THE MOD-1 STEEL BLADE

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INTRODUCTION

Since September of 1977, design, development, fabrication, testing and transport of two 100 foot metal blades for the MOD-1 WTS has been completed. This paper summarizes that activity. Because the metal blade design was started late in the MOD-1 system development, many of the design requirements (allocations) were restrictive for the metal blade concept, particularly the maximum weight requirement. The unique design solutions required to achieve the weight goal resulted in a labor intensive (expensive) fabrication, particularly for a quantity of only two blades manufactured using minimal tooling. Nevertheless, the very existence of the blades represents a major achievement in large wind turbine system development.

SPECIFICATIONS

The blade was designed to the GE Specification 273A6684, which also included an interface drawing 132D6479. The primary requirements are tabulated on Figure 1. For convenience, the requirements have been listed in geometric, structural, and performance categories, and the actual values achieved by the design have also been noted.

Weight control was a constant concern for this design. Fitting the blade structure to the specified weight limit required base metal fatigue allowables that would not allow use of mechanical fasteners and that required a better than "as rolled" surface finish.

DESIGN DESCRIPTION

Each blade comprises a 97-1/2 foot long steel welded monocoque spar and a monolithic foam filled bonded trailing edge afterbody, as shown in Figures 2 and 3. Principal elements are (1) the spar, including the interface ring and the tip weight cavity; (2) the trailing edge (afterbody) structures; and (3) the joining system which attaches the T.E. to the spar. A detailed description of each of these elements follows:
Spar: A tapered, twisted, monocoque structure, formed in 15 foot sections of A533 Grade B, Class 2 material, and welded together. Upper surface plates are machined to provide "lands" for chordwise weld joints, as shown in Figure 4. The lower surface is stiffened with T-stiffener and frames for buckling resistance (see Figure 5). The hub flange is completely machined from a ring forging (A508) to efficiently use material to carry loads around the corner into the hub bolts (see Figure 6). Tip structure is machined from a block to provide leading edge radius (too sharp to be brake formed) with a cavity for incremental balance weights.

Trailing Edge: The six afterbodies are fabricated in 15 foot sections. Foam core blocks of different densities are bonded together and contoured to proper aerodynamic shape. Stainless steel skins (24 gage 301 1/2 hard) are bonded to upper and lower surfaces, and a cap is added at the extreme trailing edge. Conical lightening holes in the foam are included in the inboard sections only, as shown in Figure 7.

Joining System: The spar is prepared by construction of a flat interface surface using foam-in-place material with nominal 10 lb./cu. ft. density. The cured foam is surfaced and contoured. T.E. sections are bonded to the foam surface. Stainless steel (024 gage 301-1/2 hard) splice plates are installed across the chordwise joints between T.E. sections and along the spanwise joints. Butt joints in the splices are overlaid with similar gage cover plates. All exposed bond edges are covered with 2 inch wide 3 mil. stainless steel foil applied with polysulfide sealant for a moisture barrier. Stainless steel bands around the spar and trailing edge at approximately 5 foot intervals are also installed with the sealant material to provide a secondary attachment system.

DESIGN PROCEDURE
Blade design was accomplished in accord with established NASA design cycle and in close cooperation with GE who retained responsibility for all loads development and for system power. A three week trade off study with GE was the concept design phase and established the basic blade geometry that optimized the power within the constraints of our welded spar concept and the conditions of the contract.

DESIGN LOADS
Design load conditions were identified as frequent or infrequent, and were presented as integrated chordwise and flapwise...
bending moment curves. For the frequent loading conditions, mean moments and cyclic moments were defined. A typical design curve is shown on Figure 8. Azimuthal phasing relationships of the chordwise to flapwise loads were supplied but for conservatism the design analyses combined the maximums. The critical frequent design condition, 35 mph wind velocity, 35 rpm, designed the structure for fatigue. Two infrequent conditions, emergency feather shutdown, a 38.9 rpm overspeed condition; and hurricane, 120 mph wind in the parked position, designed the structure for static buckling loads. The critical load diagram is shown on Figure 9.

Iteration of the design loads was accomplished by GE after the final design was completed. Based on final weight distribution and section properties, incremental loads were provided at 30° azimuthal angles for a finite element analysis. An ATLAS program was conducted with a total of 2,100 elements identified for the spar and 500 elements for the trailing edge structure. All calculated values showed positive margins for both the frequent and infrequent conditions. A typical stress distribution for the spar upper surface is shown on Figure 10.

ALLOWABLE STRESSES

Fatigue allowable stresses were established to be consistent with the AISC Handbook and the allowable developed by a fracture mechanics approach, considering the design spectra of wind loading conditions and the number of cycles expected at each wind velocity and gust factor. A simplified diagram of this approach is shown in Figure 11.

The selected allowable for RMS 125 surface finish base metal, Sr=28,600 psi, was verified for both spar and trailing edge skin materials by a fatigue test program conducted using pre-cracked A533 specimens. This test program also established that welded metal has the same response as base metal. The loading spectra were not identical to the MOD-1 system, but were similar enough to provide verification. A more comprehensive description of this test is included in G. N. Davison's paper on the MOD-2 rotor.

AISC fatigue allowables for the various weld joint categories were validated by determining the limiting defect size that a fracture mechanics approach established and then providing the inspection techniques applicable to each joint configuration to discriminate defects smaller than this limit. The results of these analyses are shown on Figure 12.
Fatigue allowable \( (Sr) \) for the epoxy bonding system shown in Figure 13 was established at 240 psi. This value considered the maximum expected operating temperature and was based on data developed for helicopter blade repair. The value was further verified by a constant amplitude fatigue test program of three specimens at bond stress levels of 240, 158, and 75 psi, all of which completed \( 5 \times 10^7 \) load cycles without failure. Static allowables for bonded joints were established by a test program that tested lap shear specimens after exposure to various environments as shown in Figure 14. The trailing edge design stresses were verified by a fatigue test of a typical section which completed \( 1.3 \times 10^7 \) load cycles at 1.2 Hz and in various temperature and humidity environments without failure or evidence of bond deterioration. Figure 15 shows the test setup.

Buckling allowables for the spar were established by curved plate analyses based on Roark's theories and the Boeing Design Manual. The degree of difficulty in determining edge fixity and the overriding effect of initial panel straightness dictated a test program. A fifteen foot long spar specimen, including a chordwise weld joint, was fabricated using prototype tooling to control distortion. Initial tests resulted in premature failure. A longitudinal stiffener was incorporated at the center (25% chord) of the lower (compression) surface and the specimen sustained bending moment in excess of design ultimate load without failure (Figure 16).

Buckling allowables for the trailing edge stainless steel skin supported by the foam were determined using the Boeing Design Manual. Compression and shear moduli for the various foam densities were obtained initially from vendor data and verified by test of each foam shipment. In addition, compression tests of single-face sandwich specimens were conducted to validate the buckling stability of the T.E. sections with the lightening holes. Figures 17 and 17(a) show typical allowables and design stresses.

DESIGN FACTORS

The one overriding design factor that influenced many of the design decisions was the specified weight limit. The limit was just too low to allow alternate design solutions that might have resulted in a simpler design. Figure 18 summarizes the influence of the weight limit.

The overall size of the blade exceeded any known facilities for high temperature autoclave bonding. As a result, the
the room temperature epoxy system was developed for steel-to-steel and steel-to-foam applications. Also, local heating techniques for postweld stress relief of the spar weldment were required because available furnaces were too short.

While not specifically a design factor, the program schedule requirements influenced many of the design decisions. The spar section length (15 ft.) was selected to fit the capacity of a number of existing brake presses. Similarly, the decision to use stainless steel for the trailing edge skins was dictated when high strength carbon steel (4130) was not available in the required gage to meet the schedule requirements.

**BLADE COST**

The MOD-I steel blade is without doubt a costly "Cadillac" structure. Even with the significant development and tooling costs not included, the costs exceeded $40.00 per pound of structure.

The cost drivers were primarily the labor costs associated with fabricating a total of only two units to a tight schedule which excluded use of automatic production type tooling and processes.

Many of these experienced costs would be substantially reduced for fabrication of follow on blades. In addition, a different schedule could provide opportunity for material substitutions to reduce costs.

To be cost competitive, however, it appears that a significant investment in production tooling (and facilities) and an increase in the blade weight ($\sim 25\%$) to eliminate machining, compression surface stiffeners and grinding will be required.

**MAJOR PROBLEMS**

The design was completed in six months (Final Design Review on March 15, 1978) and there have been no significant redesigns during the fabrication. During fabrication a number of problems occurred, as expected in a development program of this kind. The first occurred when the spar material we selected (A533 Grd B Cl 2) was bid by only one mill and required special mill run production. This delayed delivery and gave us a late start on fabrication of the spar.
A second setback occurred during in-place postweld heat treat of the first spar lower surface "clamshell" weldment. Severe distortion resulted from thermal gradients caused by improper heating techniques. See Figure 19. Although the weldment was almost completely flame straightened, engineering analyses would not confirm that full structural capability had been restored, and the weldment was replaced.

During final assembly, several small splice plates disbonded under no load conditions. Failure investigation established that the primer was not fully cured and that the final rinse prior to priming was inadequate, leaving a detergent film on the stainless and preventing the primer from adhering. Improved process control was established to prevent future occurrence, and the completed assemblies were mechanically tested to verify the bonding.

CONCLUSIONS & RECOMMENDATIONS

It is difficult and expensive to produce a blade structure to fit a set of predetermined constraints. Overall system trades earlier in the design process will reduce the downstream problems.

Fabrication costs can be reduced by minimizing the hand work requirements through design, tooling, facilities and mass production.

It is recommended that funding and schedules for this type of development program have an adequate reserve to allow resolution of unforeseen, unscheduled, and unfunded problems.
<table>
<thead>
<tr>
<th>GEOMETRY</th>
<th>Spec Requirements</th>
<th>Actual</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interface to hub</td>
<td>56-1.25 inch dia. holes</td>
<td>Same</td>
</tr>
<tr>
<td>Length</td>
<td>97.5 feet</td>
<td>97.4 feet</td>
</tr>
<tr>
<td>Airfoil shape</td>
<td>NASA 44xx</td>
<td>Same</td>
</tr>
<tr>
<td>Twist</td>
<td>11° root to tip</td>
<td>Same</td>
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<table>
<thead>
<tr>
<th>PERFORMANCE</th>
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<th></th>
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<tbody>
<tr>
<td>Operational life</td>
<td>30 yrs. (4.35 x 10^8 cycles)</td>
<td>To be determined</td>
</tr>
<tr>
<td>Design loads</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frequent</td>
<td>35 mph wind (35 rpm)</td>
<td>Same</td>
</tr>
<tr>
<td>Infrequent</td>
<td>24.8 mph wind (35 rpm)</td>
<td>Same</td>
</tr>
<tr>
<td></td>
<td>120 mph hurricane (static)</td>
<td>Same</td>
</tr>
<tr>
<td></td>
<td>Emergency feather-overspeed (38.9 rpm)</td>
<td>Same</td>
</tr>
<tr>
<td>Balance weights (tuning)</td>
<td>500 lbs @ 40 lb. increments</td>
<td>516 lbs. (43 lb. increments)</td>
</tr>
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<table>
<thead>
<tr>
<th>STRUCTURAL</th>
<th>Spec Requirements</th>
<th>Actual</th>
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<tr>
<td>Material</td>
<td>Metal</td>
<td>A533 spar, 301 trailing edge</td>
</tr>
<tr>
<td>Weight</td>
<td>20,000 lbs ± 1%</td>
<td>20,850 lbs – No. 001</td>
</tr>
<tr>
<td></td>
<td>1.17–1.45 Hz</td>
<td>20,710 lbs – No. 002</td>
</tr>
<tr>
<td></td>
<td>2.80–2.98 Hz</td>
<td>1.45 Hz (300 lbs bal. wt.)</td>
</tr>
<tr>
<td></td>
<td>&gt;17.5 Hz</td>
<td>2.67 Hz (300 lbs bal. wt.)</td>
</tr>
<tr>
<td></td>
<td>≤35% chord aft of l.e.</td>
<td>29.24 Hz (300 lbs bal. wt.)</td>
</tr>
<tr>
<td>Frequency (Rigid mount)</td>
<td>Sr=28,600 psi</td>
<td>33.66% aft – No. 001</td>
</tr>
<tr>
<td></td>
<td>Sr=16,000 psi</td>
<td>34.19% aft – No. 002</td>
</tr>
<tr>
<td></td>
<td>Sr=12,000 psi</td>
<td>Same</td>
</tr>
<tr>
<td></td>
<td>Sr=5,000 psi</td>
<td>Same</td>
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<table>
<thead>
<tr>
<th>Fatigue allowables</th>
<th></th>
<th></th>
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</thead>
<tbody>
<tr>
<td>Base metal – Cat. A' (125 rms)</td>
<td>Same</td>
<td></td>
</tr>
<tr>
<td>Welds – Cat. B</td>
<td>Same</td>
<td></td>
</tr>
<tr>
<td>Cat. C</td>
<td>Same</td>
<td></td>
</tr>
<tr>
<td>Cat. E</td>
<td>Same</td>
<td></td>
</tr>
</tbody>
</table>

Figure 1. MOD-1 Primary Blade Requirements
**Welded Spar**

Blade station

Transition section

Ring attach forging

Chordwise weld joint

See Figure 3

Trailing edge cap

Belly bands (2 in. wide)

Spanwise splices

Chordwise splices (18 in. wide)

6 places

**Bonded Trailing Edge**

Splice plate

301 stainless steel—24 gage

Upper spar panel

A533—1\(\frac{1}{4}\) to \(\frac{1}{2}\) inch thick

Foam-in-place

10 lb/ft\(^3\)

Block foam

8 lb/ft\(^3\) to 3 lb/ft\(^3\)

Trailing edge skin

301 stainless steel—24 gage

3 mil foil strip polysulphide sealer (typical all bond edges)

**Figure 2. MOD-1 Blade Assembly**

**Figure 3. MOD-1 Blade Cross Section**
Figure 4. Upper Surface Plate (Typical)

Figure 5. Lower Surface Stiffener
Material: ASTM A508 CL. b forging

Figure 6. MOD-1 Blade Attach Flange

Figure 7. Typical TE Section.
**Figure 8. Chordwise Bending Moment Distribution**

**Figure 9. Design Load Conditions**

1. 35 mph fatigue
2. 24.8 mph fatigue
3. Emergency feather
4. 120 mph down gust

N_o = 0.9 \times 10^8 \text{ cycles}
**Figure 10. Upper Surface Stress Station 301**

**Figure 11. Fatigue Load Spectrum**
<table>
<thead>
<tr>
<th>Type of welded structure</th>
<th>Weld category</th>
<th>Crack growth design allowable flaw size</th>
<th>Inspection method &amp; flaw detection capability</th>
<th>Flaw size acceptable criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper surface Chordwise welds</td>
<td>B (16,000 psi allowable)</td>
<td>.06 deep X .30 long</td>
<td>VT .005 wide X .06 long</td>
<td>.06 long (linear indications)</td>
</tr>
<tr>
<td>Transition section welds</td>
<td></td>
<td>.12 deep X .30 long</td>
<td>PT .005 wide X .03 long</td>
<td>.125 long (round indications)</td>
</tr>
<tr>
<td>Trailing edge spanwise Welds sta 51 to sta 250</td>
<td></td>
<td></td>
<td>RT 2% of t deep X .04 long</td>
<td></td>
</tr>
<tr>
<td>Lower surface Chordwise welds</td>
<td>C (12,000 psi allowable)</td>
<td>.09 deep X .44 long</td>
<td>VT .005 wide X .06 long</td>
<td>.06 long (linear indications)</td>
</tr>
<tr>
<td>T-stiffener Spanwise welds</td>
<td></td>
<td>.18 deep X .44 long</td>
<td>PT .005 wide X .03 long</td>
<td></td>
</tr>
<tr>
<td>Trailing edge Spanwise welds Leading edge Outboard of sta 250</td>
<td>E (5,000 psi allowable)</td>
<td>.54 deep X 2.70 long</td>
<td>VT .005 wide X .09 long</td>
<td>.125 long</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.08 deep X 2.70 long</td>
<td>PT .005 wide X .06 long</td>
<td></td>
</tr>
</tbody>
</table>

*Figure 12. MOD-1 Spar Welds Inspection Matrix*

Splice plate and trailing edge skin (CRES 301) surface prep
1. Vapor degrease per BAC 5408
2. Clean per BAC 5751 type 10 (phosphoric acid immersion)
3. Prime per BAC 5514-589 (BR-127)

Spar (A533) surface preparation
1. Sand blast per BAC 5748
2. Prime per BAC 5807 (MIL-P-23377)

Foam surface prep
1. Lightly sand
2. Vacuum clean

BONDING
- Adhesive bond per BAC 5010 Type 70 (EC 2216 epoxy)
- 5% glass spheres, .005 in. nom. dia.
- CAB-O-SIL as required
- Positioning fabric
- Apply pressure with vacuum
- Cure 24 hours at 100° F

*Figure 13. Surface Preparation and Bonding*
<table>
<thead>
<tr>
<th>Test</th>
<th>Environmental conditioning</th>
<th>Test temperature</th>
<th>No. of specimens</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile (lap shear)</td>
<td>120°F, 100% RH, 72 hrs</td>
<td>Room</td>
<td>5</td>
<td>3,050 psi avg (cohesive failure)</td>
</tr>
<tr>
<td></td>
<td>None</td>
<td>−31°F</td>
<td>5</td>
<td>2,992 psi avg (adhesive failures)</td>
</tr>
<tr>
<td></td>
<td>None</td>
<td>Room</td>
<td>5</td>
<td>3,050 psi avg (cohesive failures)</td>
</tr>
<tr>
<td></td>
<td>None</td>
<td>125°F</td>
<td>5</td>
<td>1,720 psi avg (cohesive failures)</td>
</tr>
<tr>
<td>Creep tests</td>
<td>None</td>
<td>5 hrs at 200°F</td>
<td>4 cycles</td>
<td>No elongation at 2.4 psi</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(from 125°F)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>5 hrs at 230°F</td>
<td>3 cycles</td>
<td>No elongation at 1.1 psi</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(from 125°F)</td>
<td></td>
<td></td>
</tr>
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</table>

Notes: Selective tests with Cab-o-Sil added for viscosity control showed no strength degradation. Tensile tests after creep cycles averaged 4,040 psi.

Figure 14. Bond System Verification

Figure 15. TE Fatigue Test Setup.
Figure 16. Spar Section Bending Test.
Summary of stresses & margins of safety

<table>
<thead>
<tr>
<th>Foam core weight</th>
<th>Wrinkling allowables at 120°F w/1.25 buckling factor</th>
<th>Wrinkling allowables at 70°F w/1.25 buckling factor</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 lb</td>
<td>-12,028 psi</td>
<td>-13,800</td>
<td>Fab'd slab foam</td>
</tr>
<tr>
<td>4 lb</td>
<td>-17,459 psi</td>
<td>-19,840</td>
<td>Fab'd slab foam</td>
</tr>
<tr>
<td>6 lb</td>
<td>-27,300</td>
<td>-31,023</td>
<td>Fab'd slab foam</td>
</tr>
<tr>
<td>8 lb</td>
<td>-38,982</td>
<td>-44,297</td>
<td>Fab'd slab foam</td>
</tr>
<tr>
<td>10 lb</td>
<td>-37,185</td>
<td>-42,256</td>
<td>Foamed in place</td>
</tr>
</tbody>
</table>

Figure 17. Trailing Edge Analysis

Figure 17a. Face Wrinkling Allowables—24 Gage 301 on Foam
• SPAR (17,000 lbs)
  • High strength steel
  • Weldability and formability
  • Notch toughness
  • Base metal fatigue allowables
  • High quality steel
  • Controlled surface finishes
  • Tapered tension side skins
  • No mechanical fasteners (no holes)

  $F_{TY} = 70 \text{ ksi}$

  $S_R = 28.6 \text{ ksi}$

• SPAR (17,000 lbs)
  • Weld area fatigue allowables
  • Weld detail per AISC spec
  • Post weld heat treatment
  • Sculptured tension skins
  • Nuclear quality weld
  • Multiple NDT of welds (UT, PT, RT, VT)
  • Buckling allowables
  • Column stiffener (test result)

  $S_R(B) = 16 \text{ ksi}$
  $S_R(C) = 12 \text{ ksi}$
  $S_R(E) = 5 \text{ ksi}$

  $F_B = 56.9 \text{ ksi}$

• TRAILING EDGE (3,000 lbs)
  • Stainless steel skins—½ H-301
  • Induced stresses + airloads
  • Density optimized foam core
  • Modulus to support skins (face wrinkling)
  • Lightening holes

  $F_{TY} = 90 \text{ ksi}$

Figure 18. MOD-1 Blade Design Solutions.
Figure 19. Twisted Weldment.