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 DESCRITPION

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 precracked 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 5×10^7 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 1.3×10^7 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-1 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 ($\approx$ 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 re quired 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.

	Spec Requirements	Actual
GEOMETRY		
Interface to hub	56-1.25 inch dia. holes	Same
Length	97.5 feet	97.4 feet
Airfoil shape	NASA 44xx	Same
Twist	11^{o} root to tip	Same
PERFORMANCE		
Operational life	30 yrs. (4.35 x 10^8 cycles)	To be determined
Design loads		
Frequent	35 mph wind (35 rpm)	Same
	24.8 mph wind (35 rpm)	Same
Infrequent	120 mph hurricane (static)	Same
	Emergency feather-overspeed (38.9 rpm)	Same
Balance weights (tuning)	500 lbs @ 40 lb. increments	516 lbs. (43 lb. increments)

	Spec Requirements	Actual
STRUCTURAL		
Material	Metal	A533 spar, 301 trailing edge
Weight	20,000 lbs, ± 1%	20,850 lbs – No. 001 20,710 lbs – No. 002
Frequency (Rigid mount)		
Flapwise	1.17-1.45 Hz	1.45 Hz (300 lbs. bal. wt.)
Chordwise	2.80-2.98 Hz	2.67 Hz (300 lbs. bal. wt.)
Torsion	>17.5 Hz	29.24 Hz (300 lbs. bal. wt.)
c. g. location	<35% chord aft of l.e.	33.66% aft – No. 001 34.19% aft – No. 002
Fatigue allowables		
Base metal – Cat. A′ (125 rms)	Sr=28,600 psi	Same
Welds – Cat. B	Sr=16,000 psi	Same
Cat. C	Sr=12,000 psi	Same
Cat. E	Sr=5,000 psi	Same

Figure 1. MOD-1 Primary Blade Requirements

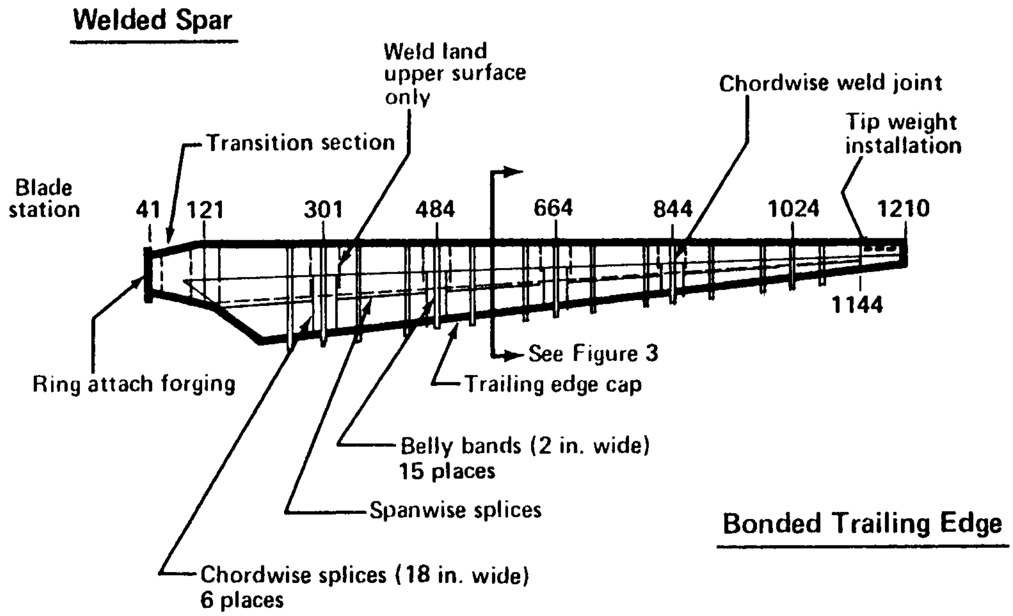


Figure 2. MOD-1 Blade Assembly

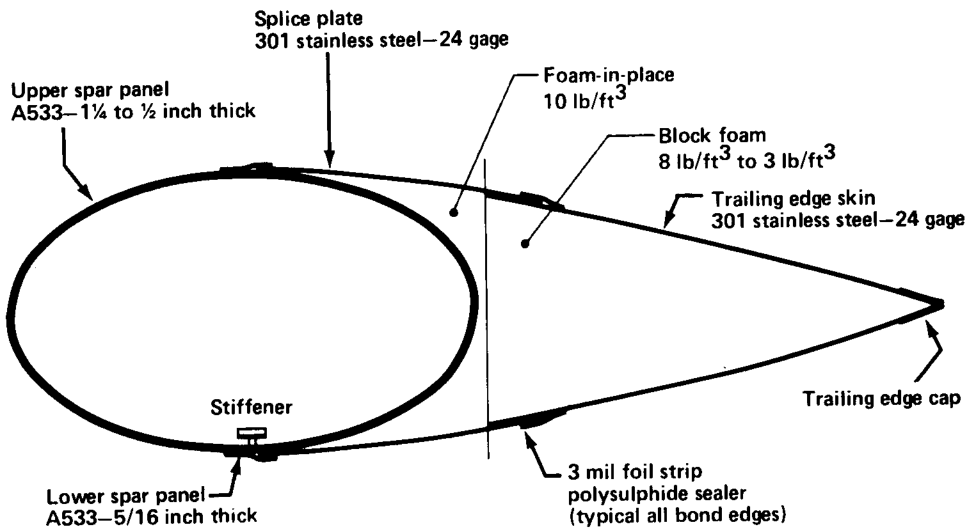


Figure 3. MOD-1 Blade Cross Section

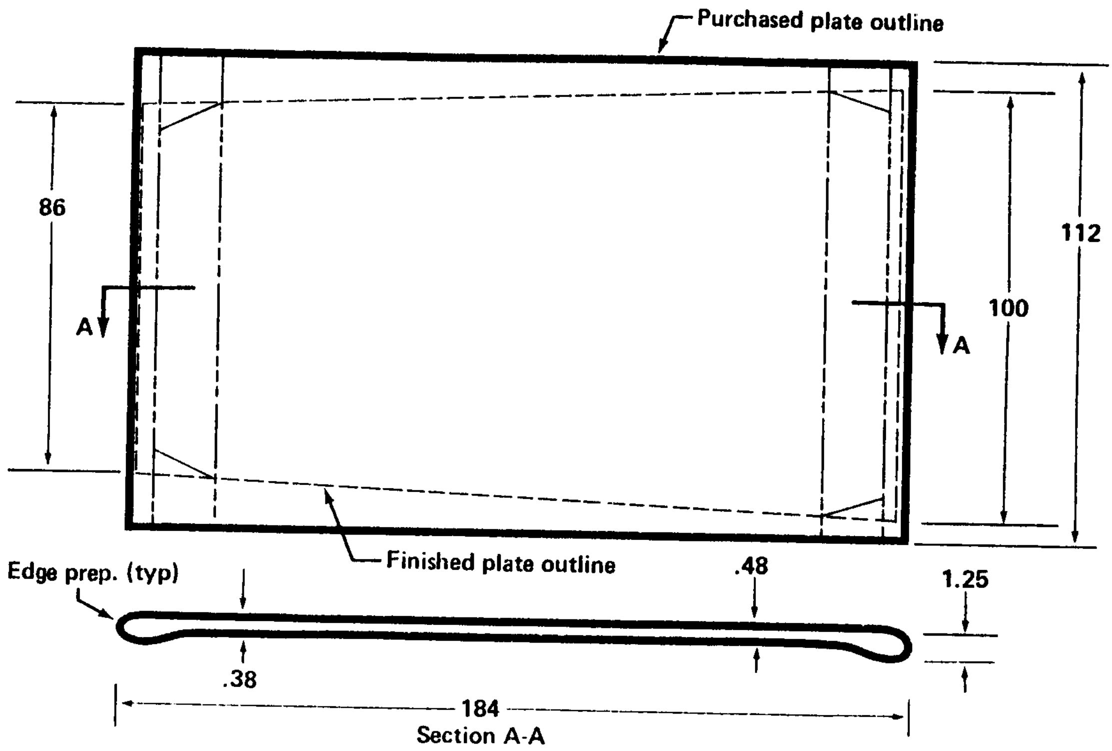


Figure 4. Upper Surface Plate (Typical)

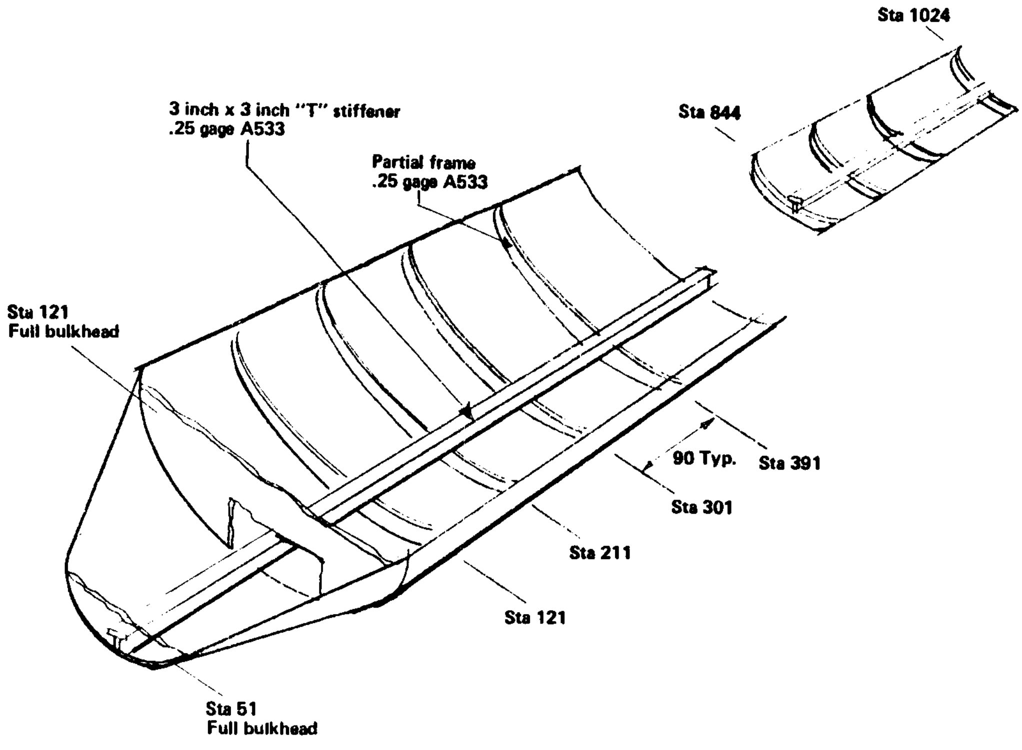


Figure 5. Lower Surface Stiffener

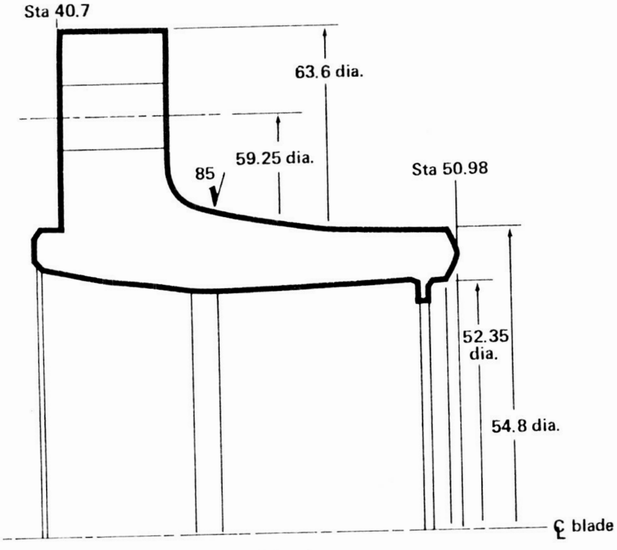


Figure 6. MOD-1 Blade Attach Flange

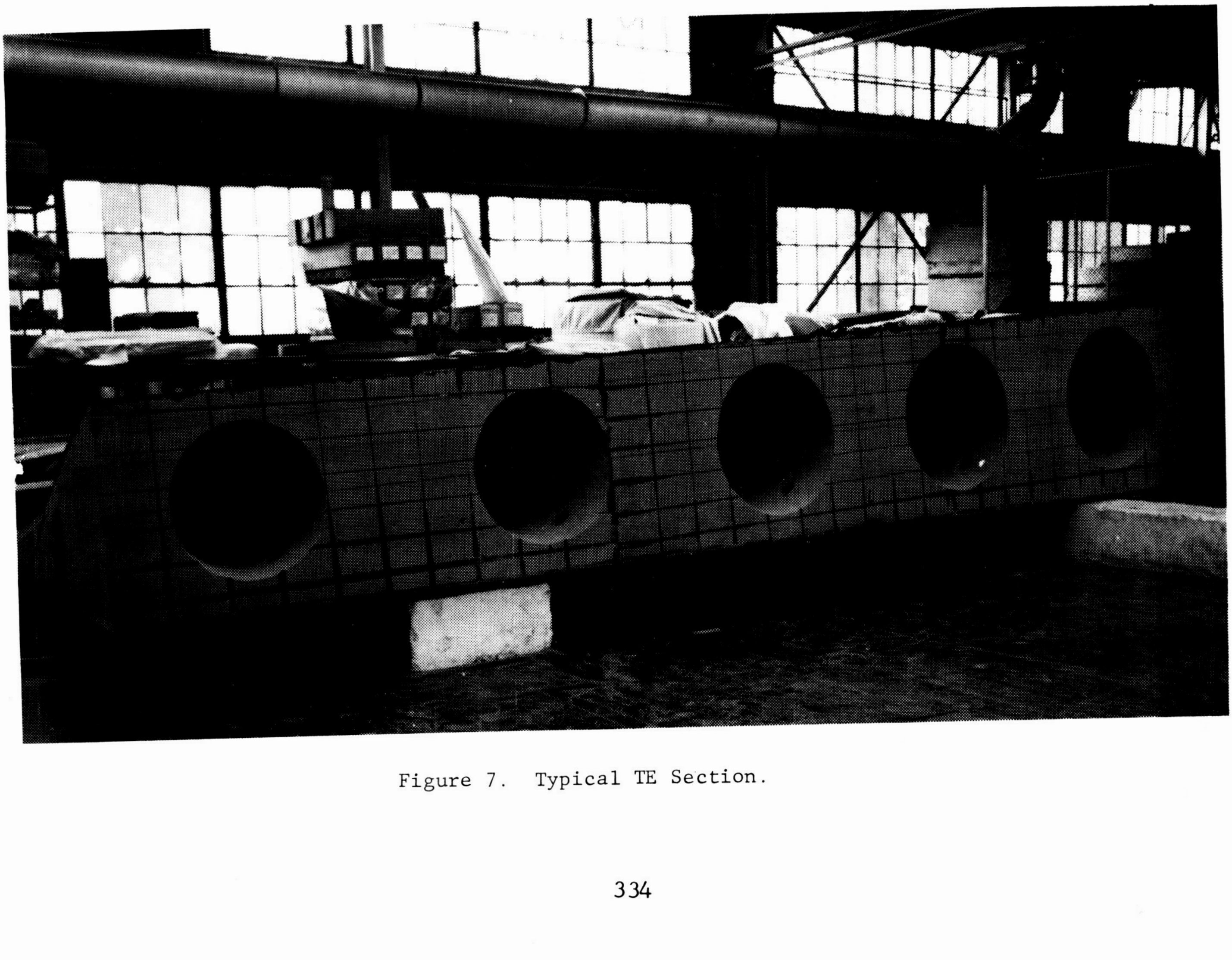


Figure 7. Typical TE Section.

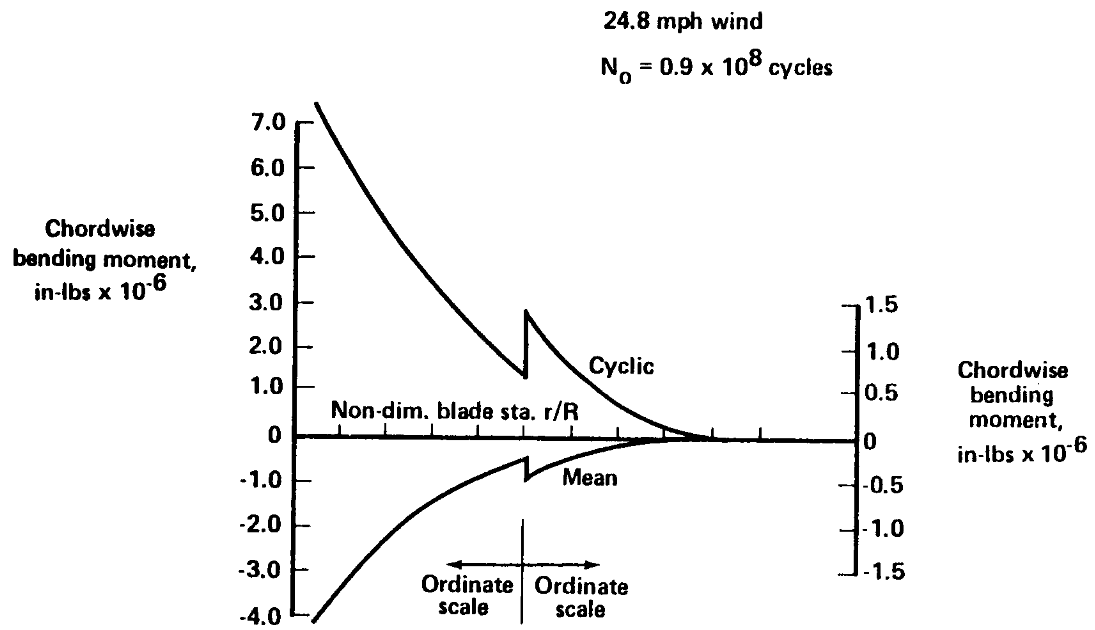


Figure 8. Chordwise Bending Moment Distribution

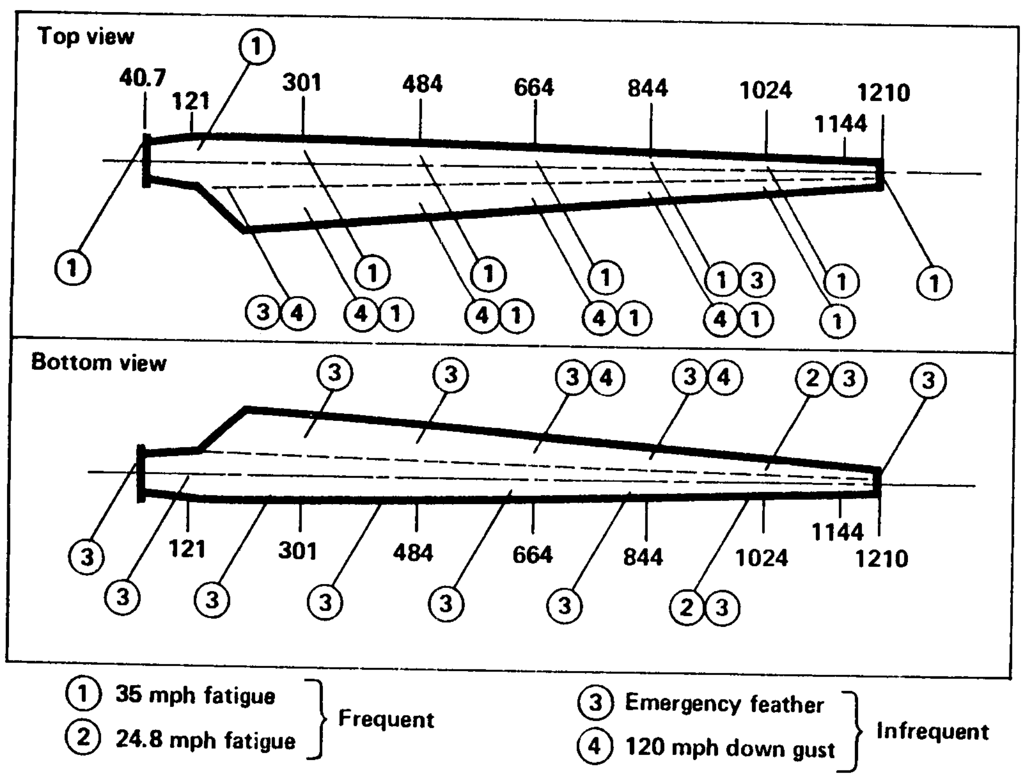


Figure 9. Design Load Conditions

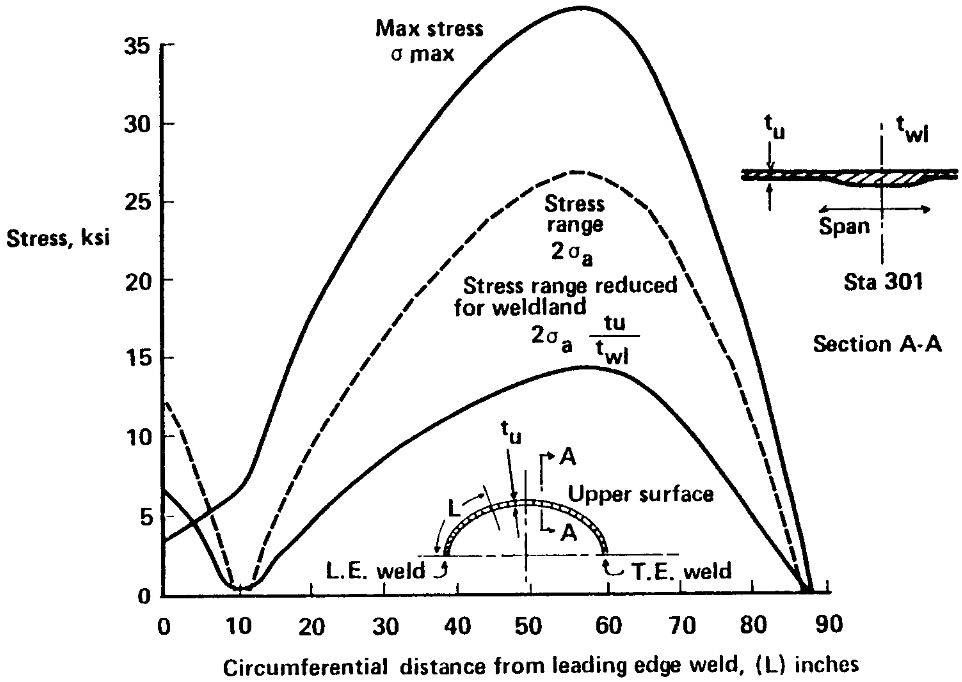
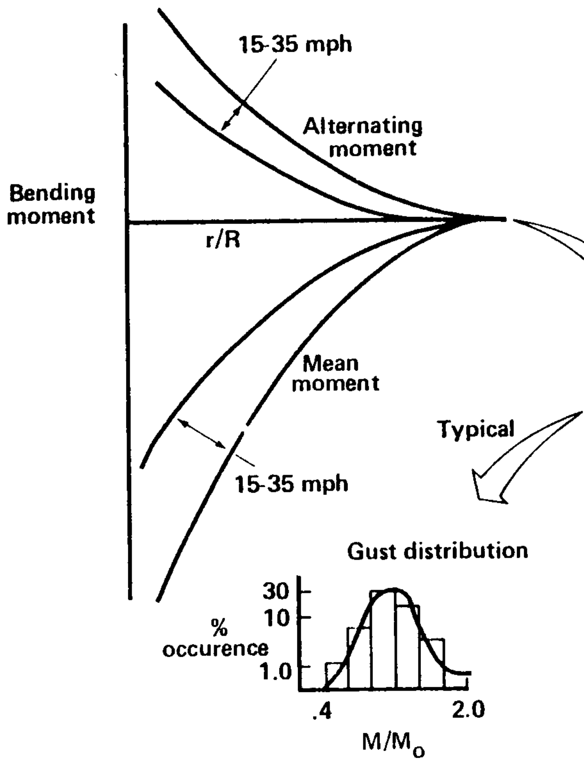


Figure 10. Upper Surface Stress Station 301



Velocity	Cycles	% Time
15	1.8×10^8	39.8
20	1.3×10^8	28.8
25	0.9×10^8	19.9
30	$.35 \times 10^8$	7.8
33	$.15 \times 10^8$	3.3
35	$.013 \times 10^8$	0.3

Figure 11. Fatigue Load Spectrum

Type of welded structure	Weld category	Crack growth design allowable flaw size		Inspection method & flaw detection capability		Flaw size acceptable criteria
		Surface	Internal			
Upper surface Chordwise welds	B (16,000 psi allowable)	.06 deep X .30 long	.12 deep X .30 long	VT	.005 wide X .06 long	.06 long (linear indications) .125 long (round indications)
Transition section welds				PT	.005 wide X .03 long	
Trailing edge spanwise Welds sta 51 to sta 250				RT	2% of t deep X .04 long	.125 long
				UT	.03 deep X .09 long	
Lower surface Chordwise welds	C (12,000 psi allowable)	.09 deep X .44 long	.18 deep X .44 long	VT	.005 wide X .06 long	.06 long (linear indications)
T-stiffener Spanwise welds				PT	.005 wide X .03 long	
Trailing edge Spanwise welds Leading edge Outboard of sta 250	E (5,000 psi allowable)	.54 deep X 2.70 long	1.08 deep X 2.70 long	VT	.005 wide X .09 long	.125 long
				PT	.005 wide X .06 long	

Figure 12. MOD-1 Spar Welds Inspection Matrix

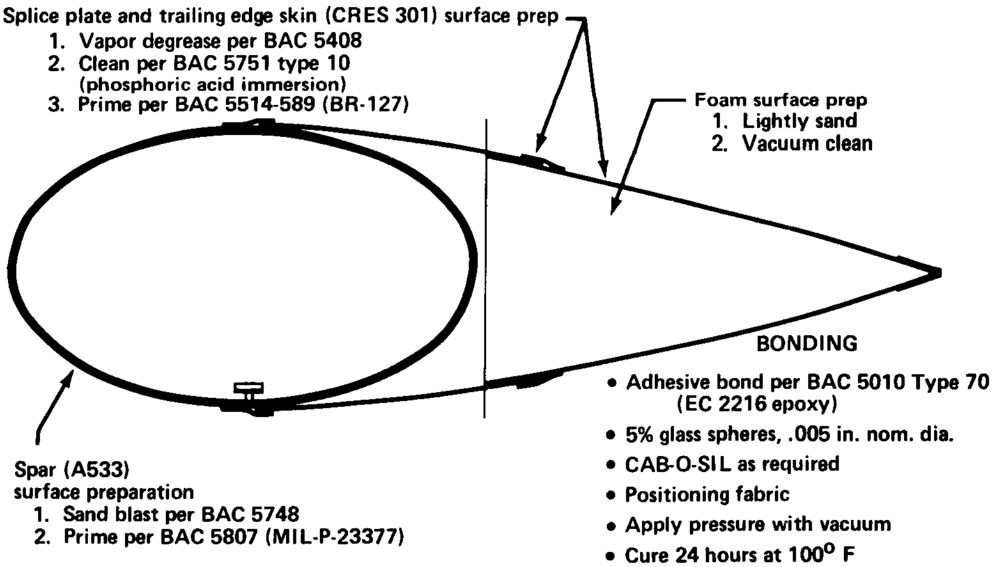


Figure 13. Surface Preparation and Bonding

Test	Environmental conditioning	Test temperature	No. of specimens	Results
Tensile (lap shear)	120°F, 100% RH, 72 hrs	Room	5	3,050 psi avg (cohesive failure)
	None	−31°F	5	2,992 psi avg (adhesive failures)
	None	Room	5	3,050 psi avg (cohesive failures)
	None	125°F	5	1,720 psi avg (cohesive failures)
Creep tests	None	5 hrs at 200°F	4 cycles (from 125°F)	No elongation at 2.4 psi
		5 hrs at 230°F	3 cycles (from 125°F)	No elongation at 1.1 psi

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

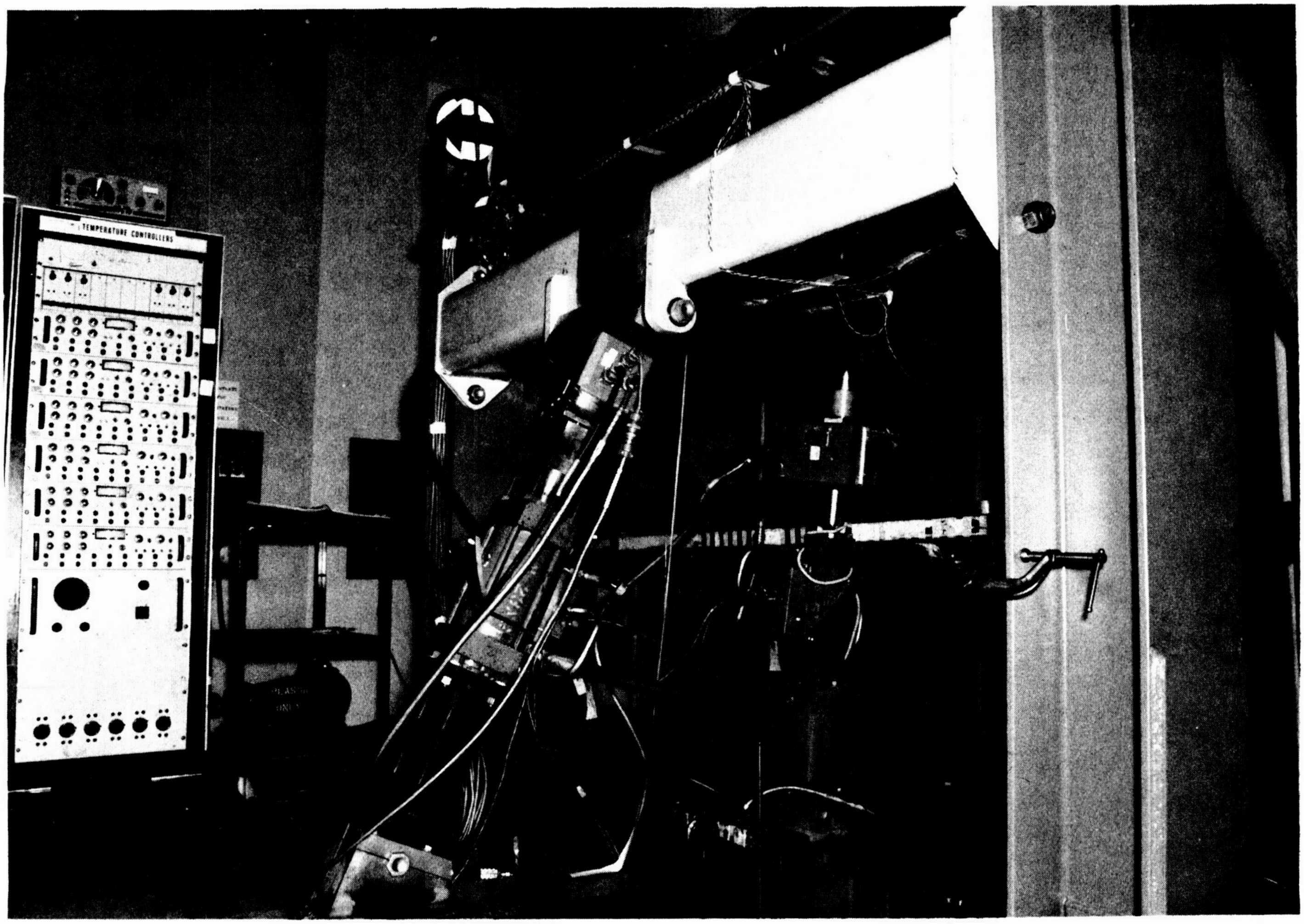


Figure 15. TE Fatigue Test Setup.

Figure 16. Spar Section Bending Test.

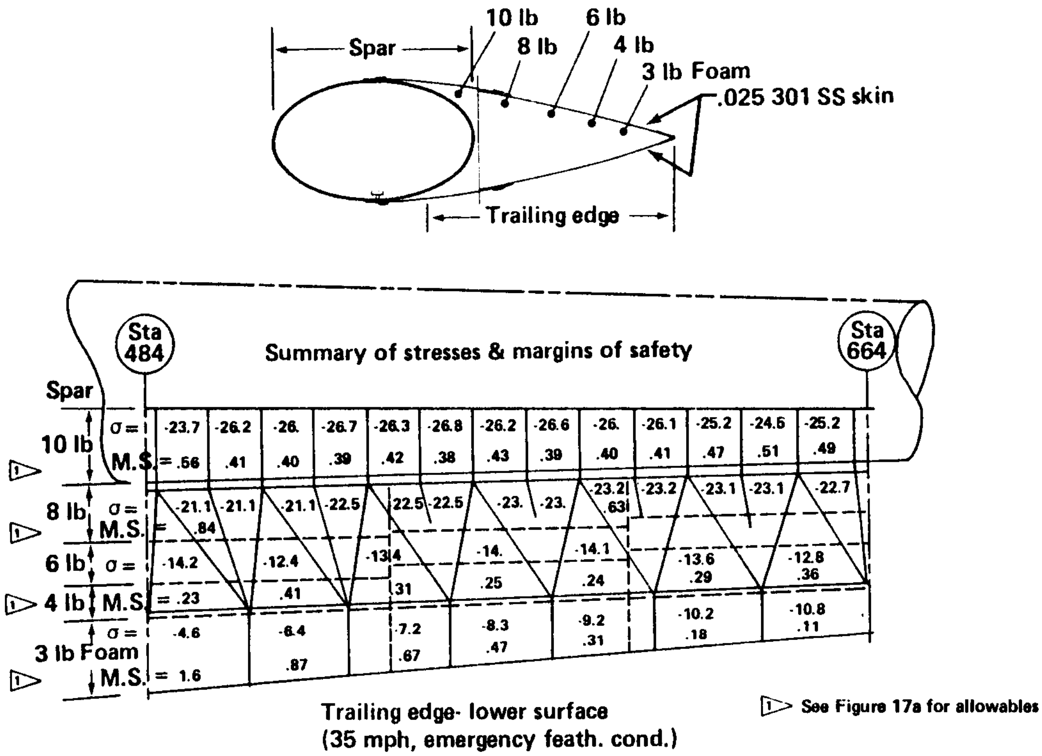


Figure 17. Trailing Edge Analysis

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

Figure 17a. Face Wrinkling Allowables—24 Gage 301 on Foam

- SPAR (17,000 lbs) — F_{TY}=70 ksi
  - High strength steel
    - Weldability and formability
    - Notch toughness
  - Base metal fatigue allowables — S_R=28.6 ksi
    - High quality steel
    - Controlled surface finishes
    - Tapered tension side skins
    - No mechanical fasteners (no holes)

- SPAR (17,000 lbs)
  - Weld area fatigue allowables — $S_{R(B)}$=16 ksi
    - Weld detail per AISC spec — $S_{R(C)}$=12 ksi
    - Post weld heat treatment — $S_{R(E)}$=5 ksi
    - Sculptured tension skins
    - Nuclear quality weld
    - Multiple NDT of welds (UT, PT, RT, VT)
  - Buckling allowables — F_B=56.9 ksi
    - Column stiffener (test result)

- TRAILING EDGE (3,000 lbs)
  - Stainless steel skins—¼ H-301 — F_{TY}=90 ksi
    - Induced stresses + airloads
  - Density optimized foam core
    - Modulus to support skins (face wrinkling)
  - Lightening holes

Figure 18. MOD-1 Blade Design Solutions.

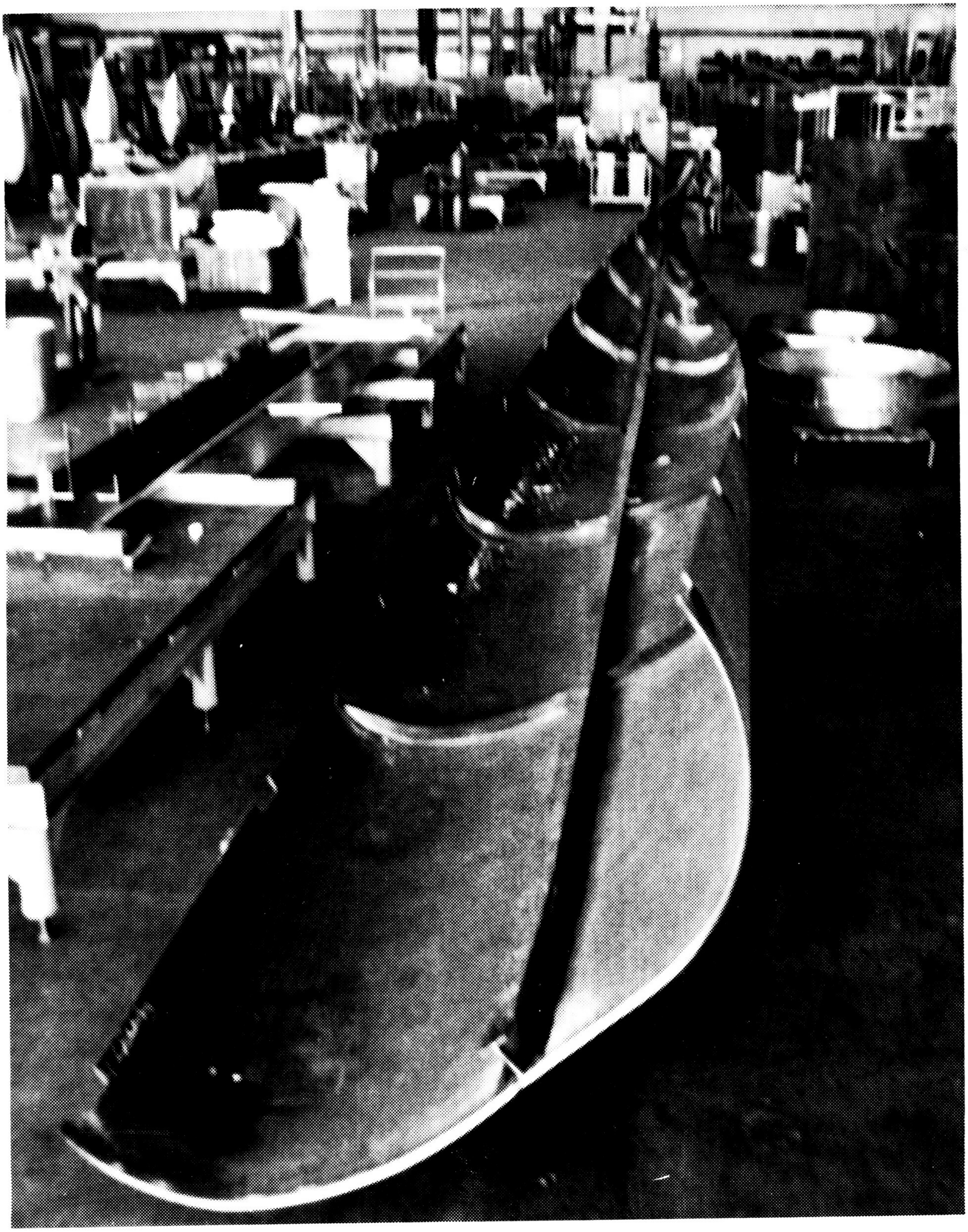


Figure 19. Twisted Weldment.