AN OVERVIEW OF FATIGUE FAILURES AT THE ROCKY FLATS WIND SYSTEM TEST CENTER

C. A. Waldon
Rockwell International
Wind Systems Program
P.O. Box 464
Golden, Colorado

INTRODUCTION

Initially, wind energy state-of-the-art advancements involved the quantity and quality of the power produced by small wind energy conversion systems (SWECS). As wind energy commercialization increases, however, SWECS manufacturers must rapidly adopt rigid reliability programs. Wind machines must not only meet design performance specifications, but they must also perform without costly component or structural failures to assure continued market growth.

This paper is intended to identify potential SWECS design problems and thereby improve product quality and reliability. Mass produced components such as gearboxes, generators, bearings, etc., are generally reliable due to their widespread uniform use in other industries. The likelihood of failure increases, though, in the interfacing of these components and in SWECS components designed for a specific system use. Problems relating to the structural integrity of such components are discussed and analyzed in this report with techniques currently used in quality assurance programs in other manufacturing industries.

SUMMARY OF FAILURES

One of the prime objectives at the Rocky Flats Small Wind Systems Test Center (WSTC) is to determine the operational characteristics of a SWECS over a range of wind speeds up to at least 85 miles per hour (mph). At some point in the testing, most SWECS experience at least one wind storm with 85 to 120 mph winds, and the severe loading on SWECS components has been sufficient to cause failures. In some cases, the entire SWECS is lost due to a critical component failure. At least 40% of the SWECS tested have experienced one or more fatigue-related failures and of all the failures experienced, at least 65% were obvious fatigue (see Table 1). The failures attributed to fatigue have been substantiated by the Rocky Flats Plant Metallurgical Group. Since most of these failures were caused by high short-term stresses, some SWECS that survived conceivably contain parts with fatigue-related damage which has degraded the materials to the point where failure is imminent even though not apparent.

Even though the Rocky Flats wind environment is severe, the accumulative damage from lower wind speeds has also been sufficient to generate a fatigue caused failure. For example, an aluminum hub on one SWECS failed during a storm with a peak velocity of 28.6 m/s (64 mph). The SWECS had previously sustained higher wind speed loadings which apparently initiated or accelerated crack growth.

From the investigations of the failures the following causes have been identified:

1. Loadings higher than expected;
2. Vibrational loading excited within operational range;
3. Thin material was unsupported;
4. Sharp edges and threads caused stress risers;
5. Poor quality assurance on fabrication, welding, handling;
6. Voids or cracks in cast parts (no x-rays made by manufacturer).

DISCUSSION OF FATIGUE FAILURES

High Loadings

The wind energy industry includes the "garage" inventors as well as high technology research companies. Load analysis of SWECS designs range from trial-and-error methods to detailed computer programs. Regardless of the degree of design sophistication, the designer must use common sense and a spatial visualization of conditions that may be detrimental to the survival of a SWECS.

Testing has uncovered such basic problems as skin material of insufficient thickness to sustain high wind loading (Figure 1). Cyclical loading of the

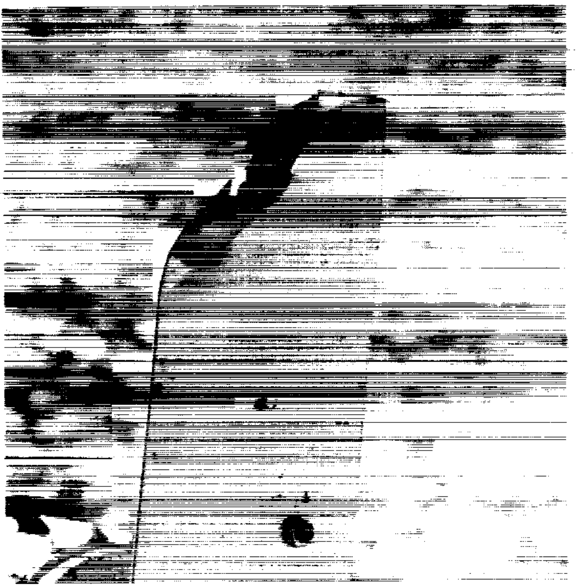

Figure 1 - Blade Skin, Fatigue Failure due to High Loading and no Support Structure.

TABLE I - SUMMARY OF WSTC FAILURES

SWECS NAME	DATE	FAILURE (PARTS & NATURE) AND REFERENCE
Dunlite 81/02550	12/04/78	Blade buckling, fatigue, and ductile fracture; tail boom and hardware fatigue; high wind - 94 mph; RFP-3028/3533/79-12.
Grumman W/S 25		None at WSTC; bolt failure and subsequent hub loss in Wyoming (modified by manufacturer).
Zephyr 15	08/14/78 01/28/78	Weld cracking from high vibration; blade failure (tied) during high winds; RFP-3041/3533/79-13.
Electro WV50G	12/04/78	Yaw shaft - coarse fatigue - multiple cracks in weld heat affected zone; RFP-3004/3533/79/7-1.
Altos 8B	03/25/79	Hub - porosity, sharp edges, hoop stresses led to rapid fatigue during gusts to 64 mph; had experienced higher; RFP-3035/3533/79-10.
American Wind Turbine AWT-16	12/04/78 12/05/78	Rotor (tied) bent in half (12/4/78),breakup (12/5/79); tail - failure still being investigated
Pinson C2E	12/04/78	Hub plates fatigue cracks from vibration; blade skins (3) fatigue cracks from vibration.
Millville 10-3 IND	12/04/78 12/05/78	Blade skins - buckling and fatigue; Weld - cracking from severe cut-in torque; Coupling - fracture from severe cut-in torque. Blade skins - buckling, fatigue and rivet pull through; RFP-2992/3533/79-3.
Parris-Dunn Free-Lite	12/05/79	Hub nut - unscrewed; Rotor shaft keyway - fracture on side; hub collar fracture; 119 mph wind storm.
UTRC (1/3 scale)	09/20/79	Caught upwind, tried to cut-in, and fractured coupling.
Dakota SI-4	12/05/79	Eye bolt weld - fracture - report not released; Blade - fractured on contact with tail boom; tail boom weld - fracture from blade strikes.
Whirlwind A240	04/06/80	Came off tower - cause unknown; Blade - fracture from high rpm and vibration.
Enertech 2 kW HR-1	12/21/79	Lightning rod - fatigue from high vibration.
North Wind 2 kW HR-1	11/79	Rotor shaft - bent, load unknown.
Windworks 8 kW Proto	03/80	Blade - ground contact fractured tip (metal to fiberglass); hub collars - fatigue in corner to porosity; bolts - cracks in threads - fatigue to failure. Report in preparation.
ASI/Pinson 2 kW HR	03/80	Cracks in welds - noted prior to testing.

blade in this example created fatigue cracking and eventual failure. This created high vibration loadings in other components and contributed to their failure as well (Figures 2 and 3).

SWECS which have induction generators must accurately control the rotor rpm and the electrical connection to the grid. The reverse torque from a cut-in at too high a rotor rpm can lead to severe damage to couplings (Figure 4). Secondary damage can be suffered by the rotor and nacelle support structure.

The fact that a SWECS is undergoing maintenance does not eliminate the possibility of damage. A rotor shaft was accidentally bent during a manual manipulation of the rotor system. The bend was discovered when machine operation revealed high rotor vibrations. The associated frequencies were close to other component frequencies and their excitation was also noted. An unbalanced rotor can have the same effect and lead to fatigue failures in several components. The shaft, in this instance, was loaded to the design stress or beyond.

VIBRATION

SWECS vibration is often generated during operation of the rotor. The wind loads on the

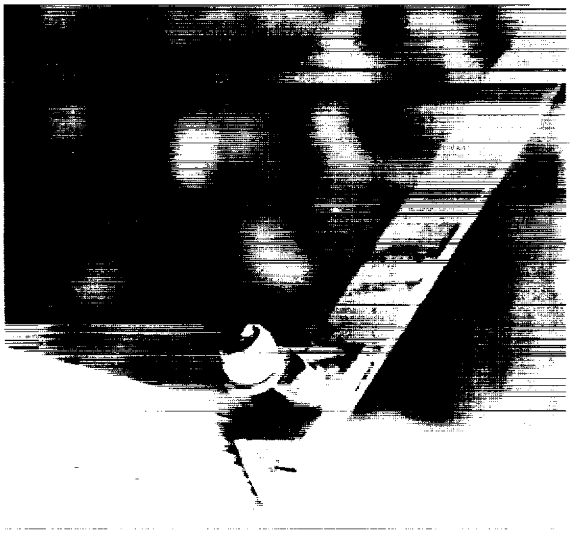

Figure 2 - Tail boom, Attachment fatigue due to high stress and vibration.

Figure 3 - Tail boom, Fatigue emanating from attachment holes.

Figure 4 - Coupling, Failure from high torque cutin.

rotor occur with somewhat random frequencies. The frequency durations are short and system damping usually prevents excitation from creating high loadings. The critical points are when SWECS operational frequencies (i.e., rotor rpm) coincide with the fundamental frequencies of the system components. The rotor blades, in particular, are critical because their excitation is transmitted throughout the system and may cause other component excitation.

The rotor vibrations of interest are: 1 per revolution (1P), 2P, and 3P; 1st, 2nd, 3rd fundamental flapwise; 1st torsional; and 1st chordwise blade frequencies. The 1P, 2P and 3P are directly related to operational rpm and are excited by rotor imbalance or aerodynamic loading (i.e., tower shadow) generic to some SWECS configurations. The critical point is where the operational frequency coincides with a blade fundamental frequency.

A typical high vibrational loading failure is shown in Figures 5 and 6. The SWECS underwent a high energy 3P rotor excitation at a frequency where the SWECS and tower interacted (4.5 Hz). The vibrational motion was termed "violent" and led to rapid fatigue growth of cracks in the blade skins and welds at the rotor shaft and support plate joint. In this case, the skin design should have eliminated the stress risers (sharp corners) and firmly attached the skin around the joint to the support arms. However, movement in the skin under operational loadings caused fatigue cracking (Figure 5), and weld cracking (shown in Figure 6) was initiated by severe motions of the rotor and tower. The welds were found to be of good quality, pointing out the need for proper SWECS and tower matching. Modal analysis was conducted after the failure and after installation of a new unit on a different tower. The tests confirmed that first tower and SWECS interacted. They also predicted the new configuration would pass through the rotor 3P excitation, with greatly reduced energy at a frequency of 2.5 Hz of the tower. A new 1P excitation was felt to be a possibility (corresponding to rotor imbalance) but has not been seen to date.

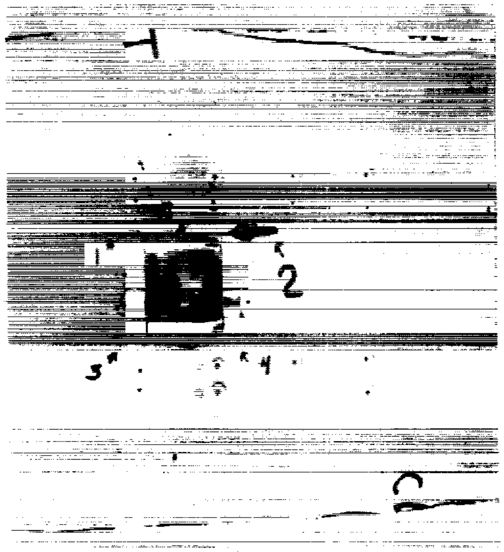

Figure 5 - Overall view of cracks in the skin of a blade. The numbers indicate the cracks.

Figure 6 - Overall view of one of the cracks in a plate on the rotor shaft.

Figure 7 shows a 2-minute visicorder trace of a SWECS rotor system with a fundamental 1st bending frequency of approximately 7 Hz. During the modal analysis, it was discovered that two sharp frequency peaks existed, one at 6.6 Hz and the other at 7.2 Hz. Figure 7 shows there is a notable increase in amplitude of the bending and torsion between the corresponding rpm's noted on the trace. An rpm of 396 represents 6.6 Hz and 420 rpm represents 7 Hz. Modal analysis of the loadings that generated this trace confirmed that the fundamental bending and torsional frequencies were present.

Several changes could be made to the system to rectify this problem, but the problem should have been originally noticed in a Fan Diagram and designed out as an undesirable operating point. A typical Fan Diagram is shown in Figure 8. It should be noted that if the diagram is generated by theoretical analysis, it must be substantiated for component compliance with predictions, which is sometimes beyond the manufacturer's capability. One possible design change is to modify the blade fundamental frequencies, in this case upward, as 420 rpm is near maximum for the machine. Another change might be to alter the rpm control and not allow the critical rpm to be reached. Both of these changes would have to be checked for interference frequencies with other components prior to implementation.

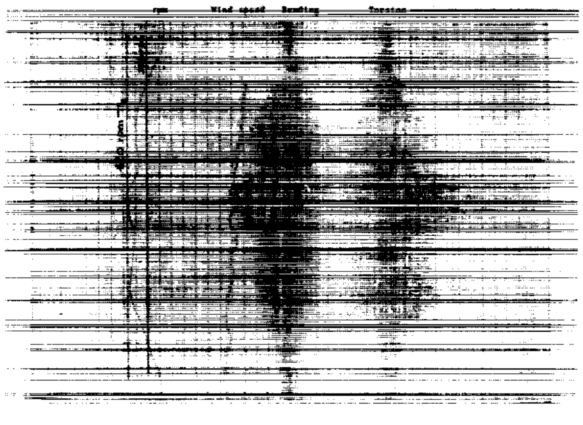

Figure 7 - Visicorder trace of bending and torsional vibration excitation on North Wind Prototype # 1 blade.

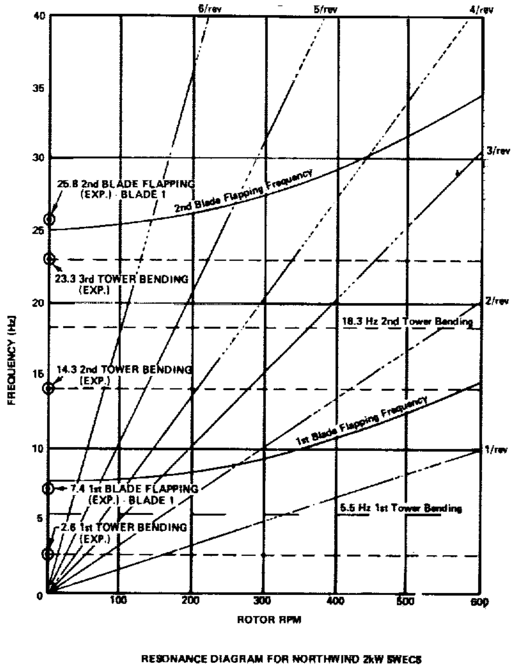

Figure 8 - Typical fan diagram.

Thin Material Loading And Attachment

When SWECS have metal blades, it is common to use a thin skin covering to create the airfoil shape. The substructure could include ribs, stringers and spars. The combination of these parts must be lightweight, yet strong enough to carry the loads. Part interfacing and placement are the areas in which problems normally arise.

The first case in point involved a SWECS that experienced a windstorm while in a maintenance orientation. The blades (which consisted of a main spar, ribs and skin) experienced buckling of the skin between the ribs. The buckling created highly stressed areas which fatigued rapidly. Figure 9 shows the buckled areas and the resulting fatigue cracking. It should be noted that the cracking also propagated along the leading edge, which was due to a tight-bend radius creating residual stresses in a material which was not sufficiently ductile. The leading edge crack was secondary, but design changes were still required to correct the problem. The blade skin between the ribs was unsupported and when bending was sufficient on the compression side of this airfoil, the skin buckled. This is commonly known as "oil canning." The redesign included the addition of stringers between the ribs that attach to and support the skin, changing the leading edge radius and adding a leading edge spar. A material change was also made which helped to reduce the residual stresses and microcracks that are present in tight radius bends in brittle materials. These changes increased the survival rating by approximately 30%.

The blade failure in Figure 1 was of a similar type, except the rotor was operating and the wind exceeded the survival rating. Since the manufacturer has a different blade for high wind speed sites, no redesign was made.

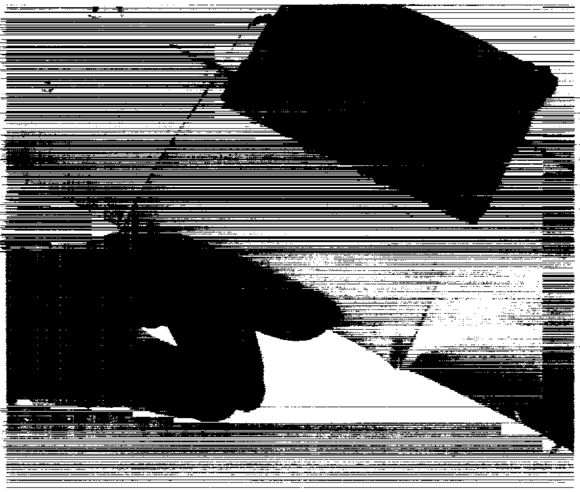

Figure 9 - View of Blade skin buckling and cracking in unsupported area. Note leading edge cracks and skin peeling.

Another blade skin problem which potentially leads to fatigue (Figure 10) is the attachment of skin sections to the ribs, where the thin skin is a load-carrying component. Riveting alone is often insufficient to transfer the loads. The movement between the skin and ribs tends to elongate the holes until rivet pullthrough occurs, which increases the stress at the remaining rivets. This movement also causes galling and fatigue cracking. Using skin doublers in this area (possibly with a bonding substance) will clamp the skins to the rib, and load can be transferred by friction between the layers as well as the rivets. Care must be taken in selecting similar materials which do not create galvanic action, and in making joints aerodynamic so that blade performance is not reduced.

Stress Risers

Stress risers are not totally avoidable. However, a few simple considerations should be reviewed to avoid spontaneous loadings and failures.

Holes represent a stress concentration factor of approximately 3. A much higher factor is possible if: 1) the hole is not deburred; 2) improper edge distances are used; or 3) the hole has sharp corners (i.e., a square hole). Figure 5 shows cracks beginning at sharp corners. Burrs in the holes can cause premature failure of the fastener as well as the surrounding metal. Scratches and notches have the same effect and precautions should be taken to avoid them.

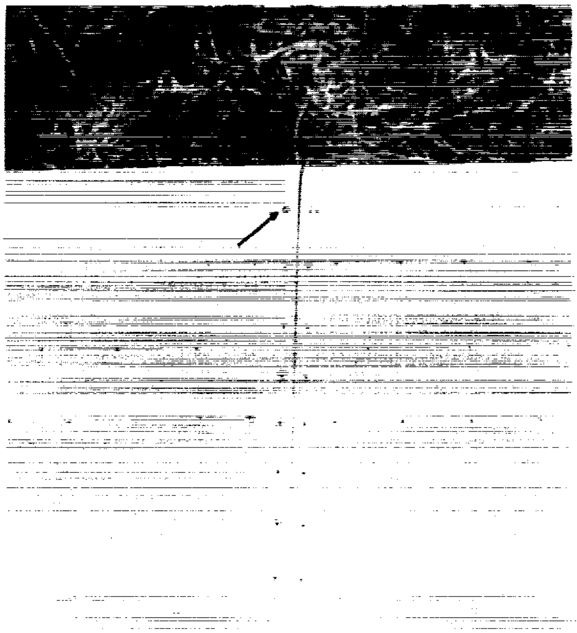

Figure 10 - An example of how skin movement caused rivet pullthrough. (arrow)

Bolts contain stress risers in the threaded area and when used in high stress areas or bending it is imperative that no threads are in the bend area. Bolts should also be of good quality, even if rolled threads are required.

It is also important to consider the environment and materials being used. Corrosion from salt water spray or galvanic action may create stress risers that lead to rapid failure. Anodized coatings and the use of bonding compounds can help avoid problems.

When parts are machined, it is important to cut proper radii and break all sharp edges. The intersection of two holes should be checked for stress risers and such intersections should be avoided as much as possible.

If the part is cast, x-rays should be taken to assure that no voids exist. Figure 11 shows an example of a cast part which contained voids. The machined hole penetrated the voids, and a fatigue crack developed which led to the failure. It is possible that the void alone may have been sufficient to cause the failure.

The heat affected zone surrounding a weld can be an area containing microcracks and residual stresses sufficient to cause fatigue cracking and eventual failure. Figure 12 shows a fractured weld in a highly stressed area of a SWECS yaw column. This failure led to the loss of the machine, which fell from the tower. Such welded areas should be designed away from the high stress areas or should be heat-treated to reduce residual stresses. Proper welding practices must be followed, and the services of a certified welder should be obtained whenever possible. Proper removal of slag and even the grinding of a small portion of the weld surface can help prevent fatigue cracking. Where multiple weld passes are necessary, the weld area may have to be "back ground" to insure integrity. Making sure of sufficient weld material and a reasonable "factor of safety" will also help prevent unwanted failure. X-rays of welds are prudent.

Figure 11 - View of hub which fatigued from area of casting voids.

Quality Assurance

The manufacturer has a basic responsibility to assure the SWECS is manufactured, handled and delivered to the dealer without undue degradation to the life of the components or system. The use of x-rays to check for casting voids and cracking in a welded area was discussed in the previous sections. Material handling is important from the initial fabrication to the final installation of the SWECS. Materials must be kept free from damage or alterations of the planned design. Fabrication discrepencies located in a highly stressed area could lead to premature failure and costly replacement. Figure 13 shows three variations of the forming of a blade trailing edge. If the deformities had been more pronounced, they conceivably could have affected rotor dynamics and caused vibration which could have led to fatigue failure. Figure 14 shows a similar deformity problem and also a crease which is the type of damage that initiates and accelerates fatigue cracking.

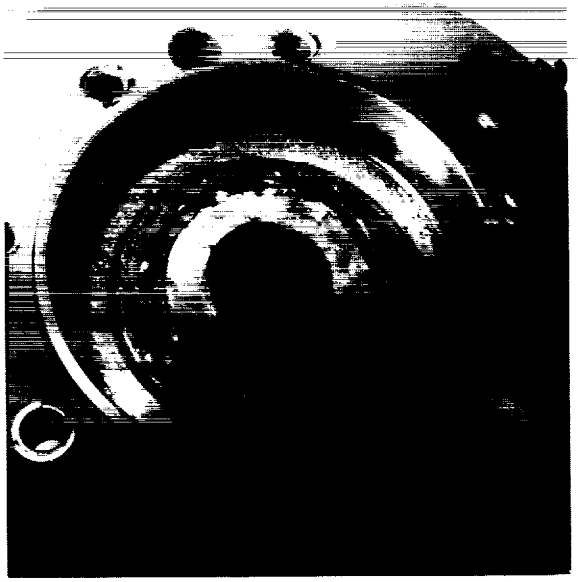

Figure 12 - View of yaw column fatigue in weld.

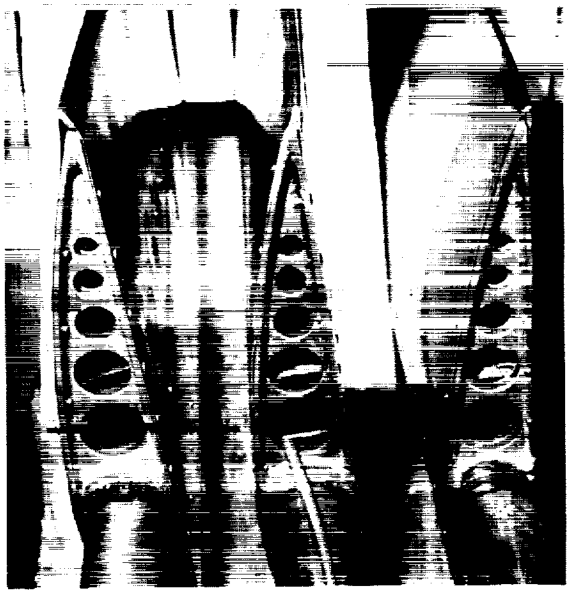

Figure 13 - Variations in manufacturing the trailing edge can lead to aerodynamic instability.

Shipping the SWECS to a buyer's site can be costly if the packaging is insufficient to protect the components. Figure 15 shows a crate which was destroyed during shipping, resulting in blade skin damage (arrow) which required replacement at the manufacturer's expense. Figure 13 shows how the blades were subsequently shipped in a box with plywood sides and foam dividers between the blades and the sides. While this method of shipping is more costly, it will probably be cheaper than replacing damaged parts.

Figure 14 - View of blade manufacturing damage. (arrow)

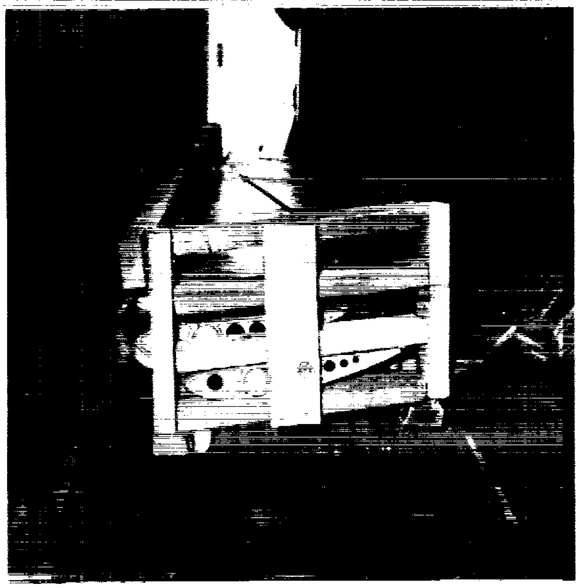

Figure 15 - View of packing crate damage and damaged blade skin. (arrow)

CONCLUSIONS

Prevention of fatigue failures is within the capability of even the most financially restricted companies. The reliability and safety of a system depend on doing the best designing, manufacturing, and installing possible. Where long-range survivability predictions are needed, component and system testing becomes necessary. While manufacturers do conduct tests, limited funds and equipment usually restrict such tests. Computer programs are available which may aid those designers and manufacturers who suffer these restrictions. In addition, the WSTC plans to perform fatigue tests on SWECS components under atmospheric loading conditions, and Rocky Flats personnel are available to discuss fatigue problems and aid in analysis.

REFERENCE

1. Waldon, C.A., "Wind Machine Fatigue Analysis and Life Prediction", Rockwell International April 1980, RFP-3135/3533/80/19.

QUESTIONS AND ANSWERS

C.A. Waldon

From: G.P. Tennyson

Q: The presentations (not just yours) indicate what the manufacturers did to contribute to problems and failures. Will there be similar presentations concerning the DOE/Rockwell contributions?

A: *Some of the DOE/Rockwell contributions to failures are included in Table I, but since they were not characteristic of fatigue, they were not discussed (i.e., AWT (TIED) rotor failure). This is a good lesson from a big mistake we made and reported. It will be brought up again and presented in the Reliability and Safety Program output.*

From: W. Frost

Q: a) Are the statistics and causes of failure reported and available to the public? If so, how does one get a copy?

b) How were the 120 mph (or 94 mph) winds you mentioned measured and where were they measured relative to the WTG?

A: *a) All failures are reported, including the mistakes made during the testing. All are considered useful lessons and specific requests should be made to Mr. Darrell Dodge, Rockwell, Int., P.O. Box 464, Golden, CO 80401 - Attn: Wind Systems Program or call 303/441-1351.*

b) The winds were measured by Propvane anemometers located upwind of the SWECS tower. Anemometer height was 5 ft below rotor centerline and approximately 5 rotor diameters upwind.

From: F.W. Perkins

Q: What do you consider "acceptable" failure behavior for prototypes? Are any failures acceptable? What RFP initiatives could reduce failures, e.g., extended contractor testing?

A: *Failures are costly, but may be a useful data point if verification of design ultimate strength is desired. Failures outside of "testing" are hurting the entire industry. Extended testing is part of the Rocky Flats Plant (RFP) plan for prototype, manufacturer testings.*

From: W.C. Walton

Q: Would you agree that the failures you have shown stem from deficient detail structural design techniques? If so, why do you connect them so strongly with aerodynamics?

A: *Most of the failures are structural in nature, but it is the difference in theoretical to actual which appears to create a failure for an otherwise adequate design. Analysis should look at nonoperating conditions and be verified for all conditions.*