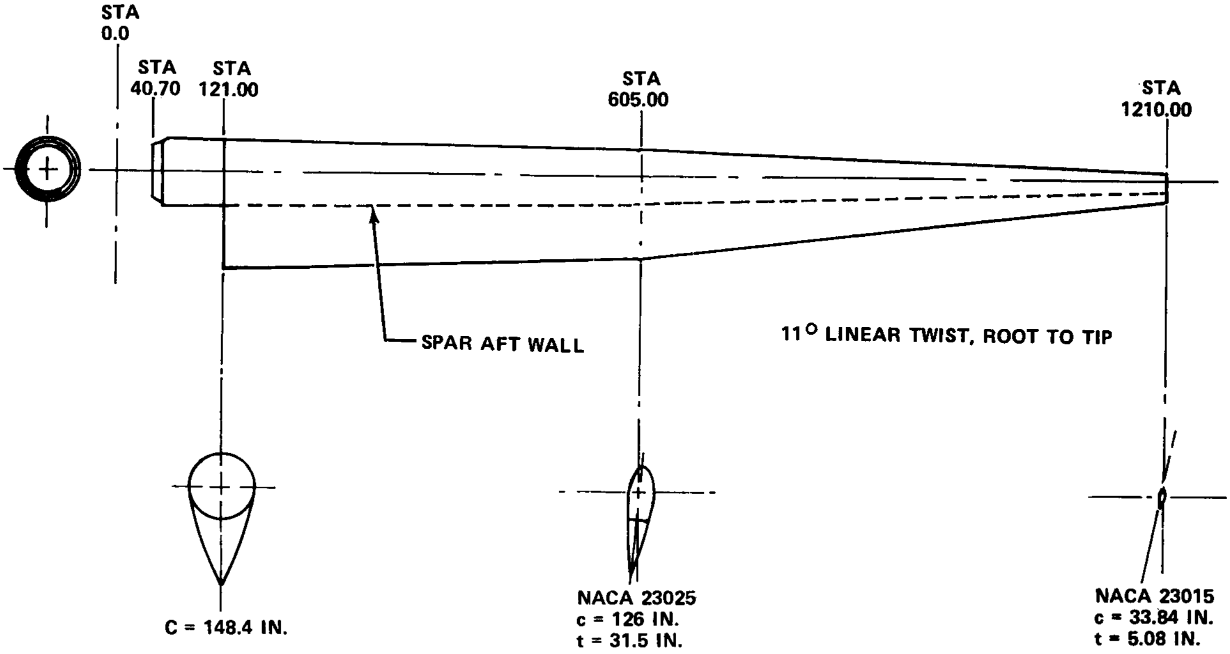

Figure 4. Mod-1 Composite Blade, General Arrangement.

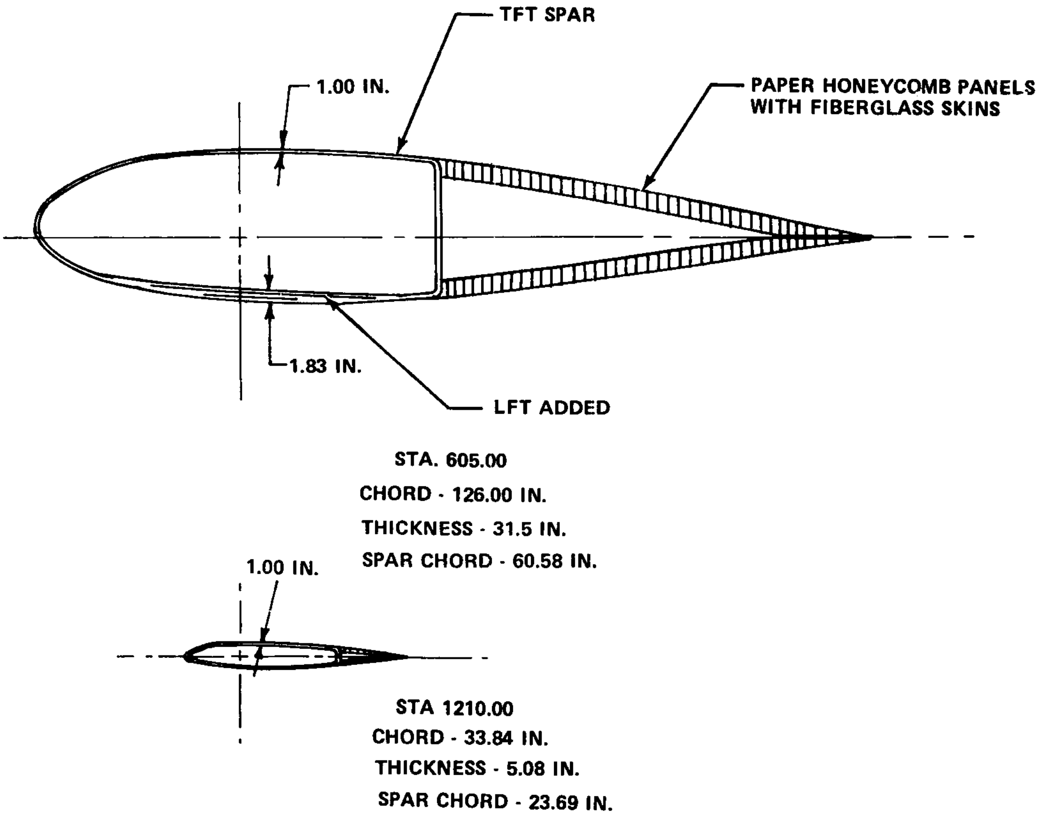

Figure 5. Mod-1 Composite Blade, Section Views.

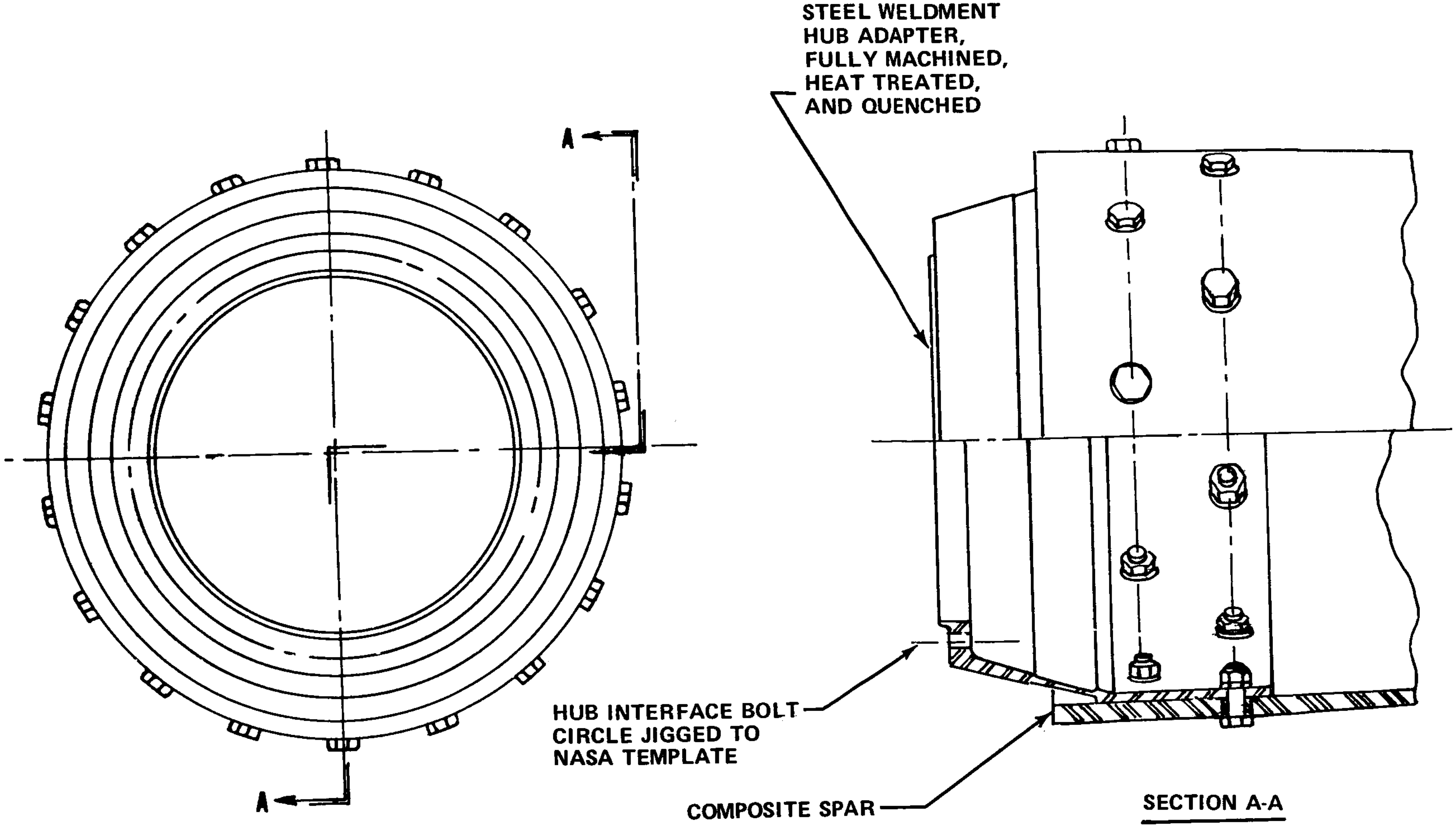

Figure 6. Mod-1 Composite Blade, Hub Adapter.

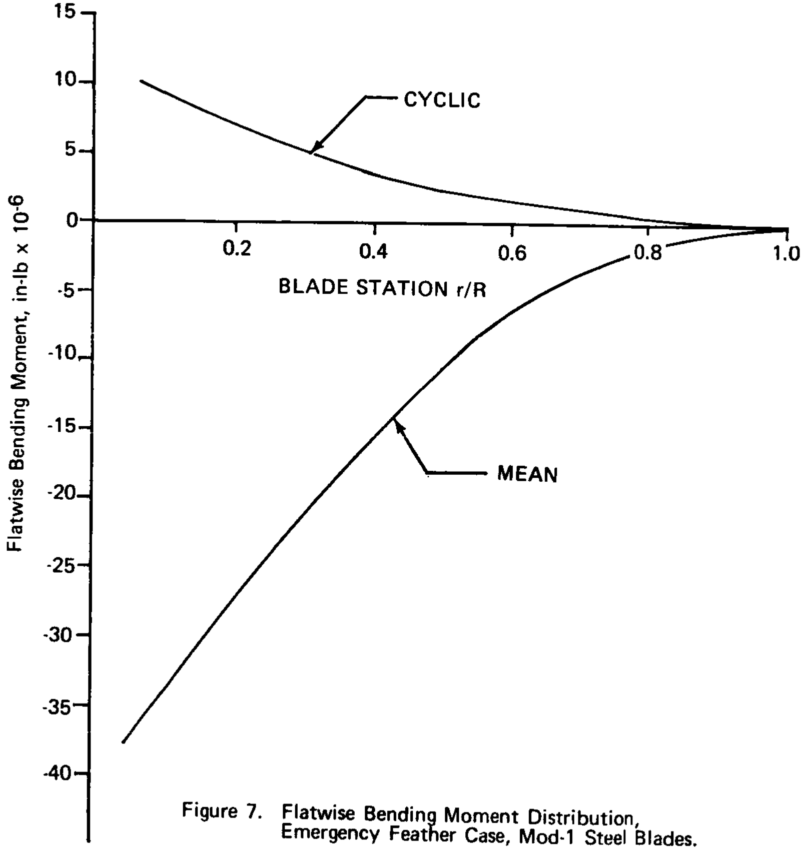

Figure 7. Flatwise Bending Moment Distribution, Emergency Feather Case, Mod-1 Steel Blades.

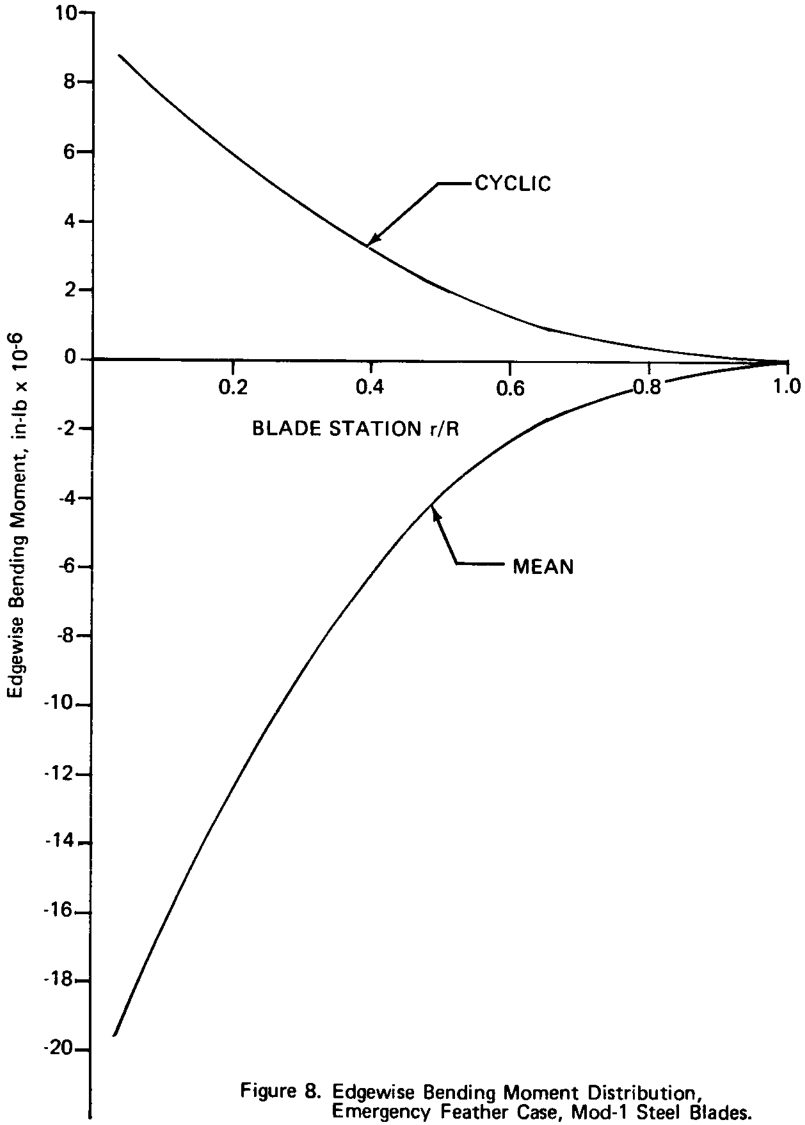

Figure 8. Edgewise Bending Moment Distribution, Emergency Feather Case, Mod-1 Steel Blades.

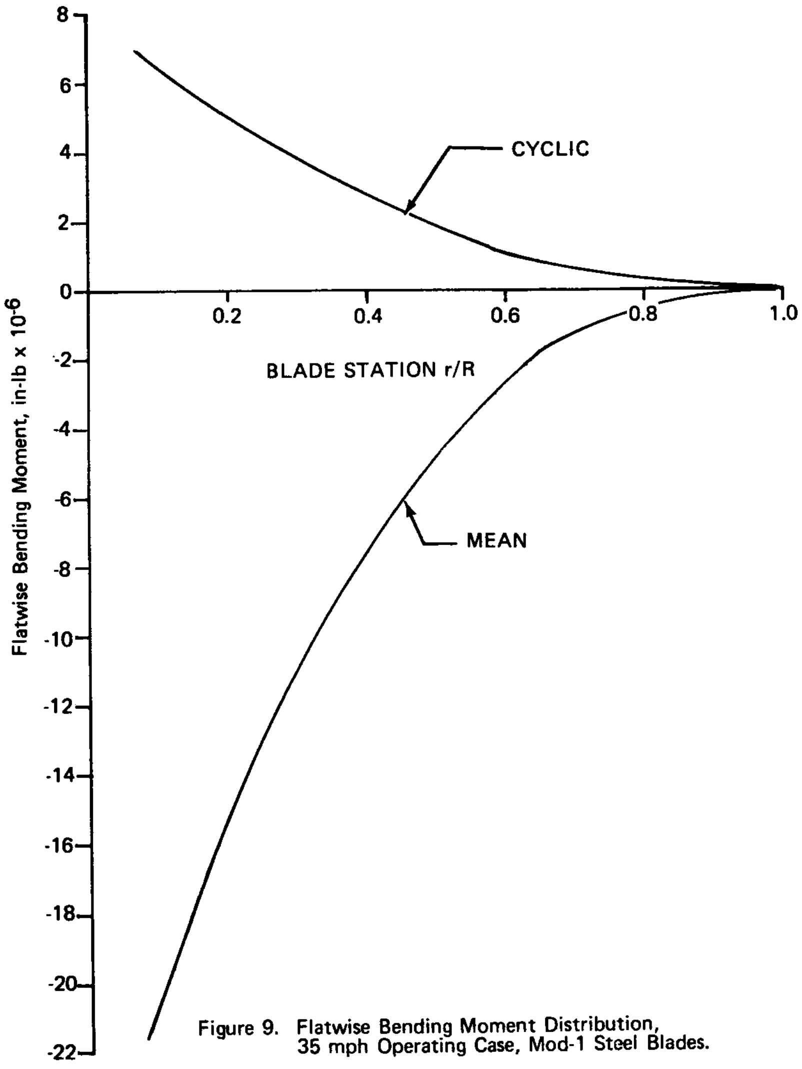

Figure 9. Flatwise Bending Moment Distribution, 35 mph Operating Case, Mod-1 Steel Blades.

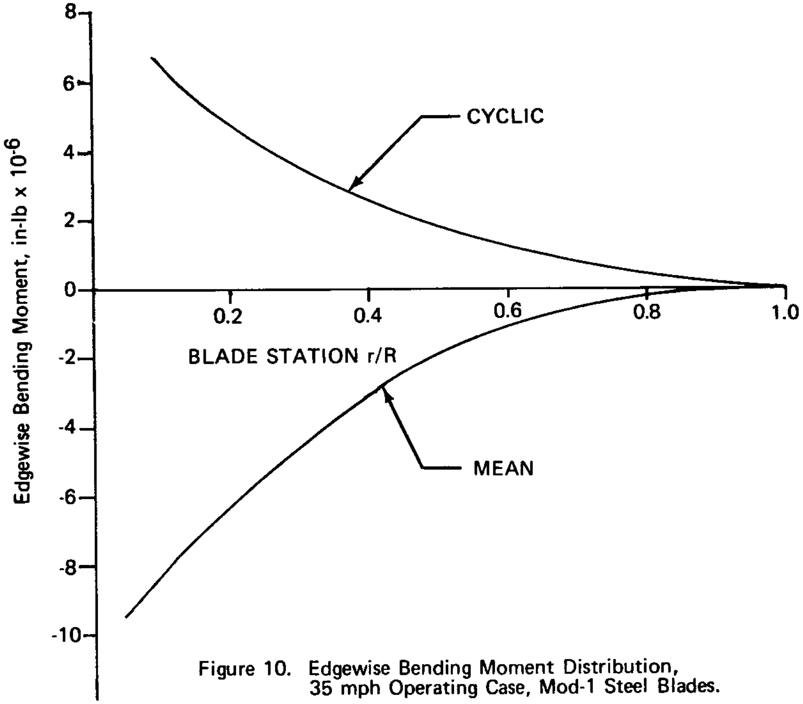

Figure 10. Edgewise Bending Moment Distribution, 35 mph Operating Case, Mod-1 Steel Blades.