LARGE-SCALE WIND TURBINE STRUCTURES

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INTRODUCTION

The purpose of this presentation is to show how structural technology has been applied in the design of modern wind turbines, which have recently been brought to an advanced stage of development as sources of renewable power. Wind turbine structures present many difficult problems because they are (1) relatively slender and flexible (2) subject to vibration and aeroelastic instabilities (3) acted upon by loads which are often nondeterministic (4) operated continuously with little maintenance in all weather, and (5) dominated by life-cycle cost considerations. Progress in horizontal-axis wind turbine (HAWT) development has been paced by progress in our understanding of structural loads, modeling of structural dynamic responses, and designing of innovative structural elements.

During the past 15 years, the NASA Lewis Research Center has developed a series of large HAWT's under the sponsorship of the U. S. Department of Energy and the Department of the Interior. This work has resulted in the design, construction, and testing of 13 HAWT's, with supporting research in aerodynamics, structural dynamics, electrical generating systems, and automatic controls. This has culminated in the recent completion of the world's largest operating wind turbine, the 3.2-MW Mod-5B power plant installed on the island of Oahu, Hawaii.

Some of the applications of structures technology to wind turbines will be illustrated by referring to the Mod-5B design. First, a video overview will be presented to provide familiarization with the Mod-5B project and the important components of the wind turbine system. Next, the structural requirements for large-scale wind turbines will be discussed, emphasizing the difficult fatigue-life requirements. Finally, the procedures used to design the structure will be presented, including the use of the fracture-mechanics approach for determining allowable fatigue stresses.
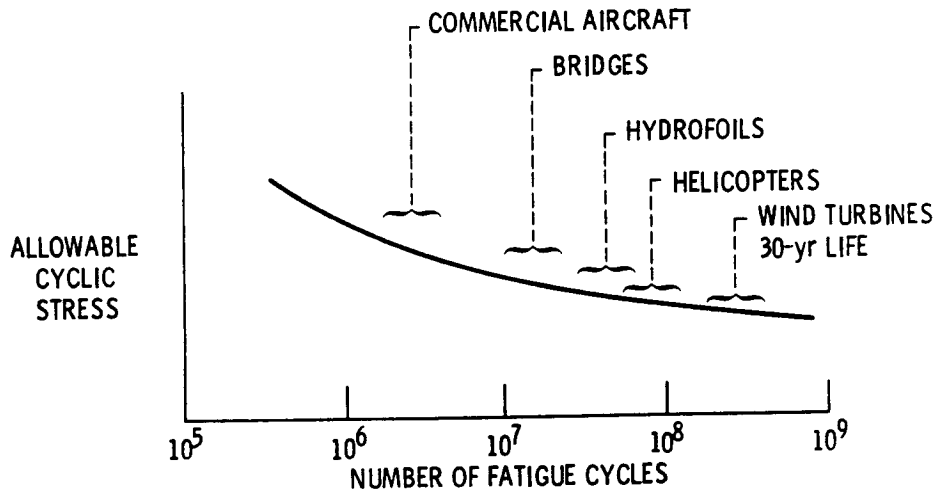
MOD-5B 3.2-MW WIND TURBINE

The Mod-5B is a third-generation horizontal-axis wind turbine that has evolved from a succession of federally-sponsored wind turbine research projects. This wind turbine, located in Hawaii on the northern tip of the island of Oahu, is the largest operating wind turbine in the world. Its design is based on technology developed during 15 years of intensive work at the Lewis Research Center, which managed the project. With a rated power of 3.2 megawatts, the Mod-5B has a rotor that spans 320 ft tip to tip, weighs 319,000 lb, and drives a power train inside a closed nacelle atop a 200-ft tower. In addition to an upwind teetered rotor, compact planetary gearbox, and pitchable tip control, the Mod-5B employs a variable-speed electrical induction generator/control system. While providing increased efficiency, variable-speed operation smooths out drivetrain and rotor tip vibrations and reduces fatigue loading because the rotor tips do not have to cycle constantly in gusting winds.
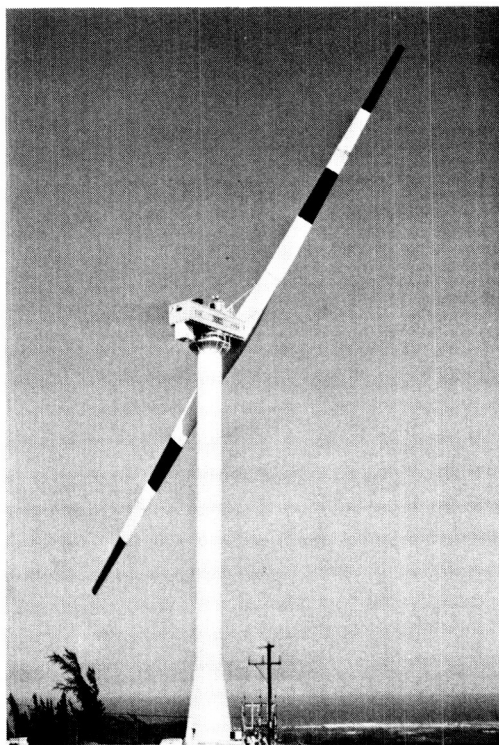
WIND TURBINE FATIGUE REQUIREMENTS ARE SEVERE
## COMPARED WITH OTHER STRUCTURES

Fatigue is a design driver for at least one-half of the primary structure of a large HAWT. In order to be cost-effective, wind turbines must achieve fatigue lives longer than structures such as airplanes, bridges, and helicopters, often by more than an order of magnitude. Almost alone among engineering structures, wind turbine blades are subject to repeated, full reversals of dead load, which occur once each rotor revolution. Thus, a large HAWT rotor such as that of the Mod-5B (which rotates at speeds from 14 to 17.8 rpm) will experience about 150 million reversals of dead weight in its 30-yr design life. This number of cycles increases inversely with rotor size.

ALLOWABLE CYCLIC STRESS vs NUMBER OF FATIGUE CYCLES

COMMERCIAL AIRCRAFT, BRIDGES, HYDROFOILS, HELICOPTERS, WIND TURBINES 30-yr LIFE

10^5 10^6 10^7 10^8 10^9
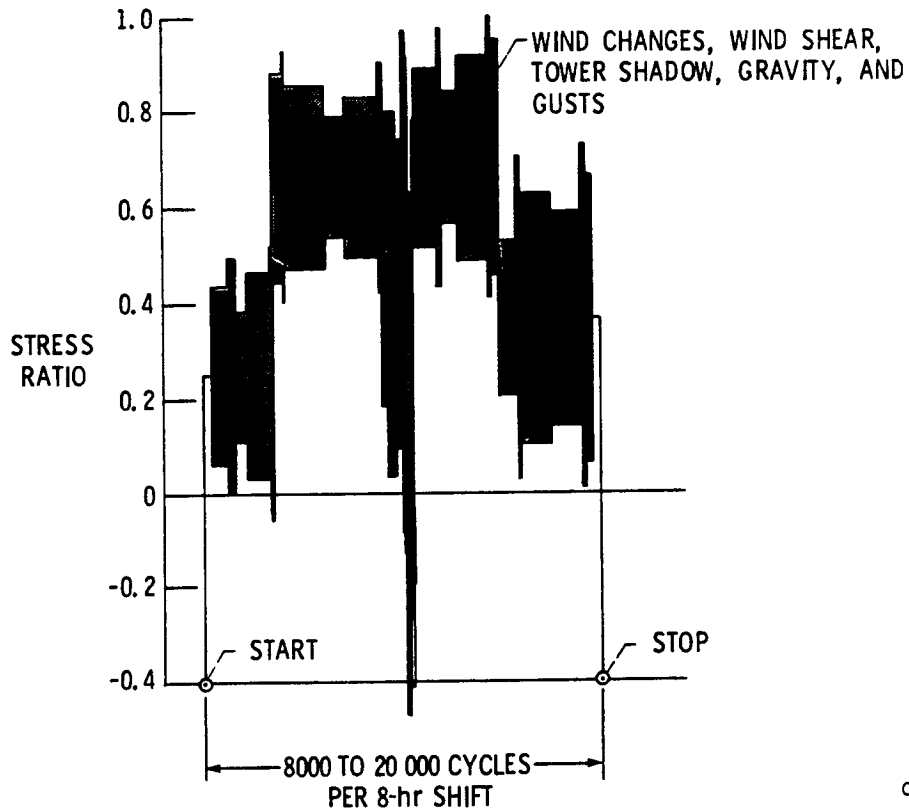
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BOMBER WING STRESS SPECTRUM

As an example of a conventional structure subject to fatigue loading, consider
a typical bomber aircraft wing. In a 4-hr flight, the wing may experience 100
measurable, significant cycles of fatigue loading, or 0.4 cpm, compared with a
minimum of 14 cpm for a wind turbine blade. Even more important is the fact
that a partial reversal of gravity loads occurs only once per flight, namely,
during the so-called "ground-air-ground" cycle. The amplitudes of intermedi-
ate load cycles are generally limited to small fractions of the G-A-G cycle.
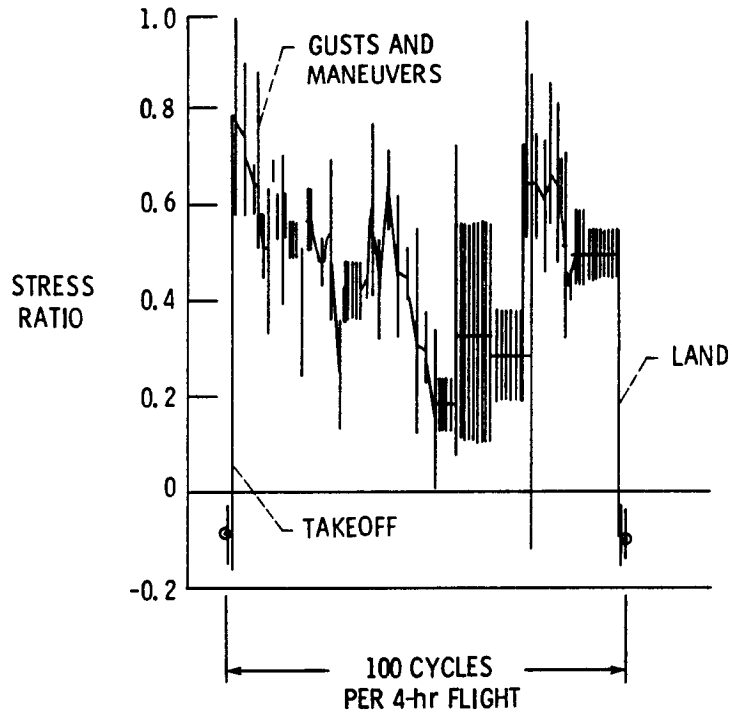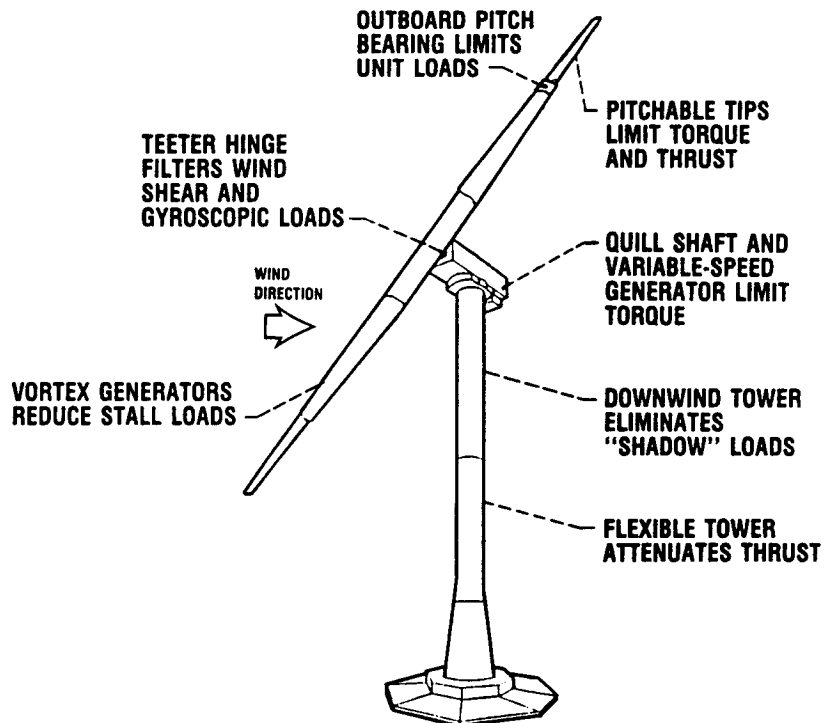
WIND TURBINE BLADE STRESS SPECTRUM

Wind turbine blades also experience a major "ground-air-ground" cycle during each period of operation. In addition, blades are subjected to two other types of load cycles which must be considered by the designer. The first type of load cycle occurs at least once per rotor revolution and is caused by gravity, wind shear (vertical gradient of wind speed near the ground), inflow distortions (tower blockage of the wind), and small-scale turbulence (smaller than the rotor diameter). The second type of load cycle is caused by longer-term changes in wind speed and large-scale turbulence.

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# THE MOD-5B AERO-STRUCTURAL-MECHANICAL CONFIGURATION REDUCES FATIGUE LOADS

The configuration of the Mod-5B wind turbine is a result of a design develop-ment process which has incorporated active and passive load reduction into each major subsystem. Small tabs, called vortex generators, are located along the upwind leading edges of the blades, for the purpose of increasing the stall angle and reducing unsteady stall loads. The entire rotor is hinged at the hub to permit a teetering action, automatically balancing tip loads and largely eliminating gyroscopic loads during yawing. Pitching only the outboard ⅓ of the blade, to control torque and thrust, reduces unit loads on the pitch bear-ings. A flexible quill shaft and variable-speed generator work together to reduce torque cycles. The flexible tower has a natural frequency of 1.3 per revolution to attenuate thrust and side loads from gusts. Its downwind loca-tion eliminates pulse loads on the blades caused by tower shadow.

OUTBOARD PITCH BEARING LIMITS UNIT LOADS

PITCHABLE TIPS LIMIT TORQUE AND THRUST

TEETER HINGE FILTERS WIND SHEAR AND GYROSCOPIC LOADS

WIND DIRECTION

QUILL SHAFT AND VARIABLE-SPEED GENERATOR LIMIT TORQUE

VORTEX GENERATORS REDUCE STALL LOADS

DOWNWIND TOWER ELIMINATES "SHADOW" LOADS

FLEXIBLE TOWER ATTENUATES THRUST

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STRUCTURAL DESIGN DRIVERS

While fatigue resistance is a critical design consideration for wind turbines, the design of large portions of the structure is governed by limit loads and by stiffness requirements for proper natural frequency placement. Some components, such as the quill shaft (the torque tube leading from the rotor to the gearbox) must meet both limit and stiffness requirements. Similarly, the tower must meet both fatigue and stiffness criteria. The geometric parameters available to the designer, such as diameter, wall thickness, and length, are sometimes not sufficient to meet all requirements. When this happens, fracture mechanics analysis is used to determine a combination of design allowable stress and inspection criteria that will lead to an acceptable design.
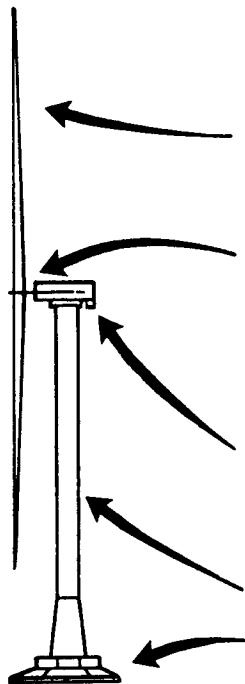
| COMPONENT	DESIGN DRIVERS		
	FATIGUE	LIMIT	STIFFNESS
ROTOR			
UPWIND SIDE	✔	---	---
TEETER STOPS	✔	✔	---
DOWNWIND SIDE	---	✔	---
DRIVETRAIN			
ROTOR CAP	✔	---	---
LOW-SPEED SHAFT	✔	---	✔
GEARBOX	✔	---	---
QUILL SHAFT	---	✔	✔
HIGH-SPEED SHAFT	---	✔	---
NACELLE			
TRUSS	✔	✔	✔
YAW DRIVE	---	✔	---
YAW BRAKES	---	✔	---
TOWER	✔	---	✔
FOUNDATION	---	✔	---

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WELDED STEEL ROTOR TECHNOLOGY

Reducing the high cost of the rotor while maintaining its aerodynamic effi-
ciency, ultimate strength, fatigue resistance, and stiffness has been the major
technical challenge of wind turbine development. Welded steel was recognized
as an ideal production material for large rotors, but technical risk was high
because of severe fatigue requirements. A successful design, based on frac-
ture mechanics technology, has been achieved. It tailors elements and joints
to reduce stresses, and maintains strict quality assurance of materials, welds,
and distortions.

Mod-5B Rotor Technical Data

Material .... Welded ASTM-A633
Diameter, ft 320
Total Weight, lb 318,000
Pitchable Tip Length, percent .. 34
Hub/Tip Chord, ft 13.7/4.1

Tip Speed, mph .... 147 to 198
Airfoil .... NACA 23010 to 23028
Appendages ... Vortex Gen., TE Tabs
Solidity 0.03
Twist, deg 7
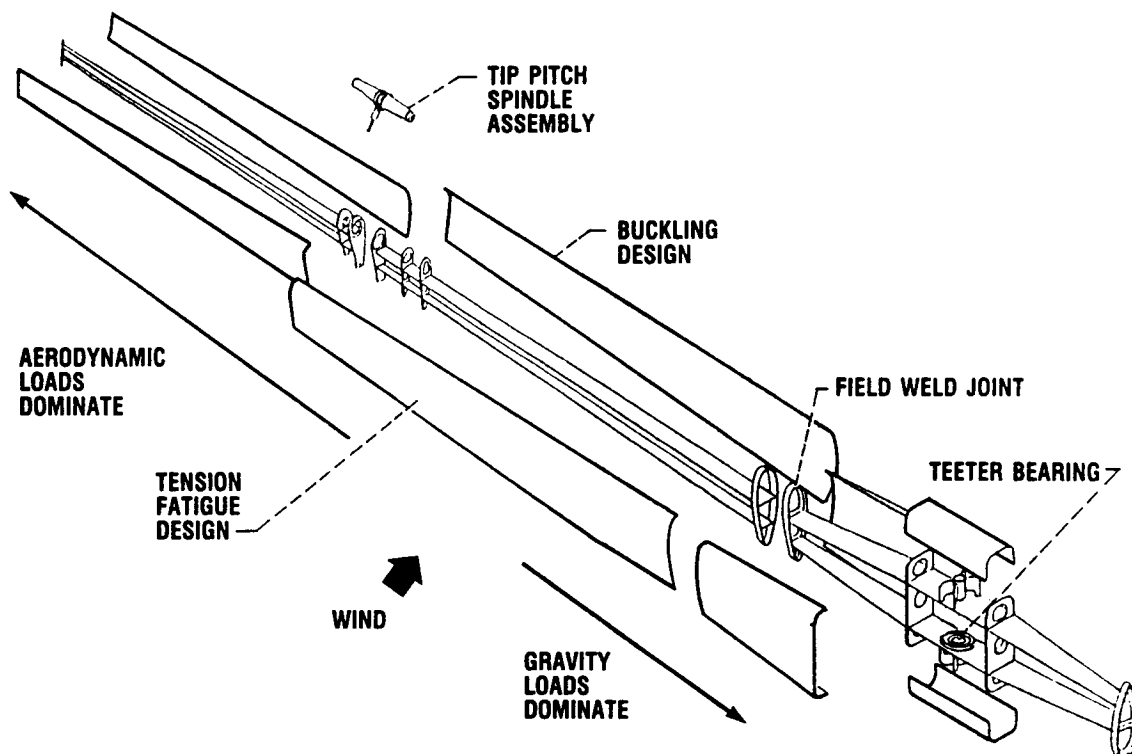
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FATIGUE DESIGN PROCEDURE

As an example of the fatigue design procedure, consider a cross-section weld joint in the rotor blade. Once the spectrum of fatigue loads acting on this cross section has been defined (including the probability of occurrence of mean and cyclic components of load), stress spectra can be calculated for points around the section. Using appropriate design flaws and a crack propagation model, a fatigue design life is calculated for each point. The stress spectrum at each critical point (a point with relatively short life) is then scaled up or down until a fatigue design life of 30 years is obtained. The 99.9th percentile stress in this scaled spectrum is then defined as the "design allowable stress" for that point and the selected inspection criteria.

Next, the dimensions of the elements in the section are changed in an iterative fashion until, considering all applicable factors of safety, the design margin at the most critical point is positive and approximately zero. Margins at other points around the section are calculated, and inspection criteria may be adjusted to optimize the trade-off between weight and cost.

- **GIVEN: INTERFACE LOADS VS WIND SPEED VS PROBABILITY OF OCCURRENCE**
- **GIVEN: INITIAL DIMENSIONS, ASSUMED INITIAL CRACK SIZE AND CRACK GROWTH MODEL**
- **CALCULATE ANNUAL FATIGUE LOAD SPECTRUM (MEAN AND CYCLIC) AT CROSS-SECTION**
- **CALCULATE ANNUAL STRESS SPECTRUM AND FATIGUE LIFE AT POINTS IN SECTION**
- **SCALE STRESS SPECTRUM AT EACH CRITICAL POINT UNTIL LIFE EQUALS 30 YEARS**
- **"DESIGN ALLOWABLE STRESS" AT POINT IS 99.9TH PERCENTILE STRESS IN SCALED SPECTRUM**
- **APPLY SAFETY FACTORS AND ITERATE ELEMENT DIMENSIONS UNTIL DESIGN MARGIN AT MOST CRITICAL POINT IS ZERO**
- **CALCULATE MARGINS AT OTHER POINTS AND ADJUST INSPECTION CRITERIA FOR COST-EFFECTIVENESS**

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CRACK GROWTH RATE MODEL

An empirical crack growth rate model for the A-grade steels used in the Mod-5B wind turbine was developed on the basis of laboratory fatigue tests of pre-cracked specimens. These specimens were subjected to load spectra which simulated the highly variable stress cycles characteristic of wind turbine components. As is usual in such models, the amount by which the crack grows during a given cycle depends on the maximum and minimum stress intensities in the cycle, which, in turn, are dependent on the instantaneous crack size.

The crack growth rate model which best fit the test data was found to have the following characteristics:

o   A threshold stress intensity below which the growth rate is assumed to be zero. This threshold increases with increasing "R" ratio (i.e., ratio of minimum to maximum stress in the cycle).

o   A retardation factor which, for the same stress intensities, significantly reduces the growth rate under variable-spectrum loading compared with steady fatigue loading.

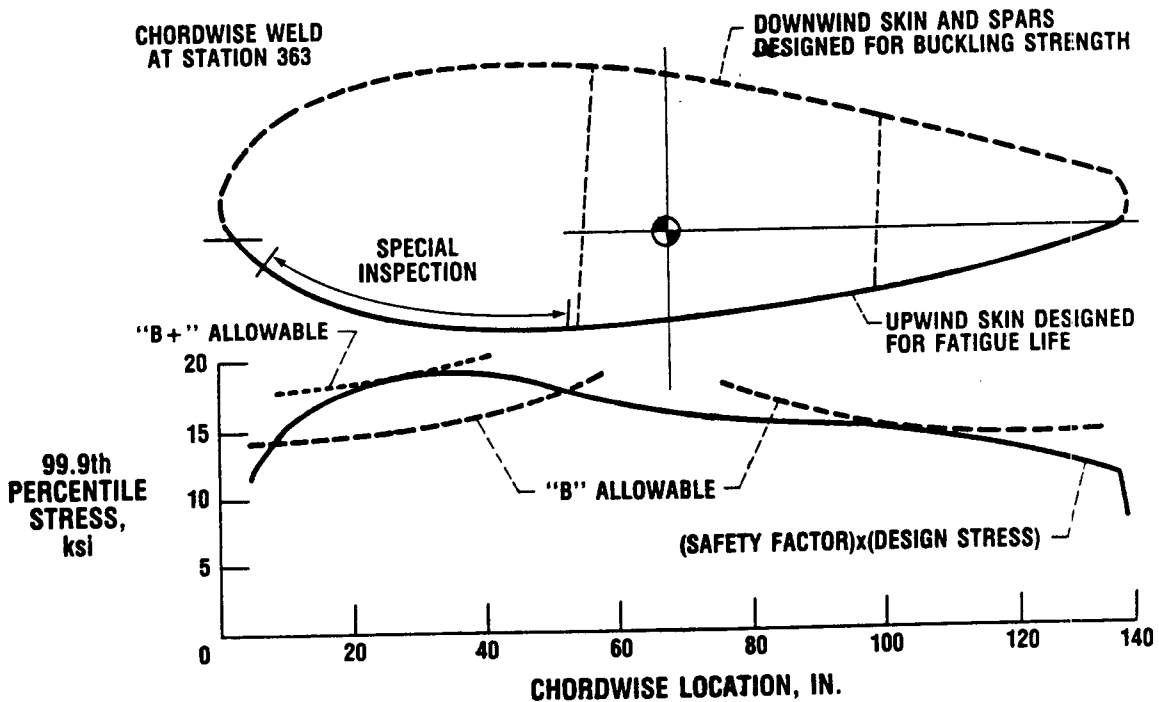o   No effect of welding on crack growth rates in stress-relieved specimens.

$$dA/dN = 3 \times 10^{-10} (1-R)^{2.4} (K_{max})^3 (K_{max}/K_{99.9})^2$$

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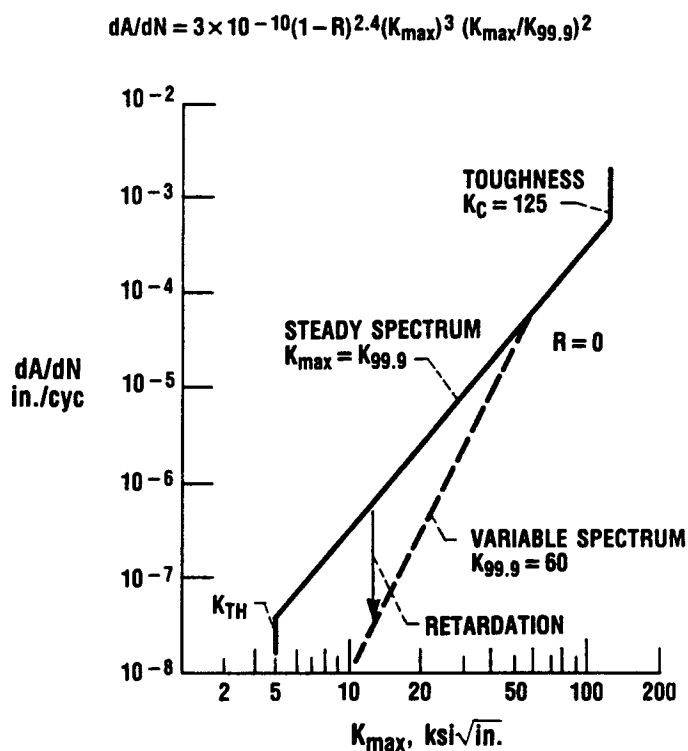
TYPICAL ROTOR DESIGN STRESS ALLOWABLES

A typical result of the Mod-5B fatigue design process is shown by this cross-section weld in the rotor blade at a station 363 in. from the shaft centerline (19 percent of span). The upwind skin, in which aerodynamic thrust produces tension loads, is designed for fatigue life requirements, while the downwind skin, which is generally in compression, is designed for buckling strength.

The inspection criteria for most of this weld is "B", with design allowable stresses in the range of 13,500 to 18,000 psi, depending on the "R" ratio which dominates the local stress spectrum. A "B" weld characteristically joins plates of equal thickness and is ground flush parallel to the stress direction.

However, a special "B+" inspection procedure has been specified for a small forward area. This special inspection detects smaller flaws and thus permits the design allowable stress to be about 25 percent higher than that for the "B" inspection. It is cost-effective to use extra inspection in this small but critical area.


CHORDWISE WELD AT STATION 363

DOWNWIND SKIN AND SPARS DESIGNED FOR BUCKLING STRENGTH

SPECIAL INSPECTION

UPWIND SKIN DESIGNED FOR FATIGUE LIFE

"B+" ALLOWABLE

99.9th PERCENTILE STRESS, ksi

"B" ALLOWABLE

(SAFETY FACTOR)x(DESIGN STRESS)

CHORDWISE LOCATION, IN.

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BLADE CRACK DETECTION SYSTEM

The Mod-5B rotor contains an air-pressure system for detecting a crack through the blade skin. Dried air is pumped into each blade independently and vented through calibrated exhaust ports. Air flow rates to the two blades are constantly compared, and a differential flow above an allowable level causes the automatic control system to shut down the turbine and signal the possible presence of a crack.

Fracture mechanics theory was used to calculate crack-opening displacements as a function of crack size and level of applied stress, in order to determine if there would be sufficient flow early enough to provide adequate warning. It was found that the toughness of the A-grade steel in the rotor was great enough that large cracks with detectable air flows were still stable. Tests were run to verify these flow calculations, using large plates containing 24-in. long through cracks and stressed to about 18 000 psi. Measured and predicted crack-opening displacements and air flows were found to agree.
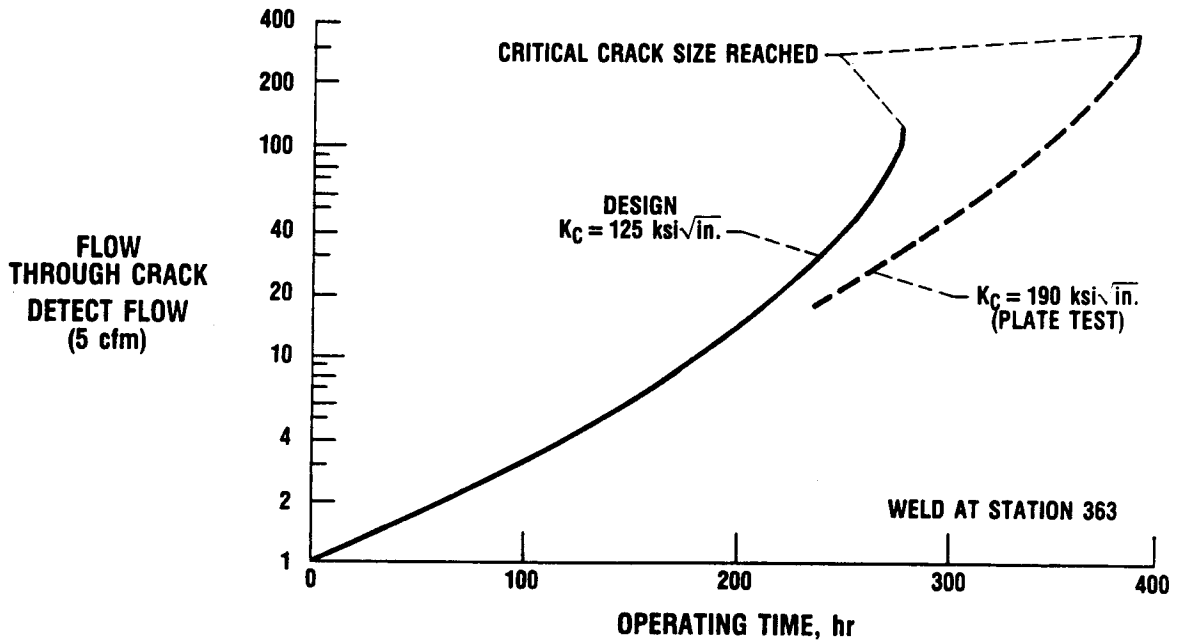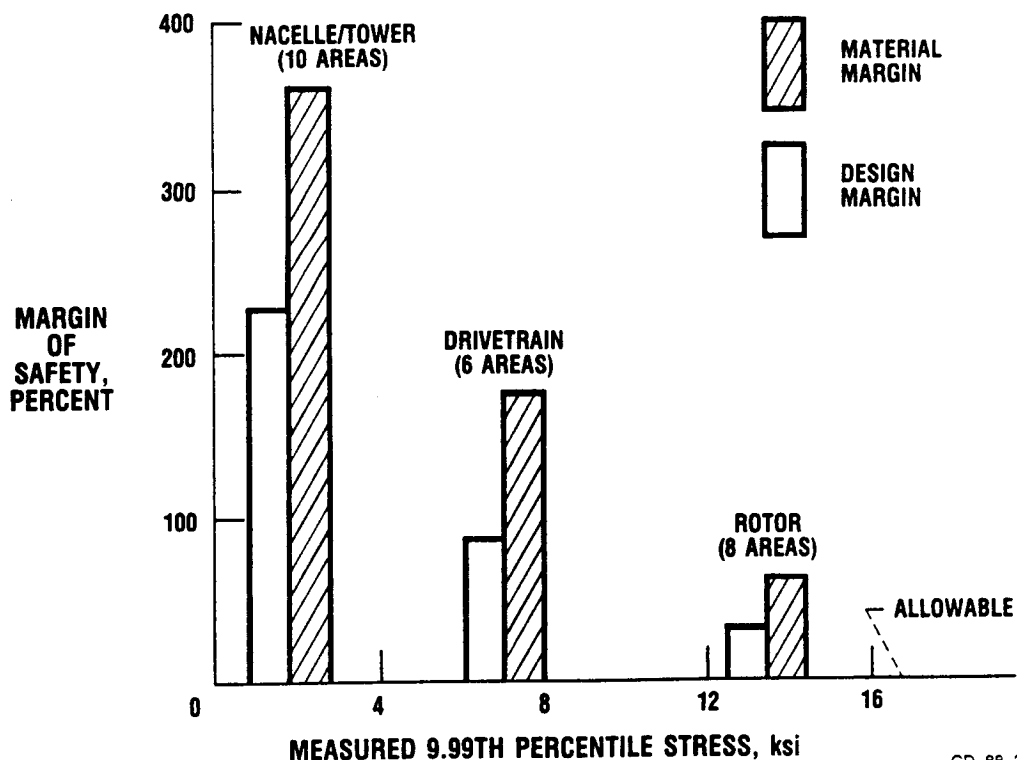

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ASSESSMENT OF MOD-5B STRUCTURAL INTEGRITY

As part of a six-month series of acceptance tests, the structural integrity of the Mod-5B wind turbine was evaluated by measuring fatigue loads and local stresses during operation. Local stresses were monitored at 24 critical locations throughout the rotor, drivetrain, nacelle, and tower structures. Cumulative test time of over 25 hr represented in proportion the operating conditions which the turbine will experience in its lifetime. The continuously recorded dynamic stress data were analyzed statistically to determine the 99.9th percentile level for each critical location, and this level was then compared with the predicted design stress and the material allowable stress for that location.

The following conclusions were drawn from this assessment:

o   Stress and load levels were at or below design predictions and well below material allowables.

o   The assumptions on which the 30-yr design life of the structure was based have been verified, and meeting this design goal still appears feasible.

o   Steel rotor technology, including the fracture mechanics approach to fatigue-resistant design, has been verified.

o   Technical risk in building and operating steel wind turbines with diameters up to 320 ft is now commercially acceptable.