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STRUCTURAL TESTING OF THE NORTH WIND 250 COMPOSITE ROTOR JOINT

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ABSTRACT

The North Wind 250 wind turbine is under development at Northern Power Systems (NPS) in Moretown, VT. The turbine uses a unique, flow-through, teetered-rotor design. This design eliminates structural discontinuities at the blade/hub interface by fabricating the rotor as one continuous structural element. To accomplish this, the two blade spars are joined at the center of the rotor using a proprietary bonding technique. Fatigue tests were conducted on the full-scale rotor joint at the National Renewable Energy Laboratory (NREL). Subsequent tests are now underway to test the full-scale rotor and hub assembly to verify the design assumptions. The test articles were mounted in dedicated test fixtures. For the joint test, a constant moment was generated across the joint and parent material. Hydraulic actuators applied sinusoidal loading to the test article at levels equivalent to 90% of the extreme wind load for over one million cycles. When the loading was increased to 112% of the extreme wind load, the joint failed by buckling. Strain levels were monitored at 14 locations inside and outside of the blade joint during the test. The tests were used to qualify this critical element of the rotor for field testing and to provide information needed to improve the structural design of the joint.

INTRODUCTION

In 1990, the United States Department of Energy (DOE) began funding for the National Renewable Energy Laboratory (NREL) for advanced wind turbine research and development. Northern Power Systems (NPS) was among those companies selected to design more reliable, commercially viable wind turbines to meet the DOE cost-of-energy goal of $.05/kWh by the mid-1990s. Northern Power Systems' effort to design and build the North Wind 250 wind turbine is currently underway. Figure 1 gives an overview of the turbine specifications and shows a profile sketch of the turbine [1]. The North Wind 250 turbine is a two-bladed upwind machine with a patented aileron control system. One of the turbine's innovations is a unique teetering system for the rotor. The two rotor blades are designed to function as a seamless structural element and are mounted in a saddle with elastomeric cushions. This mounting technique allows the structure to flex and helps reduce the impact of the stochastic load cycles.

The development strategy was to build and test the first prototype as a proof-of-concept (POC) design which encompassed all of the features of the final design. The second prototype would use the experience gained from the POC to move toward a refined production design. The greatest design challenges associated with the rotor design were the development of aileron control devices and the production of the continuous "flow-through" rotor. This paper reports on the structural testing of the latter only.

The rotor joint provides a "flow-through" structural connection between the two 12½-meter-long (41-foot) blades. This eliminates the need for the heavy and expensive flange connections commonly used on large wind turbines. The POC blade manufacturing used hand layup of fiberglass and vinylester over a foam core. At the root, the fiberglass wall is approximately 13 mm (0.5 in) thick on an elliptical cross-section 38 cm high by 71 cm wide (15 by 28 inches). The root end of each blade was laid up with a tapered wall thickness by dropping off laminates. The top laminate stopped 38 cm (15 in) from the blade root. Fabricators aligned the two blades so that the roots butted against each other. They laid fibers of appropriate lengths around the interface to create two, stepped seams as shown in Figure 3. The joint layers use the same laminate schedule as the blade.

The test approach is to fatigue-test the full-scale joint as an independent structure in four-point bending. The purpose is to determine how much, if any, the strength of the rotor is degraded by fiber discontinuities in the joint. A second test is to investigate the impact on strength of the spar/saddle connections and of the transition from elliptical to D-spar cross-section. Finally, field tests will provide load data under operating conditions.

To properly test the joint it was necessary to develop a specialized test fixture which represented the loading of a teetered hub. This meant that the additional degrees of freedom at the hub connection had to be permitted a departure from previous NREL tests on single blade elements. This added complexity and required that a greater portion of the rotor be included in the testing to get accurate blade information.

NREL TEST FACILITY

NREL's structural test facility [2,3] is used primarily for testing full scale wind turbine blades. The capabilities include fatigue testing, ultimate static strength testing, and several non-destructive techniques, such as photoelastic stress analysis. Fatigue tests use an MTS Systems Inc. closed-loop servo-hydraulic system to apply cyclic loads to blades up to 20 m (66 ft). Although multiple actuators are possible with this system, the actuator load for this test was applied at a single point using a 67 kN (15,000 lb) hydraulic actuator. Constant amplitude, sinusoidal load blocks were used for simplicity, although variable amplitude, variable frequency loading is possible. The actuator was equipped with anti-backlash, swivel end connections and was mounted between the blade and a base plate bolted to the floor. The hydraulic power supply was an MTS Model 506.41 that supplied hydraulic power to the hydraulic actuators at flow rates up to 2.5 liters/sec (40 gal/min). An MTS Model 290.13 hydraulic service manifold, positioned between the power supply and the actuator, provided protection from high-energy transients, secondary hydraulic filtration, suppression of line-pressure fluctuations, and a controlled shut-off and turn-on of hydraulic pressure to the actuators.

The fatigue load history is defined and loaded into the control software and delivered by the T/RAC (Realtime Active Controller) to the actuator. The load profile is first sent to the analog system controller, a microprocessor based unit called the MTS 458.10 MicroConsole, that provides control and signal monitoring functions. MTS 458.12 DC and MTS 458.14 AC control modules plug in to the MicroConsole chassis and provide conditioning and feedback control from the load cell and linear variable differential transformer (LVDT) transducers. They also provide high-level load and displacement signals to the data acquisition system. The command signal is sent from the analog controller to the servo-valve, which translates the electronic signal to a hydraulic flow rate to the actuator.

FLOW-THROUGH ROTOR JOINT TEST

Joint Test Fixture

The test article consisted of the joint centered in a 4.9-m (16-ft) fiberglass beam manufactured at EDO Fiber Science in Salt Lake City, Utah. The beam was manufactured with a constant elliptical cross section over its entire length, even though the actual rotor transitions from the elliptical section to a D-spar beginning at the one-meter (40-in) blade station. The fiberglass beam was fitted with steel sleeves covering the outer meter of each end. Both ends were bonded inside the sleeves and reinforced to prevent local stress risers. The sleeves were connected through flange joints to 3.66-m (12-ft), steel I-beams. Thus, the overall length of the test article was 12.2 meters (40 ft) with the joint in the center. The purpose of the I-beams was to move the load point further from the joint to reduce the shear stresses in the fiberglass joint to levels that were representative.

The modified four-point bending test fixture was designed by NPS and NREL to provide a constant bending moment across the joint section and the adjacent material. This fixture is shown in Figure 2. The test section was located at the center of the test fixture and was approximately 1.5 m (5 ft) across. The test section was straddled by two load reaction saddles. Each saddle was 25 cm (10 in) wide and was centered 63.5 cm (25 in) from the center of the joint. Elastomeric blankets between the steel saddles and the fiberglass test article softened these connections. Each saddle was connected through a linkage to a rocker arm which pivoted on a base plate bolted to the floor. The fixture was designed so that a single actuator at one end of the test article could provide all the bending loads. The other end of the fixture was pinned to a rigid support.

Instrumentation

The test article was instrumented with ten strain gauges, as shown in Figure 3. Gauges #1 and #7 were three-element, rectangular rosettes with each element connected to measure strain individually. Rectangular rosettes were oriented in a 0/45/90 degree configuration to measure both longitudinal and transverse strain levels. Most gauges were oriented to measure external strain levels across the top compressive fibers of the joint. Two gauges were embedded inside of the joint during manufacturing, but failed during the test.

Load cell force, actuator displacement, and surface strain data were processed through a 16-channel Measurements Group, Model Series 2400, signal conditioner, which was connected to a Keithley 500, analog-to-digital interface. Digital signals were recorded using Labtech Notebook™ software on a 386 PC computer. Data files were recorded at least once per day during the testing. Hand-held and fixed video cameras recorded the test set-up and key portions of the test, including the failure.

Loading

Loads were applied using a hydraulic actuator with a load capacity of 67 kN (15,000 lbs) over a 51-cm (20-in) stroke. The actuator was equipped with a load cell and LVDT displacement transducer with a resolution of better than 1% of full scale.

The test plan called for sinusoidal loads to be applied in a series of one-million-cycle blocks. Maximum bending load in the first block was 244,000 N-m (180,000 ft-lb) at the joint. This load is equivalent to 90 percent of that expected during exposure to a 50-year, extreme wind as defined in the International Electrotechnical Commission standard for Class 1 wind turbines [4]. In the second block, the maximum load was to increase by 25 percent. Designers expected that the joint would fail by composite fatigue partway through the second block.

Figure 4 shows the load distribution for the extreme wind case and the load distribution during the first block of fatigue testing. It also shows the design strength of the composite portions of the rotor which were based on the rotor withstanding 1,000 extreme wind events. Note that the saddle should provide additional strength at the root sections of the rotor since it provides an alternate load path for bending loads.

Test Procedure

After initial setup and checkout of the test, the tare weight of the blade and test fixture was determined by calculating the weights of various components of the test apparatus and determining the resultant force acting at the actuator attachment point. These calculations indicated that approximately 4 kN (1000 lb) of actuator force was required to achieve zero bending moment in the joint. An additional 18 kN (4000 lb) was needed to offset the weight of the remaining portions of the test fixture to eliminate backlash in the system during dynamic testing. Thus, to assure smooth stable operation of the test, a 22 kN (5000-lb) load was used as the lower limit of the fatigue test.

Including the tare weight, the upper load limit of the initial fatigue load range was 49 kN (11,000 lbs) to achieve a bending load of 244,000 N-m (180,000 ft-lbs) at the joint. This loading was equivalent to a load amplitude ratio of $R=.4$. Initially, the joint was loaded statically between the upper and lower limits to determine the actuator stroke range and to measure initial strains. From this static deflections were determined. These static displacements were used to define the test limits, control the actuator motion, and establish the initial stiffness of the structure.

The joint was loaded at a cycle rate of approximately one hertz for 1,013,835 cycles. Completion of this load block established that fiber discontinuities in the joint did not substantially weaken the composite spar. Figure 5 shows that compressive strains did not change significantly during the million cycles. This result suggests that fatigue damage was minimal.

Following the completion of the first load block, the peak bending load was increased toward a target load of 325,000 N-m (240,000 ft-lbs), where an additional million cycles was to be applied. The load was increased gradually on the first cycle to determine the actuator stroke range and to check strain levels. At a bending load of 305,000 N-m (225,000 ft-lbs) in the joint section, the test article buckled and fractured. The fracture occurred almost instantaneously with no warning cracks. Analysis of video tape records indicated that crack propagation took place in less than 1/30th of a second and was accompanied by a loud retort. The compressive surface collapsed inward with a chordwise crease located 9 cm (3 in) from the center of the joint on the side opposite the hydraulic actuator. The buckle zone extended over the entire upper surface, but did not propagate around to the tensile side.

Buckling analyses often overpredict the strength of thin-shelled composite structures because imperfections present in the materials and manufacturing processes are not accurately modeled. Designers commonly apply a knockdown factor to account for this uncertainty. This test provided the designers a valuable datum for calibrating their analysis model. Using a COSMOS finite element model (FEM), designers had predicted buckling at a load of 513,000 N-m (378,000 ft-lbs) on the compressive side of the elliptical joint section. The part actually buckled at a load of 305,000 N-m (225,000 ft-lbs), or 60 percent of the FEM prediction. Figure 6 shows the buckling analysis for the elliptical structure at the center joint. This new empirical information will be incorporated into a structural model of an improved design that will be fabricated later this year.

WORK IN PROGRESS

The next phase of this testing is currently underway at NREL. This phase involves fatigue testing a composite spar that includes the transition from elliptical to D-spar cross sections and the normal connections to the saddle and yoke assembly. This configuration differs from the joint test set-up because the saddle provides a secondary load path around the joint section for bending moments. Loading the spar in this way is expected to move the critical bending location from the joint to an outer spanwise station. The FEM analysis of the spar shows that critical buckling is likely to occur first at the 125-cm (50-in) station where the elliptical section transitions to the D-spar shape and the two degrees of blade coning is achieved. Figure 7 shows the test arrangement during the initial set-up.

One end of the test article (the far end as seen in Figure 7) uses the same I-beam extension as the joint test article. The hub hardware consists of an aluminum cast saddle spanning the entire joint area, the teeter pins, and the yoke. The yoke is a wishbone-shaped piece that connects the teeter pin assemblies to the turbine's low-speed shaft. In the test stand, the yoke is bolted to the floor through an adaptor plate. The loading actuator (not seen in the figure) is attached to the D-spar 6.1 m (20 ft) from the teeter axis. This position replicates the extreme-wind load distribution over the inner 3 m (10 ft) of the blade span. Tests are now in progress to determine whether this assembly is limited by fatigue or by buckling.

CONCLUSIONS

Structural tests of a critical joint in the North Wind 250's rotor provided valuable information for the designers and developers of this new wind turbine. The tests confirmed that the joint could resist fatigue damage at loads close to those that might be encountered under extreme winds. This finding significantly reduced concern that the fiber discontinuities in the joint might significantly lower the strength of the spar. Field testing of the wind turbine can now proceed with greater confidence of rotor structural integrity.

Secondly the test indicated that the present design is susceptible to buckling failure at loads well below the ultimate strength of the composite material. This datum combined with results of current testing will help to refine the rotor design. Designers are currently investigating the potential for new layups and geometries to increase the buckling strength so it is closer to the ultimate strength of the material. With these simple changes, the new design will use the composite material more efficiently and thus achieve higher strength with little, if any, cost increase.

ACKNOWLEDGMENTS

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NORTH WIND 250 TECHNICAL DATA

PERFORMANCE SPECIFICATIONS

- Cut-in wind speed: 4 m/s (9 mph)
- Rated wind speed: 13 m/s (29 mph)
- Survival wind speed: 54 m/s (120 mph)

ROTOR

- Up-wind, 2-bladed, teetering rotor
- 25-meter diameter (490 square meters sweep area)
- 2° coning, flow-through rotor structure
- 50 RPM
- Composite rotor construction
- Aileron controls
- Elastomeric teeter bearings
- Teeter control system, dampers, brakes

DRIVE TRAIN

- Integrated modular assembly
- Parking/service brake

TRANSMISSION

- Proprietary planetary/helical gearbox
- Asynchronous generator 1800 RPM, 250 kW, 480 VAC

YAW SYSTEM

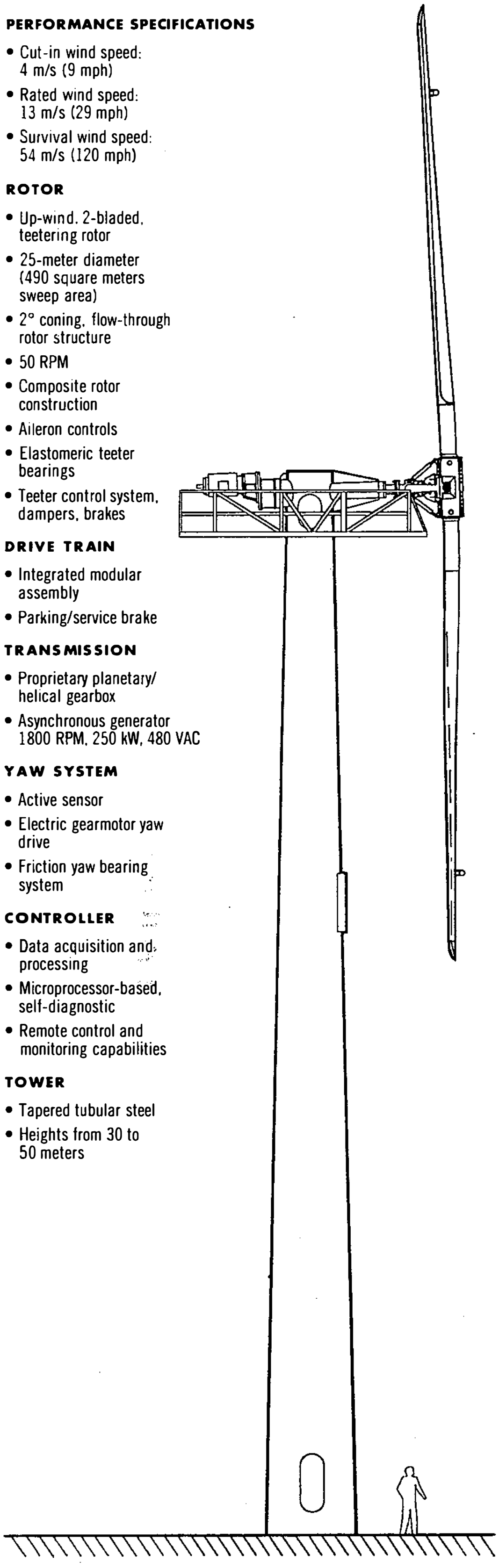
- Active sensor
- Electric gearmotor yaw drive
- Friction yaw bearing system

CONTROLLER

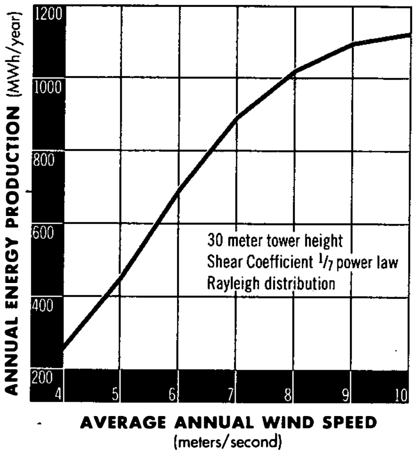
- Data acquisition and processing
- Microprocessor-based, self-diagnostic
- Remote control and monitoring capabilities

TOWER

- Tapered tubular steel
- Heights from 30 to 50 meters



NORTH WIND 250
YEARLY ENERGY PRODUCTION
FOR VARIOUS WIND SPEEDS



NORTH WIND 250
POWER GENERATION CURVE

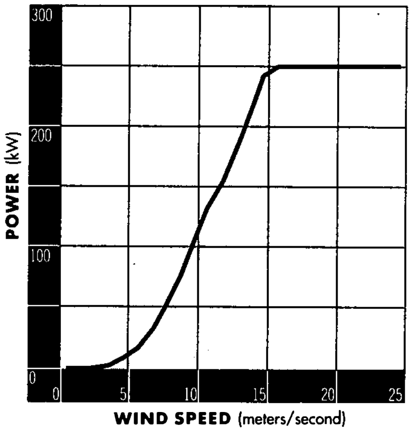


Figure 1 - North Wind 250 Turbine Technical Data

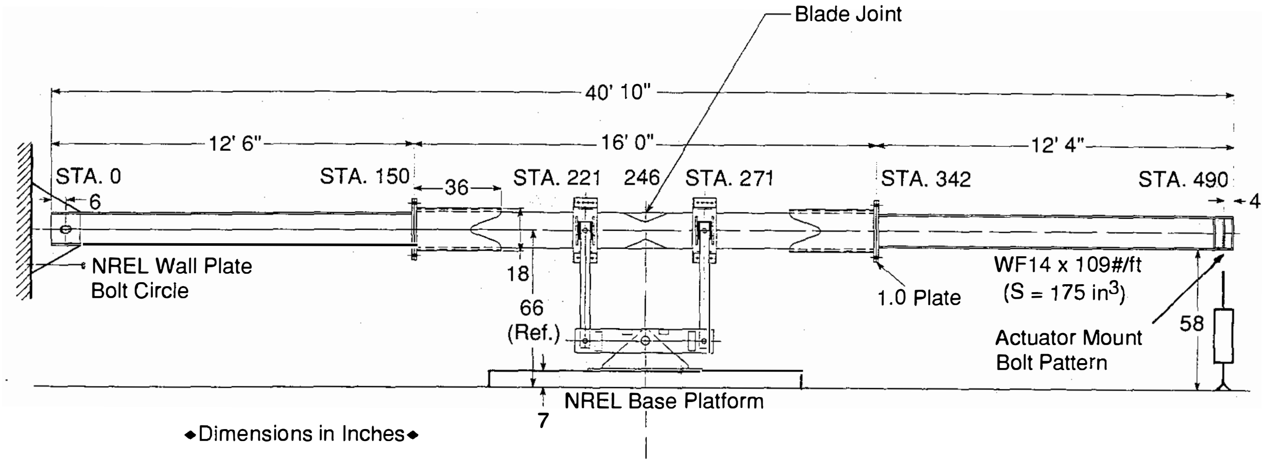


Figure 2 - Schematic of Fixture Used for North Wind 250 Joint Test

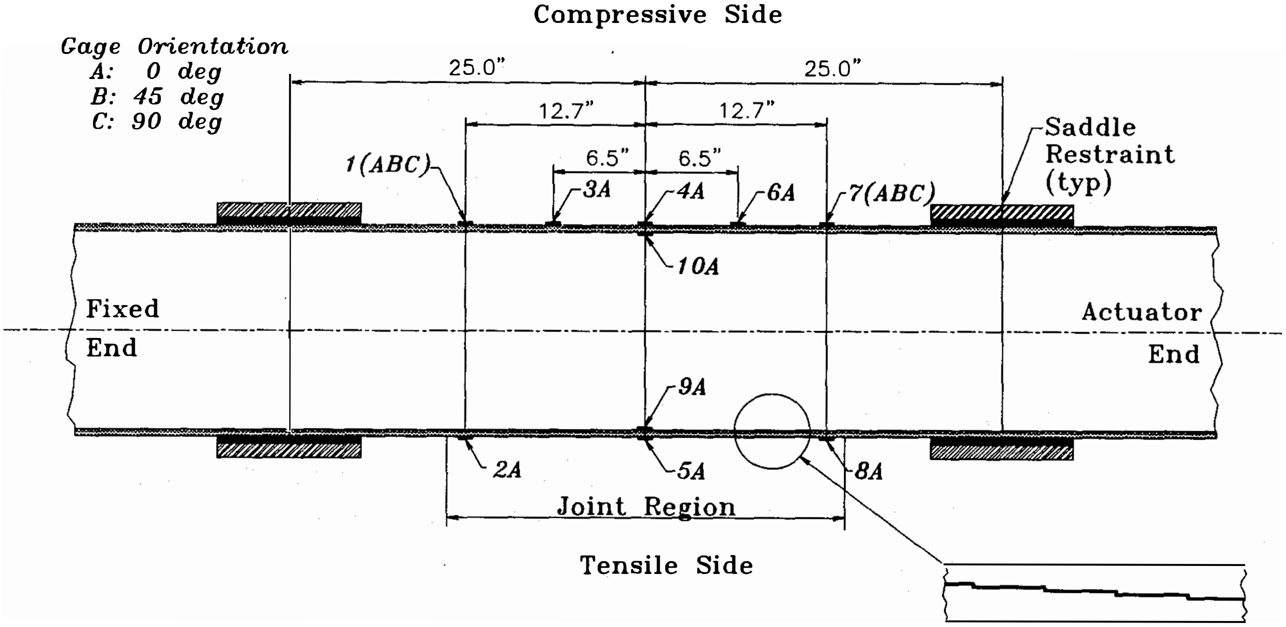


Figure 3 - North Wind 250 Rotor Joint Showing Strain Gage Locations

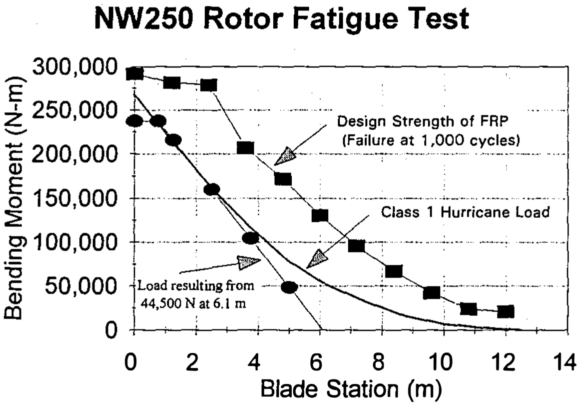


Figure 4 - Fatigue Loading of North Wind 250 Rotor Joint Compared with Hurricane Load Case and Calculated Blade Strength

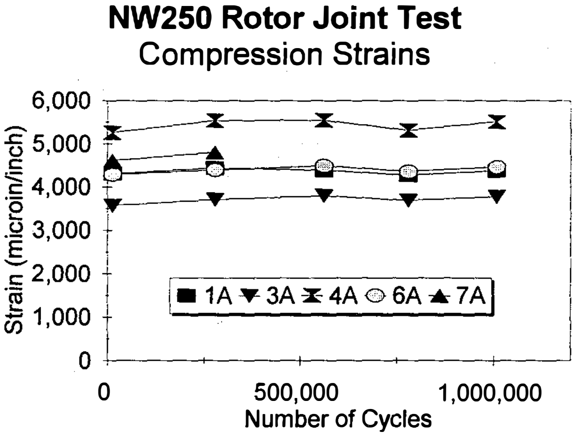


Figure 5 - Strain Measurements on Composite Joint for Test Period

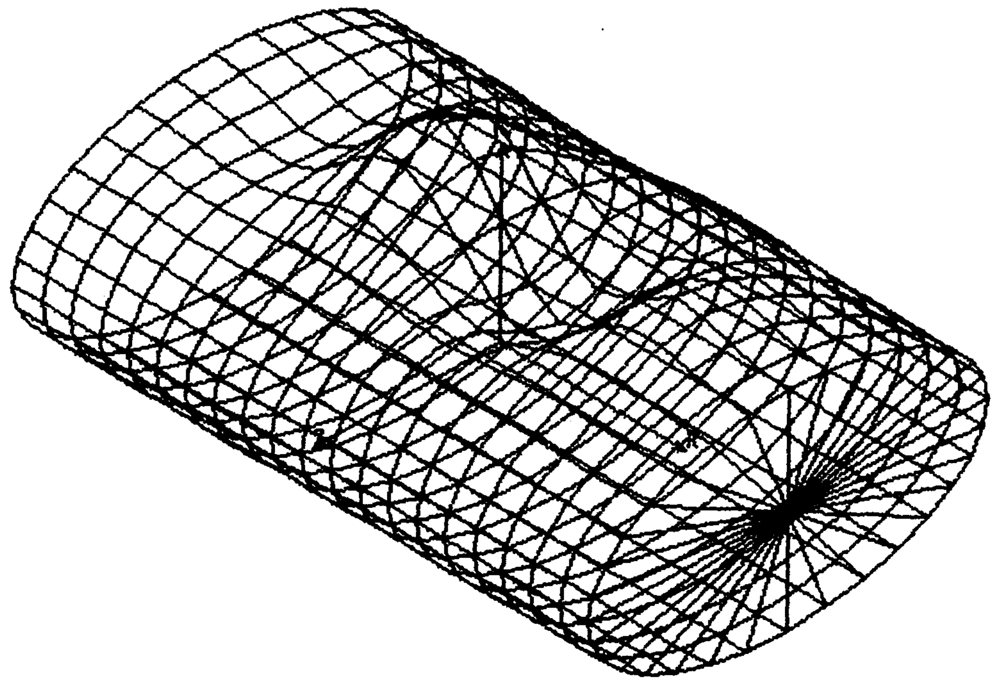


Figure 6 - Buckling Analysis for North Wind 250 Rotor Joint

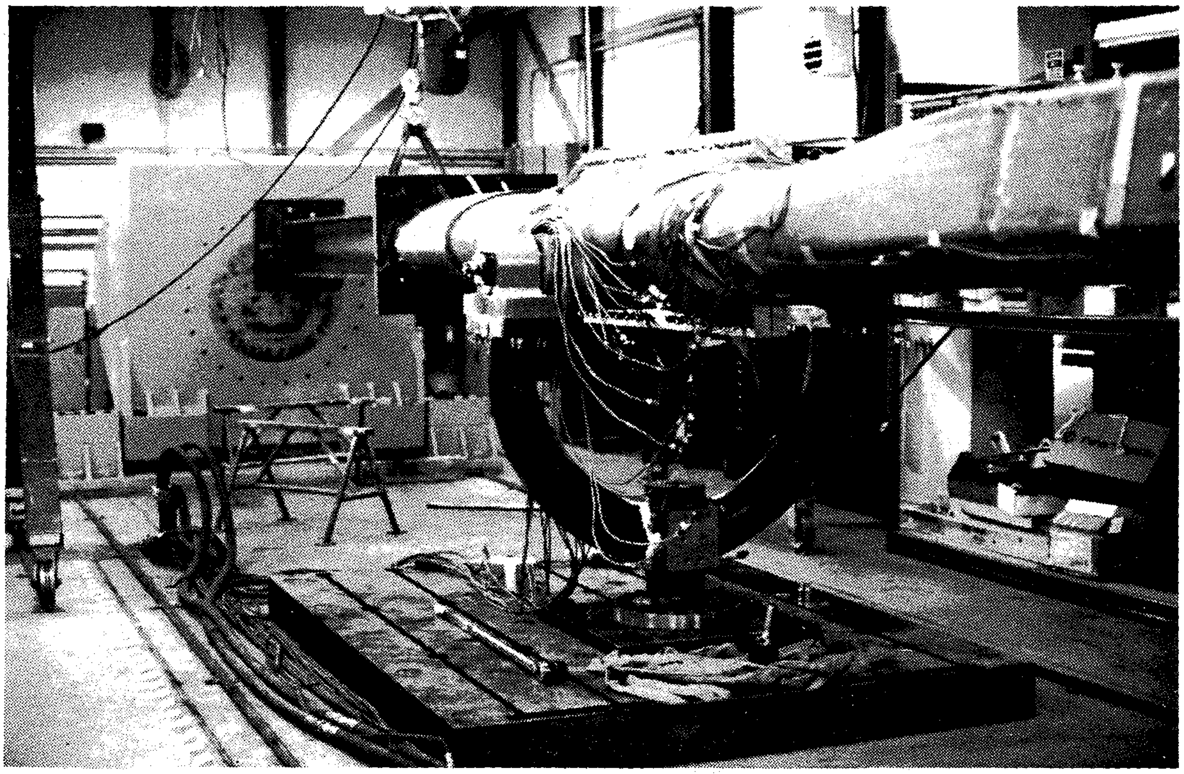


Figure 7 - North Wind 250 D-Spar Test in Fatigue Test Stand