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Technical Assessment of the National Full Scale Aerodynamic Complex Fan Blades Repair

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Foreword

This report summarizes technical activities related to problems encountered during fan blade repairs for the National Full Scale Aerodynamic Complex (NFAC) at the NASA Ames Research Center. These activities represent a joint effort between the authors, who were members of an NFAC Blade Repair Technical Review Team, and the NASA Ames Blade Repair Project Team.

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Summary

This report describes the principal activities of a technical review team formed to address National Full Scale Aerodynamic Complex (NFAC) blade repair problems. In particular, the problem of lack of good adhesive bonding of the composite overwrap to the Hyduliginum wood blade material was studied extensively. Description of action plans and technical elements of the plans are provided. Results of experiments designed to optimize the bonding process and bonding strengths obtained on a full scale blade using a two-step cure process with adhesive primers are presented. Consensus recommendations developed by the review team in conjunction with the NASA Ames Fan Blade Repair Project Team are provided along with lessons learned on this program. Implementation of recommendations resulted in achieving good adhesive bonds between the composite materials and wooden blades, thereby providing assurance that the repaired fan blades will meet or exceed operational life requirements.

Introduction

The National Full Scale Aerodynamic Complex (NFAC) is located at the NASA Ames Research Center, Moffett Field, California. The wind tunnel operates in both a closed circuit (40x80) or open (80x120) circuit configuration as shown in figure 1. The wind tunnel has six fans with 15 wooden blades per fan as illustrated in figures 2 and 3.

Recent cracking of the National Full Scale Aerodynamic Complex (NFAC) wooden fan blades has been attributed to higher mean loads and higher cyclic loads due to complex fan inflow disturbances. The blade configuration and material composition is shown in fig. 4. Hydulignum is a compressed material that is manufactured from birch veneers approximately 1/16 in. thick (ref.1). Hyduliginum is a very dense material with tensile strengths up to 30 ksi in the grain direction. Sitka Spruce is a lighter wood with lower strength, but has long been the standard material used for wooden fan blades construction for NASA Wind Tunnels, see ref. 2. For the NFAC blades, the hyduliginum laminates (pressed boards) indicated in fig. 5, are approximately ¾ inch. thick. Physical evidence of cracking is illustrated in fig. 5. Based on diagnostic test data obtained in 1996, and utilizing full scale fatigue test data (ref. 1), all evidence and analyses indicate that the blade(s) cracked in the manner expected, and at about the operational hours expected. Because of fan inflow disturbances, the high. 1/Rev. blade dynamic loading is the main contributor to fatigue damage (i.e. cracking). Also, a 4/Rev. blade dynamic loading was found to be significant, and higher than expected. There is ample evidence that the close proximity of the first fundamental mode frequency to a strong 4/Rev. disturbance (see fig. 6 taken from ref. 3) has contributed to the higher than expected 4/Rev. cyclic loading.

As a result of the fan blade cracking problem, repairs are being implemented for all of the fan blades in order to keep NFAC operating safely until a new replacement set can be designed and manufactured. The goal was to achieve the best repair possible. The present fan blade repair concept was formulated in 1996 and utilizes a carbon composite overwrap (glove) that is designed to transmit 30% of the mean (static) plus dynamic loads to the threaded metal cuff. The repair concept is illustrated in figure 7. The carbon fiber inner wrap (patch) illustrated in figure 7 is shown installed on the blade in the photo of figure 8. The metal cuffs are flange connected to blade retention shafts which are attached to the fan hub. Based on detailed structural analysis, operational loads measurements, and full scale fatigue data developed when the initial set of blades were built (ref. 1), transfer of 30% of the load away from the highly stressed, threaded portion of the wooden blade attach root (where fatigue cracks initiated) would assure 30 months or more of operational life, while replacement blades are being procured. In addition, the blade repair concept would provide some blade containment capability i.e. would reduce the risk of catastropic failure such as blade shear out at the blade attachment. The repair design would also prevent the loss of large sections of the blade due to crack propagation in the spanwise direction.

After extensive lab and prototype testing by NASA Ames Project personnel, the initial set of 5 repaired blades were cured in an autoclave. However, for the second set of 5 blades, the composite overwrap delaminated (disbonded) from the fan blade Hydulignum material after removal from the autoclave. As a result of problems encountered with the blade repair fabrication, a technical review team was formed to work with NASA Ames project personnel to solve the problem.

The purpose of this report is to document the technical investigations and report on the results achieved to solve the repair fabrication problem in order to assure a blade repair that meets or exceeds operational life requirements.

Description of Blade Repair Design and Fabrication

An illustration of the repair design is given in figure 7. Photos of a repaired blade are provided as figures 8 and 9. The repair consists of a carbon composite patch that is tailored to transmit 30% of the peak loads (static + dynamic) to the exterior of the metal cuff. The patch is then overwrapped with carbon and fiberglass composite lay-ups around the blade root section and metal cuff. The loads are transmitted by shear through the bond between the blade and composite overwrap into the steel cuff. This unloads the blade by 30 percent in the highly stressed threaded root inside the metal cuff (fig. 4).

Chordwise belts around the blade at the root and outboard edge of the lay up (see figures 9 and 10) were added to retard crack growth, provide transition and containment. A principal decision was the selection of an adhesive that would provide a strong bond between the composite material, the wooden blade and steel cuff. A Minnesota Mining and Manufacturing (3M) AF-126 film adhesive was selected for bonding the composite material to both the wood and steel. See the adhesive specification provided as Appendix A.

Extensive NASTRAN finite element analyses were performed for the fan blade assembly with the repair installed (see figures 11 and 12). Note that in figure 12, that the blade retention shaft is modeled along with the blade assembly. The most recent finite element analysis indicates that the overwrap is transfering about 40% of the load instead of 30%, which would give the repaired blades even longer operational life.

Fabrication

The first step in the repair process was to inject resin into the existing cracks. This was done successfully, and verified by ultrasonic examination. The second step was to do a wet lay up of the composite materials on the blade and steel cuff. However, due to problems encountered during prototype testing and adhesive selection, it was determined that the repair would have to be cured at high temperature and pressure in an autoclave. A one-step cure cycle of 12 hrs. at a maximum temperature of 185°F and 90 psi pressure was selected. The autoclave cure temperature was limited to 185°F to prevent degradation of the Hydulignum strength properties (ref. 1). With the selected one step cure cycle it was expected that the composite overwrap and film adhesive could be co-cured to achieve the desired repair.

Problems Encountering During Fabrication

The first set of five blades that came out of the autoclave appeared to have cured properly. However, after the second set of 5 blades was removed from the autoclave, 4 out of the 5 blades delaminated during cool down, i.e. the carbon composite overwrap disbonded from the blade over the portion of the blade made from Hydulignum. This was determined to be an adhesive failure to the wood. The fifth blade was put into a refrigerator at around 15°F and it too delaminated.

Evaluation of the problem suggested that the delamination occurred as a result of residual thermal strains induced as a result of large variations in coefficient-of-thermal-expansion (C.T.E) between the dissimilar materials. Typical C.T.E. values for the various materials are as follows: (1) Hydulignum, $25\text{x}10^{-6}$ in./in./°F in the transverse direction, and $15\text{x}10^{-6}$ in the longitudinal direction (fig. 13). (2) Carbon composite wrap is 3.3 to $5.5\text{x}10^{-6}$ in./in./ °F; (fig. 13) (3) Sitka Spruce, $10\text{x}10^{-6}$ in./in./ °F and (4) steel cuff, $6\text{x}10^{-6}$ in./in./ °F.

The very large (~800 lbs) and thick wooden blade assembly is a large heat sink with poor heat transfer properties. In an effort to relieve the build-up of thermal strain, and allow more heat penetration into the wood at the edges of the composite overwrap bond line, slots were cut into the overwrap, 2 each on the upper and lower surface of the blade and in the sharp transition root area. The slots are shown in the finite element model illustration in figure 14 and in the final repair photos of figures 9 and 10. The slots are not desirable from a structural design point of view since the slots introduce structural discontinuities and stress risers, in both the overwrap and blade. Finite element analysis of the overwrapped blade with slots was used to examine the change in load transfer into the root section and metal cuff, and associated stress distributions to assure that the composite material and wooden blade stresses were acceptable.

The third set of 5 blades was fabricated with slots in the overwrap and went through the autoclave cure cycle. These blades appeared to cure properly, but delaminations at the Hydulignum interface again occurred when exposed to cold temperatures (~ 20°F). It now became apparent that the bond between the composite wrap and blade had little or no strength even with the slotted wraps. This was verified by examining large pieces of the unbonded composite overwrap which had virtually no wood present at the failure surface (bond line). In particular, it was observed that the delaminations were occuring only over the Hydulignum surface. The adhesive was bonding well to the Sitka Spruce blade material. Also, in areas thought to be good (i.e. tap tests did not indicate a problem) for the first set of blades cured, composite material samples were removed, which visually showed lack of composite material bond to the Hydulignum surfaces on the blade, i.e. no failure in the wood at the bond line.

Investigation of Repair Problems

Initial discussions and review of the fabrication problem by the first and second authors of this report and NASA Ames personnel began around mid May, 1997. This review resulted in the following observations and technical recommendations:

1. Observation: Delamination of repair overwrap from blade due to poor bond strength of composite to blade, and large differences in coefficient of thermal expansion between materials (i.e. thermal mismatch). This resulted in residual shear and normal (interlaminar) stresses at the bond line. Visual evidence indicated very poor bond strength and lack of adhesive flow. It was clear that bond strength was well below lab test specimen(s) results. Recommendations: (1) change chordwise belt material (graphite + fiberglass) to a higher C.T.E. material such as fiberglass only; (2) examine differences (scale effects, process effects) between lab process using test specimens and fabrication process used for the full scale blade; (3) use low-temperature cure for outer chordwise belt lay up; (4) pre-cure film adhesive to blade as a primer before curing composite overwrap (2 step process); (5) test bond strength using flat tensile specimens subjected to the full scale cure cycle process.

2. Observation: Delaminations will grow on both upper and lower surface of blades, and inside root cut-out during cyclic loading. Probable cause is that flat tensile (interlaminar) strength in laminate is expected to be higher than strength of adhesive bond to Hydulignum. Recommendation: Improve bonding process to achieve higher strength in the bond of the repair overwrap to the hydulignum.

3. Observation: Unconstrained crack growth during load cycling will reduce operating life of blade(s). Recommendation: (1) Add an additional chordwise fiberglass belt at blade root to aid in keeping crack(s) closed, and reduce crack propagation rate. (2) avoid using slots in overwrap if possible, and (3) expedite fatigue test of a blade with slotted overwrap.

It was clear that the bond strength would have to be increased significantly in order for the blade repair to have the desired effect. The one step cure cycle, was designed to co-cure the carbon composite overwrap and AF-126 film adhesive on to the fan blade. However, the carbon composite material cures at about 160°F whereas the film adhesive is cured at 185°F. It should be noted that film adhesive should be cured at 250°F to achieve optimum strength (see specification provided as Appendix A.) Also, the fact that the composite material cures (hardens) at around 160°F suggests that the overwrap could not be counted on to apply uniform pressure to the film adhesive to aid in adhesive flow and curing later in the cycle and at the higher temperature, (185°F). Adhesive flow is enhanced by increased heat up rate which is precluded in the one-step cure process by the low thermal conductivity of the repair layup and the fan blade materials. Therefore, it appeared that the film adhesive should be cured on the blade before the composite overwrap was cured, i.e. a two-step process. Also, the selection of the 3M film adhesive for bonding the composite material to the wooden blade appeared questionable, because of limited flow and the fact that this modified epoxy film is designed for structural bonding of metals. At this point, two nationally recognized adhesive experts (third and fourth authors) were added to the review team to aid in solving the bonding problem. A primary objective was to continue to use the selected adhesive if the experts felt that high quality bonds could be fabricated.

Action Plan

At a June, 1997 meeting at NASA Ames Research Center, an action plan was developed jointly by the Technical Review Team and the NASA Ames NFAC Blade Repair Project Team. Principal elements of the plan agreed upon by the teams and approved by NASA Ames management were as follows:

1. Use full scale blade (No. 120) as test bed for demonstrating fix for the bonding problem. It was clear that the small scale lab specimen testing could not be relied on to solve the problem.

2. Use coupling agent(s) (primer) to improve bonding of film adhesive to the Hydulignum. Candidate primers were (1) Furfural alcohol (2) Isocynate (3) Forest Product Lab (FPL) resorcinal based primer (ref. 4) (4) Weldwood and (5) pin prick surfaces. Surface roughness (sanding) was also selected as a variable in the experiments. The intent was to optimize the bonding process.

3. Test Hydulignum material surfaces for composition and possible contamination.

4. Conduct rheology tests on AF-126 film adhesive to determine viscosity properties at varying heat up rates and cure temperature (185ºF).

5. Use 2 step process (2 autoclave cycles) plus wet lay-up of the two chordwise belts to fabricate repair on full scale test bed fan blade (No. 120).

6. Once blade test bed (No. 120) Hydulignum surfaces were primed with different candidate primers/roughness (designated patch areas on blade), the blade would be subjected to the first cure cycle.

7. After first cure cycle, pull test samples from blade 120 Hydulignum patches, to determine flat tensile (interlaminar) strength of adhesive bond to Hydulignum.

8. Subject test blade to second step cure and determine bond strength for different candidate primers/roughness.

9. Select primer that gives best bond strength and durability properties.

The above recommendations were agreed upon by both teams and the plan elements were to the implemented as soon as possible.

Results and Discussion

This section presents a discussion of the results of implementation of the action plan elements.

Bonding Process Optimization. In the course of trying different primers, the Furfural alcohol (F.A.) would not set up properly and was discarded. The isocynate was dismissed as a result of concern over potential toxicity issues. Also, the Forest Products Lab (FPL) resorcinol based primer was judged to be similar to the Weldwood product selected by the fabricator. It should be noted that the use of the above mentioned primers would have required custom mixing the primers on-site with the potential of limited set-up time, i.e. impacting the fabrication process.

The blade repair fabricator purchased an off-the-shelf Weldwood adhesive product to try as a primer, and NASA Ames personnel suggested pricking the surface using a roller device with small sharp pointed blades to put small indentations in the wood surface, i.e. over the Hydulignum. In addition, both a 60 grit and 120 grit sanded finish were tried for each primer candidate. Unfortunately, a control patch (smooth surface) was not used, but most likely would have shown less bond strength.

Pull Test Results. Pull test results for blade 120 with the candidate primers are tabulated in Table I. The loading device used for these tests is shown in fig. 15. The hand operated loading device was attached to metal cylinders approximately 1 inch in diameter, (see fig. 16) which were in turn bonded to the AF 126 adhesive layer at the patch location(s) where the candidate primer(s) was applied. The device is designed to test the flat tensile strength of the adhesive layer by pulling normal to the blade surface (fig. 15). However, at places on the blade with significant curvature, this was not possible, therefore some peeling load was introduced at these locations.

As can be seen from Table I for blade 120, the pin prick surface (with the 60 grit finish) gave an average strength of 1687 psi with failure in the wood. The weldwood primer gave averages of 2292 psi and 1846 psi for the 60 grit and 120 grit surface respectively, with even more failure in the wood. The photo given in figure 16 illustrates the metal cylinders (plugs) and failure surfaces for the blade 120 pull tests on the adhesive layer and composite overwrap. Unfortunately, the failure surfaces are not clear in figure 16 due to poor resolution. The five cylinders on the extreme right side of the photo have failure surfaces at the adhesive bond line. These strength results coupled with a significant amount of failure occurring in the wood (as well as some failure in adhesive), were judged to be excellent compared to little or no bond strength visually observed on previously cured blades, i.e. no failure in the wood.

After the second step cure, pull tests were conducted on the composite overwrap (metal cylinders shown in first and second rows of figure 16) and the adhesive layer (third row of figure 16). These tests were witnessed by members of the technical review team in early July, 1997. Failures in the carbon laminate occurred as expected (see Table I). The adhesive layer bond strengths given in Table I, after step 2 were basically the same as those bond strengths obtained after the first step cure.

Upon review of the pull test results, it was found that the Weldwood primer used by the fabricator was not resorcinol based but was urea-melamine-formaldehyde (UMF) based and contained chlorine. Chlorine is harmful to wood when the bond line is exposed to heat or loads for a long period of time, and is also corrosive to metal. As a result, the use of this off-the-shelf product as a primer raised the question of durability. The decision was made to use a resorcinol based Weldwood as a primer, since this product is commonly used as an adhesive for wooden fan blades, and should have as good or better strength properties then the UMF based Weldwood. The optimum surface primer selected was to use a 60 grit finish with pin prick, plus resorcinol based Weldwood for the prototype and production blades.

Pull tests were also conducted on the sheet adhesive to metal cuff. Tests were conducted at four sites with the test results given in Table I. These tests gave an average strength of about 5400 psi which is considered to be very good.

Pull test results on 4 inch diameter specimens (see Table II) at the NASA Ames test lab (one step process) gave flat tensile strengths in the range of 600 to 1300 psi but failures occurred both at the adhesive layer and in the wood specimen itself (i.e. along a 45º plane) typical of a combined tensile + shear failure (possibly associated with test setup). These results were judged to be qualitative i.e. not conclusive because of the failure mode, test methods, and scale effects.

Surface Contamination. Infrared (IR) spectral analysis of the Hydulignum surface wood at the NASA Langley Polymers Laboratory did not show the presence of any contaminate other than an epoxy material. Since the fan blades were overwrapped with a fiberglass epoxy material used as a moisture barrier and for damage protection, the presence of epoxy residue was explained.

Rheology Tests. Initial rheological testing of a sample of the 3M AF-126 film adhesive acquired from NASA Ames was done at the NASA Langley Polymers Lab. These tests showed very poor flow characteristics (i.e. high viscosity) for various heat-up rates with a final cure temperature of 185°F. Initial observation suggested that the film had pre-cured from ageing, with viscosity properties about like caulking compound, i.e. just doesn't flow, without pressure being applied. Subsequently, a fresh (new) sheet of film adhesive was acquired from 3M and tested at NASA Langley. This test showed a major difference in that the new film seemed to cure properly and viscosity was very much less for the new adhesive, when compared to the previously tested film adhesive being used by the fabricator. This raised the issue of "old" or aged" adhesive being used for repair fabrication, which could contribute to the poor bond strength observed for the initial blade repairs.

Subsequent testing of samples acquired from the fabricator labeled "old" and "new" was carried out at NASA Langley. The "old" adhesive manufactured date was unknown while the "new" adhesive was manufactured in late 1996. The difference between the flow characteristics (viscosity) was dramatic in that the 'new" sample adhesive viscosity exhibited proper curing behavior with lower viscosity properties while for the "old" sample, viscosity was high and indicated a lack of proper curing at test temperature (185°F).

These results clearly showed that the new ("fresher") adhesive is better. The review team recommended that new "fresh" adhesive be procured for fabrication. NASA Ames agreed to this recommendation and all of the "old" adhesive is to be discarded (i.e. not used for blade repair fabrication).

Process Enhancements. Using information obtained from the full size blade test bed (No. 120), further process enhancements were to be implemented for the prototype and production blades. These include: (1) roughen the steel cuff surface over the area to be bonded, (2) Apply the Chemlock metal adhesive primer to within 1/16 –1/4 inch. of edge of cuff, (3) look into availability of tinted primer to assure complete primer coverage on the steel cuff, (4) leave film adhesive off the filabond material in steel cuff transition area and steel cuff edge (1/16 – 1/8 inch. from edge of steel cuff), (5) locally vent area around joint between filabond and steel cuff to allow out-gassing to avoid contaminating the film adhesive and (6) install layer of fiberglass between carbon tow wrap and edge of steel cuff, to prevent galvanic action.

Prototype Blades Pull Tests

Three prototype blades were fabricated using the selected primer, comprised of resorcinol based Weldwood, with pin prick, 60 grit sanded surface and "fresh" adhesive. Pull tests (see fig. 15) were conducted on the adhesive layer at outboard stations on both surfaces of each of the three blades. These locations were selected so as to not compromise the integrity of the repair. The purpose of the pull tests on the 3 prototype blades was to verify that the bond strength values would be as good or better than those achieved on the full scale test bed (blade 120). Also the resorcinol-based Weldwood was used for this application so that bond strength verification was mandatory. Results of the prototype blade pull tests are provided in Table II. The Pull tests were conducted in the same manner as those conducted on the test bed blade No. 120. The flat tensile strengths results given in Table II are very good. Excluding the strength values in Table II, where the pull test was not normal to the blade surface, testing gave the following statistical strength values for the 3 prototype blades. The mean strength value is 1835 psi with a standard deviation of 297 psi or about 16% of the mean. Comparing the 3 prototype blades mean strength value with the mean strength value obtained for blade 120 in Table I for both the pin prick and UMF Weldwood with 60 grit finish gave a difference of about 8% based on blade 120 mean value. The prototype pull test results obtained after the first step cure were judged to be acceptable. The 3 prototype blade repairs were then laid up and cured in the autoclave (step 2).

It should be noted that for the 3 prototype blades chordwise belt wraps, i.e. the root and outboard overwraps (see figures 9 and 10) were cured during the step 2 autoclave process. This is contrary to the review team recommendation that the chordwise belts be layed up after step 2 and cured at room temperature (or slightly elevated temperature) to avoid possible thermal contraint effects from the belts during the second step cure. The decision to do this by the Ames Project Team was based on poor quality lay-up results from the third step process using the testbed blade 120, and subsequent successful 2 step cure results on the three prototype blades.

Upon removal from the autoclave, the three prototype blades were exposed to temperatures of 30-35 °F with no evidence of significant delaminations or disbonds. Two of the three blades were to be installed in the two available fatigue test fixtures at NASA Ames (see figure 17). In light of the excellent bond strengths obtained along with other process/design enhancements implemented for the blade repair, coupled with good fatigue strength of the low bond strength repair on blade 136, fabrication of all remaining blades is underway. Fatigue tests of 2 of the prototype blades (see Appendix B) will determine the expected fatigue life for the newly repaired blades with adhesive primers and process enhancements.

Lessons Learned

The following is a list of "lessons learned" from this activity. These lessons may be of benefit to the technical community if faced with a similar problem or application.

1. The choice of using film adhesive (3M AF-126) for bonding composite material to the Hydulignum fan blade material was not prudent for a one-step cure. Adhesive selection was based on bonding composite material to steel, not hydulignum. Adhesive was made to work by using primers, fresh adhesive and a two-step cure process.

2. The 3M AF-126 film originally used for the blade repairs was found to exhibit pre-cure (aged) characteristics with very high viscosity at cure temperature (185 °F). The date of manufacture was and still is unknown. Good quality control could have assured a fresh, low viscosity film. Rheological testing of the film early in the program would have confirmed that the initial batch of adhesive film did not meet specifications.

3. Small test samples (wooden specimens) were used to establish bond strength characteristics. These test specimens were not representative of the full scale blade, heat up rate, etc. and should not have been used to establish adequacy of bond strength.

4. The one-step cure cycle could not yield an adequate bond between the composite overwrap and the wooden blade. The carbon composite cures at about 160°F. The low heat up rate, and low adhesive cure temperature at 185°F coupled with lack of uniform pressure from the pre-hardened composite overwraps resulted in insufficient flow, poor wettability and poor adhesive strength due to inadequate pressure transfer and high viscosity of the 3M AF-126 adhesive at cure temperature.

5. The NASA Ames Blade Repair Project Team was on the right track initially by considering a two-step cure process. The two-step process (which was subsequently adopted) cures the adhesive layer onto the wood as the first step, before the composite overwrap is applied and cured during the second cycle. The two-step process was abandoned during the development stage, due to additional cost and schedule considerations.

6. Bonding of the composite material to the wooden fan blade is critical to a successful repair. In critical applications for bonding dissimilar materials, nationally recognized experts in the field of adhesives should be consulted. If this had been done earlier in the development program, it is felt that the bonding problem encountered during fabrication could have been avoided.

Conclusions and Recommendations

The technical review team activities related to the NFAC fan blade repairs are complete and documented in this report. An action plan formulated by the Technical Review Team and the NASA Ames NFAC Blade Repair Project Team to address NFAC fan blade repair problems was successfully carried out in a timely manner. An optimum adhesive primer was selected, and a two-step cure process implemented which provided the necessary adhesive bond strength between the composite overwrap and the wooden blade. The completion of this activity has resulted in successful fabrication of three prototype blade repairs having very good structural integrity. An operational life of 5 years or more for the repaired blade set is expected.

It is recommended that this report be distributed to appropriate engineering and operations personnel at NASA Ames for future reference until the repaired blades are replaced by a new set. Distribution of this report is also recommended for other NASA sites, having wind tunnels with wooden fan blades, such as the NASA Langley and NASA Lewis Research Center.

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Appendix A

Adhesive Film AF-126
Product Specification

Scotch-Weld®
BRAND

Aerospace
Product Specification

Issue No. 2
March 1, 1986
Supersedes previous
product data

Structural Adhesive Film AF-126

Introduction:

"Scotch-Weld" Structural Adhesive AF-126 is a thermosetting, non-volatile, modified epoxy film adhesive designed for structural bonding of metals. This unique product offers the following advantages:

- Cure at temperatures as low as 225°F. Optimum results obtained with a cure of 250°F. for 1 hour.
- Excellent strength in metal-to-metal and honeycomb sandwich applications over a temperature range of − 67 to 250°F. Provides exceptionally high metal-to-metal overlap shear and peel values.
- Releases no volatile by-products during cure thereby permitting low pressure bonding.
- Low film weight version (0.03 lbs./sq. ft.) permits use of high (100 psi) pressure bonding without excessive adhesive flow in metal-to-metal applications.
- AF-126 .06 and .08 weights with EC-2320 primer are qualified to the requirements of MIL-A-25463 Type I Class 2 and MMM-A-132 Type I Class 2.
- AF-126 .03 weight with EC-2320 is qualified to the requirements of MMM-A-132 Type I Class 2.
- High degree of tack in the uncured state.
- AF-126 films can be used with EC-3960 corrosion inhibiting primer.

Description:

	AF-126 (.03)	AF-126 (.06)	AF-126 (.08)
Form:		Suported film adhesive with protective liners	
Color:	Green	Green	Red
Nominal Weight: (lbs./sq. ft.)	0.030	0.060	0.080
Nominal Caliper: (Approx. inches)	0.005	0.010	0.015
Volatile Content:		Less than 1%	

Product Performance: (cont.)

AF-126 .03 Wt./EC-2320 Overlap Shear & T-Peel (Etched Aluminum) Low Temperature Cure

Bonds Cured @ 180°F. 50 psi for:		**Test Temperature**		
		−67°F.	**75°F.**	**180°F.**
3 hours	Shear	712 psi	278 psi	40 psi
	T-Peel	2.5 piw	21 piw	4.5 piw
6 hours	Shear	675 psi	1985 psi	358 psi
	T-Peel	3 piw	30 piw	5.5 piw
9 hours	Shear	4825 psi	3885 psi	2430 psi
	T-Peel	14 piw	22 piw	19 piw
12 hours	Shear	4700 psi	3800 psi	2765 psi
	T-Peel	12 piw	23 piw	20 piw
24 hours	Shear	4625 psi	3810 psi	3000 psi
	T-Peel	16.5 piw	22.5 piw	18 piw

AF-126 .06 Wt./EC-2320 L/T Ratios (Etched Aluminum)

L/T Ratio Overlap Length	**Test Temperature**		
	−67°F.	**75°F.**	**160°F.**
8 (0.50")	6640 psi	6225 psi	4268 psi
16 (1.00")	3964 psi	3902 psi	3448 psi
24 (1.5")	2668 psi	2666 psi	2493 psi
40 (2.5")	1695 psi	1574 psi	1545 psi

Cured for 1 hour @ 250°F., 30 psi, 6-8°F./minute rise

Etched Aluminum Metal to Metal Climbing Drum Peel with EC-2320 Primer (20 mil to 40 mil face sheets)

Test Temperature	**Test Results**	
	.03 Wt.	**.06 Wt.**
75°F.	80 in. lbs./in.	100 in. lbs./in.

Cure — 1 hour @ 250°F., 50 si, 6-8°F./minute rise

Chromic Acid Anodized Aluminum Metal to Metal Climbing Drum Peel with EC-2320 Primer (20 mil to 40 mil face sheets)

Test Temperature	**Test Results**	
	.03 Wt.	**.06 Wt.**
75°F.	80 in. lbs./in.	100 in. lbs./in.

Cure — 1 hour @ 250°F., 50 psi, 6-8°F./minute rise

Etched Aluminum Floating Drum Peel with EC-3909 Primer

Test Temperature	**Test Results .06 Wt.**
−67°F.	66 piw
75°F.	85 piw
180°F.	70 piw

Cure — 1 hour @ 265°F., 50 psi, 4-5°F./minute rise

Appendix B

Fatigue Tests

The fatigue test plan and fatigue test rig were reviewed by the team. Conclusions were that the fatigue testing should be representative of maximum blade operational loads in the tunnels, with added conservatism in dynamic loads application.

The purpose of fatigue testing repaired blades is to verify that fatigue strength of repaired blades will meet the wind tunnel operational life requirements until new replacement blades are procured. A factor of 2.5 is applied to the projected 4/rev. load cycles over an operational period of 30-months. Therefore, the blades were to be tested to about 22 million cycles and beyond if needed or desired.

The fatigue test apparatus with fan blade installed is illustrated in figure 17. The NASTRAN finite element model representation of a blade installed in the fatigue test rig is illustrated in figure 18. Loads are applied as follows: The blade axial load is applied as a steady (static) load while the resultant axial and tangential static + dynamic loads are applied by a load actuator clamped to the blade outboard at about mid. span. Cyclic loads are applied at a rate of about 5 Hz. Resultant loads are monitored by load cells, and strain gages are placed on the blade at specified locations to monitor stress (strain) distributions, i.e. load transfer.

Fatigue results to date are quite encouraging even though fatigue testing of the final blade repair prototypes is incomplete. Initially, a cracked blade was tested with only a partial repair. The crack grew beyond about 35 inches spanwise without blade failure. Evidence of additional cracking in adjacent laminates at the blade root began to appear near the end of the test. (Note: This was also observed in full scale fatigue tests for the initial blade set, ref. 1) Also, in an attempt to fail the blade, the resultant bending and torsional loads were increased to the limits of the loads actuator, without failure.

A second blade (No. 136) with the slotted overwrap but without the primer adhesive, i.e. one step cure, was recently fatigue tested to over 22 million cycles without structural failure. Although this blade had residual thermal stress and poor bond strength, it demonstrated that a less than desired repair coupled with the highly resilient blade structure has significant remaining fatigue life. Eventually, the overwrap did delaminate and load drop-off was recorded. A destructive examination of this blade is to be performed.

Fatigue tests of cracked blades to date have exhibited good fatigue life and substantial residual strength, with and without repair. These results suggest that blades cured with the 2-step process and optimum bond strength will have an operational life of 5 years or more. The next step is to fatigue test prototype and production blades with the final repair process configuration. These tests will determine expected fatigue (useful) life and set criteria for operational life and inspection requirements until replacement blades are installed.

Table I. Pull test results on blade 120 test bed.

Results from Blade Bond Testing at Applied Aerospace				
and Ames Research Center				
Blade 120 - Blade with sheet adhesive only - Chilled to 35°F 24-Jun-97				
Flat Side	Gage Reading (psi)	Load (lbs)	Stress (psi)	Comment
Pull Test #1	250	1191	1527	60 grit finish - pin prick - failure in wood
#2	300	1440	1846	60 grit finish - pin prick - failure in wood
#3	350	1660	2128	60 grit finish - weldwood primer - more failure in wood
#4	400	1915	2455	60 grit finish - weldwood primer - more failure in wood
#5	300	1440	1846	120 grit finish - weldwood primer - more failure in wood
#6	300	1440	1846	120 grit finish - weldwood primer - more failure in wood
Blade 120 - After Carbon Wrap Cure - Chilled to 35°F 1-Jul-97				
Round Side	Gage Reading (psi)	Load (lbs)	Stress (psi)	Comment
Pull Test #7A	200	1000	1282	Failure in Carbon Laminate
#8A	250	1191	1527	Failure in Carbon Laminate
#9A	< 50			Cylinder damaged test sample
#6A	250	1191	1527	Failure in Carbon Laminate
#5A	275	1250	1603	Failure in Carbon Laminate
#4A	175	900	1154	Failure in Carbon Laminate
#1A	100	530	679	Curved area of blade - may not be pulling normal
#2A	250	1191	1527	Failure in Carbon Laminate
#3A	100	530	679	Curved area of blade - may not be pulling normal

Table I. (cont'd)

Results from Blade Bond Testing at Applied Aerospace and Ames Research Center

Blade 120 - Pull Tests of Sheet Adhesive from Steel Cuff - Chilled to 35°F - 8 Jul 97

	Gage Reading (psi)	Load (lbs)	Stress (psi)	Comment
Test # F1	800	3693	4735	Sudden and clean failure from steel surface
Test #F2	1100	5078	6511	Sudden and clean failure from steel surface
Test #F3	750	3463	4439	Sudden and clean failure from steel surface
Test #F4	1000	4617	5919	Sudden and clean failure from steel surface

Blade 120 - Pull Tests of Sheet Adhesive from Hydulignum- Chilled to 35°F - 8 Jul 97
After carbon lay-up and cure - Carbon Removed

	Gage Reading (psi)	Load (lbs)	Stress (psi)	Comment
Test #1B	350	1616	2072	Pin Prick Surface Only
#2B	350	1616	2072	60 grit - Weldwood - Wood Failure
#3B	300	1385	1776	120 grit - Weldwood
#4B	300	1385	1776	Pin Prick Only - Failure at Glass Layer
#5B	275	1270	1628	60 grit - Weldwood Wood Failure
#6B	350	1616	2072	120 grit Weldwood
#7B	250	1154	1480	Pin Prick Only - Wood Failure - 20%
#8B	200	923	1184	60 grit - Weldwood - Wood Failure
#9B	200	923	1184	120 grit Weldwood

Table II. Pull tests results for test specimens and three prototype blades.

Results from Blade Bond Testing at Applied Aerospace and Ames Research Center				
4 Inch sample tests at Ames Research Center				
		Load (lbs)	Stress (psi)	Comment
Test #1	NA	7450	593	Sanded surface - dry wipe (One Step Process)
Test #2	NA	12500	995	Sanded surface - pin prick (One Step Process)
Test #3	NA	16200	1290	Sanded surface - weldwood primer (One Step Process)
Test #4	NA	> 19080	> 1519	Sanded surface - pin prick (Two Step Process)
Test #5	NA	> 19080	> 1519	Sanded Surface - weldwood and pin prick (Two Step Process)
Prototype Blades - Pull Tests of Sheet Adhesive from Hydulignum- 29 Jul 97				
Test	Gage Reading (psi)	Load (lbs)	Stress (psi)	Comment
186 -1	325	1500	1924	
186 -2	300	1385	1776	
186 -3	325	1500	1924	
186 -4	175	808	1036	Plug not pulling normal to surface
168 -1	375	1731	2220	Blade 168 lost vacuum bag during cure
168 - 2	250	1154	1480	
168 -3	225	1039	1332	
168 -4	175	808	1036	Plug not pulling normal to surface
143 -1	350	1616	2072	
143 -2	375	1731	2220	
143 -3	275	1270	1628	
143 -4	300	1385	1776	

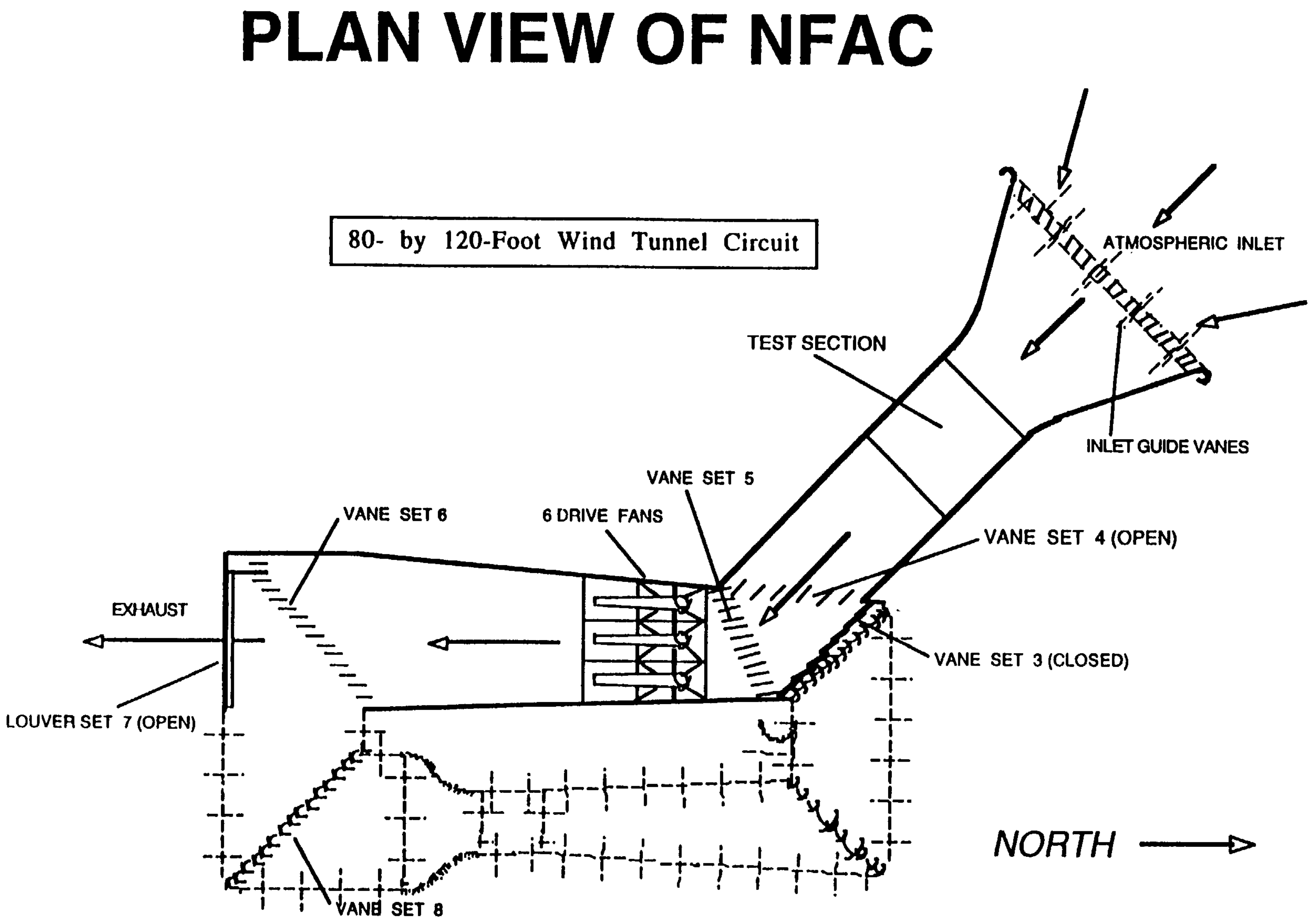
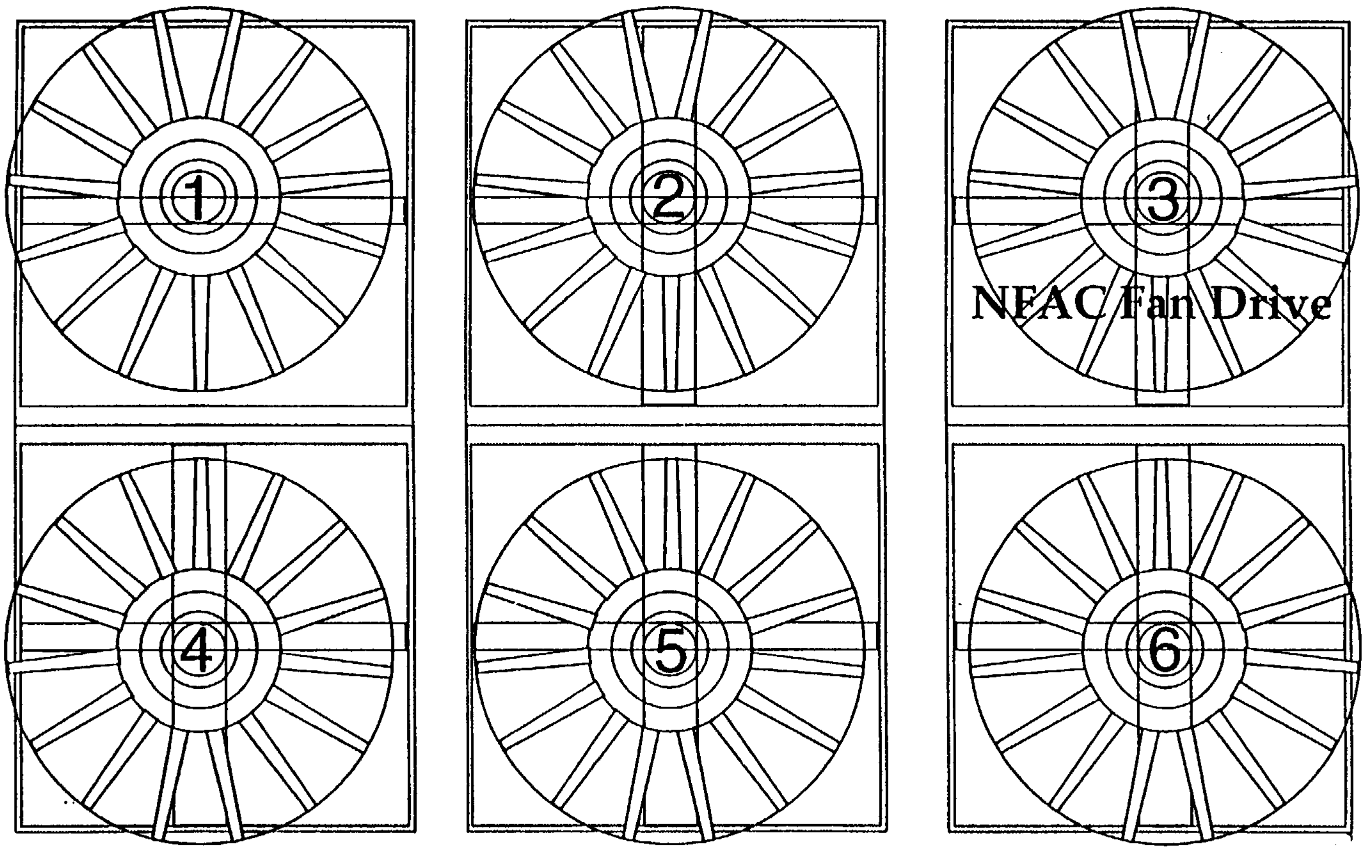


Figure 1. Plan view of the NFAC - 80x120-ft circuit illustrated.



- operates at constant speed (180 rpm)
- variable pitch (-5° to 49° blade angle)
- temperature (fan drive) = 20 to 140° F
  moisture environment = dry

Figure 2. NFAC fan drive configuration - looking downstream.

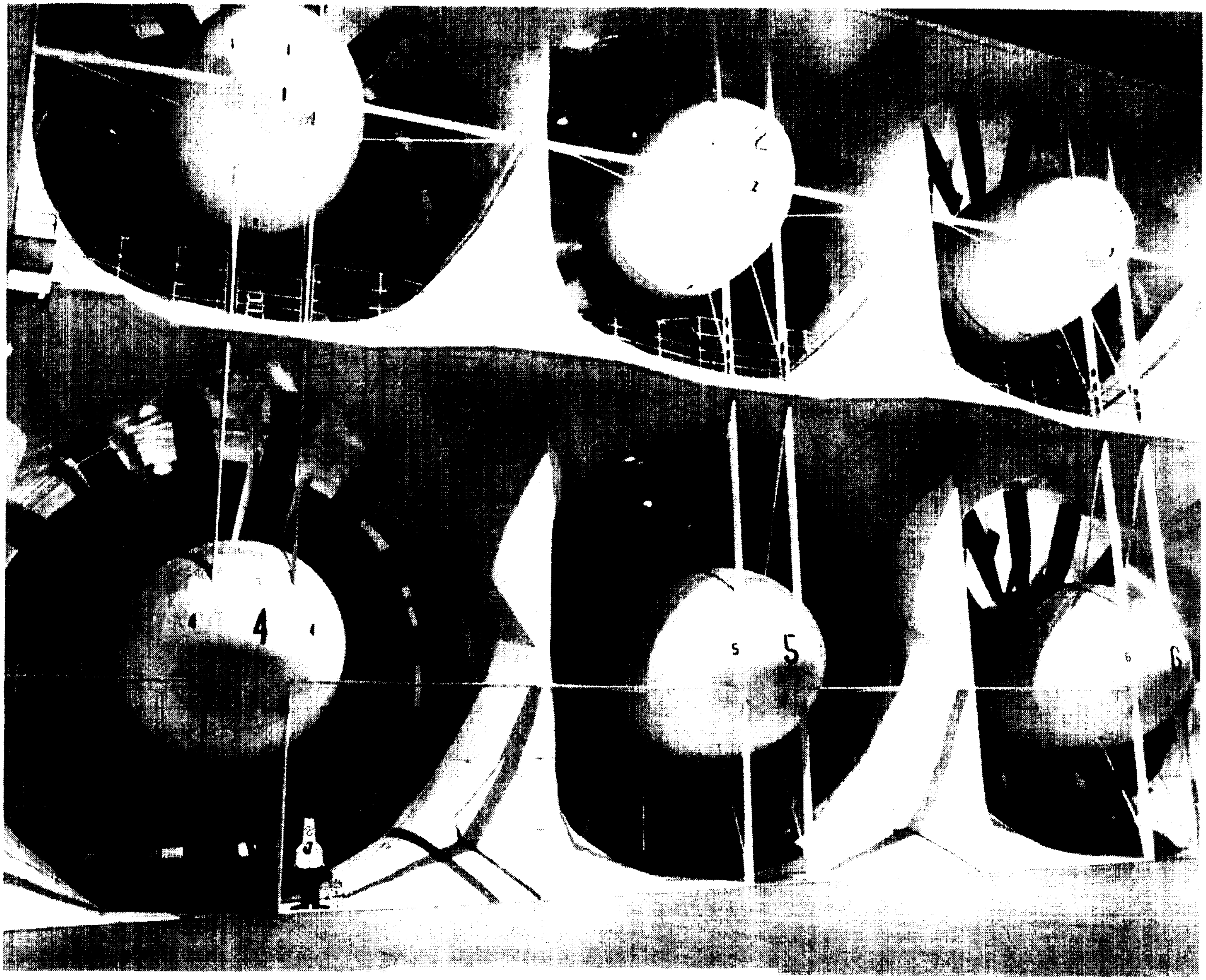
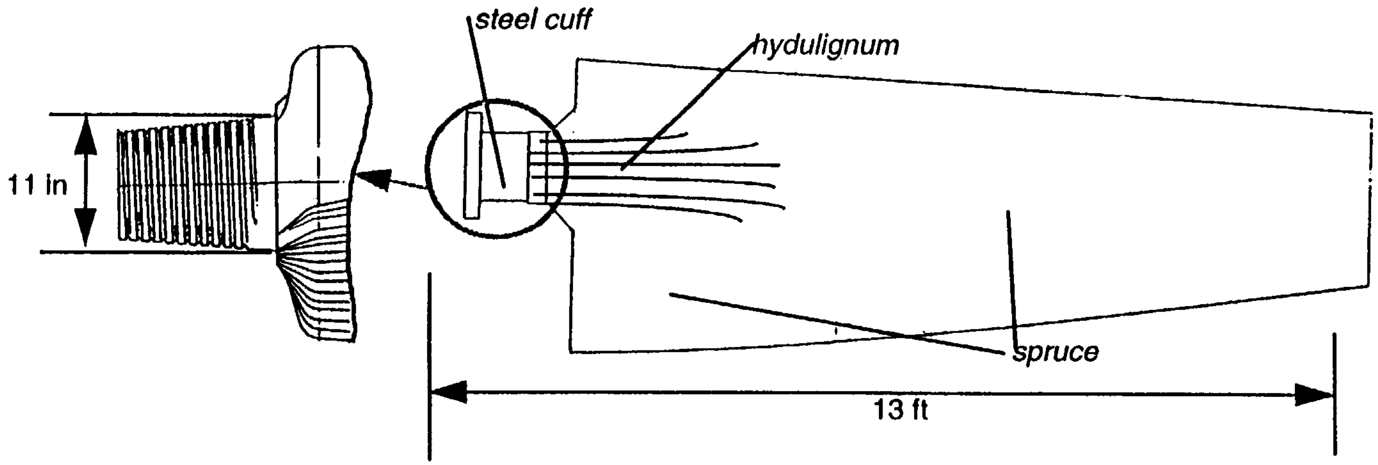


Figure 3. Photo of NFAC fan drive.

Blade Materials



- Hydulignum: yellow birch compressed wood
  1/16″ veneers
  impregnated with phenolic resin
  tensile strength = 30 ksi (RT)
  20% reduction (recoverable) in strength @ 140F
  fatigue strength = 9 ksi (RT, 10^8 cycles, R=-1, reversed bending)

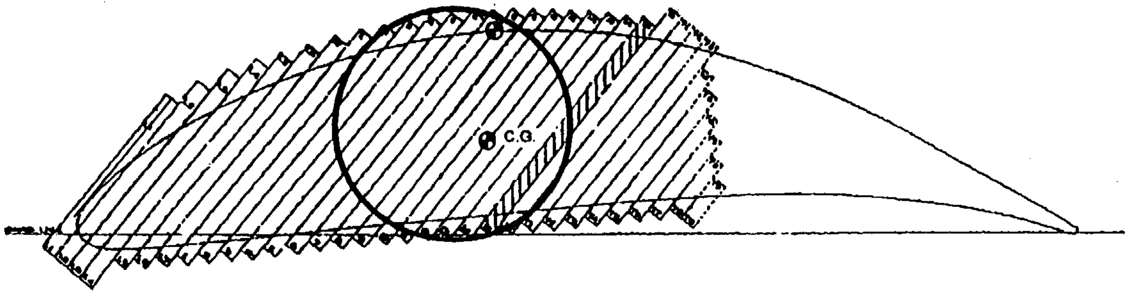
- Sitka Spruce: tensile strength= 12 ksi (RT)
  fatigue strength = 4 ksi (10^8 cycles)

- Steel: normalized 4340
  yield strength = 55 ksi

Figure 4. NFAC blade assembly materials.

Physical Evidence

- Cracking occurs in nearly identical locations in the root area
- Cracking typically confined to hydulignum laminates 15 and 16.
- Cracks remain within the laminate (as opposed to along the glue joint between laminates).



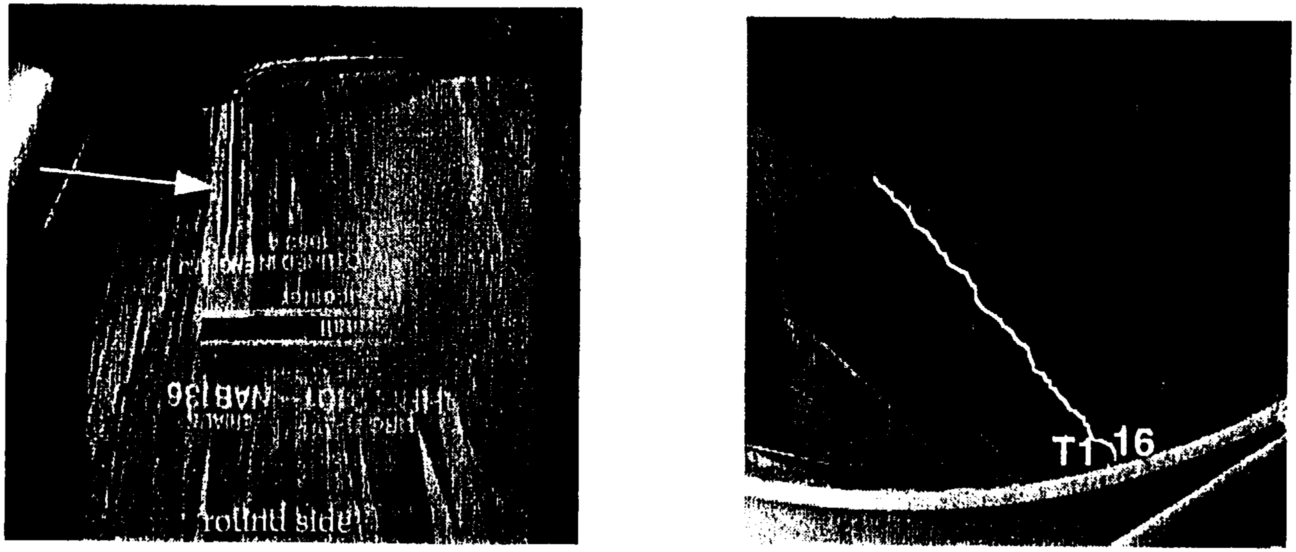


Figure 5. Physical evidence of cracking in root area of NFAC blade.

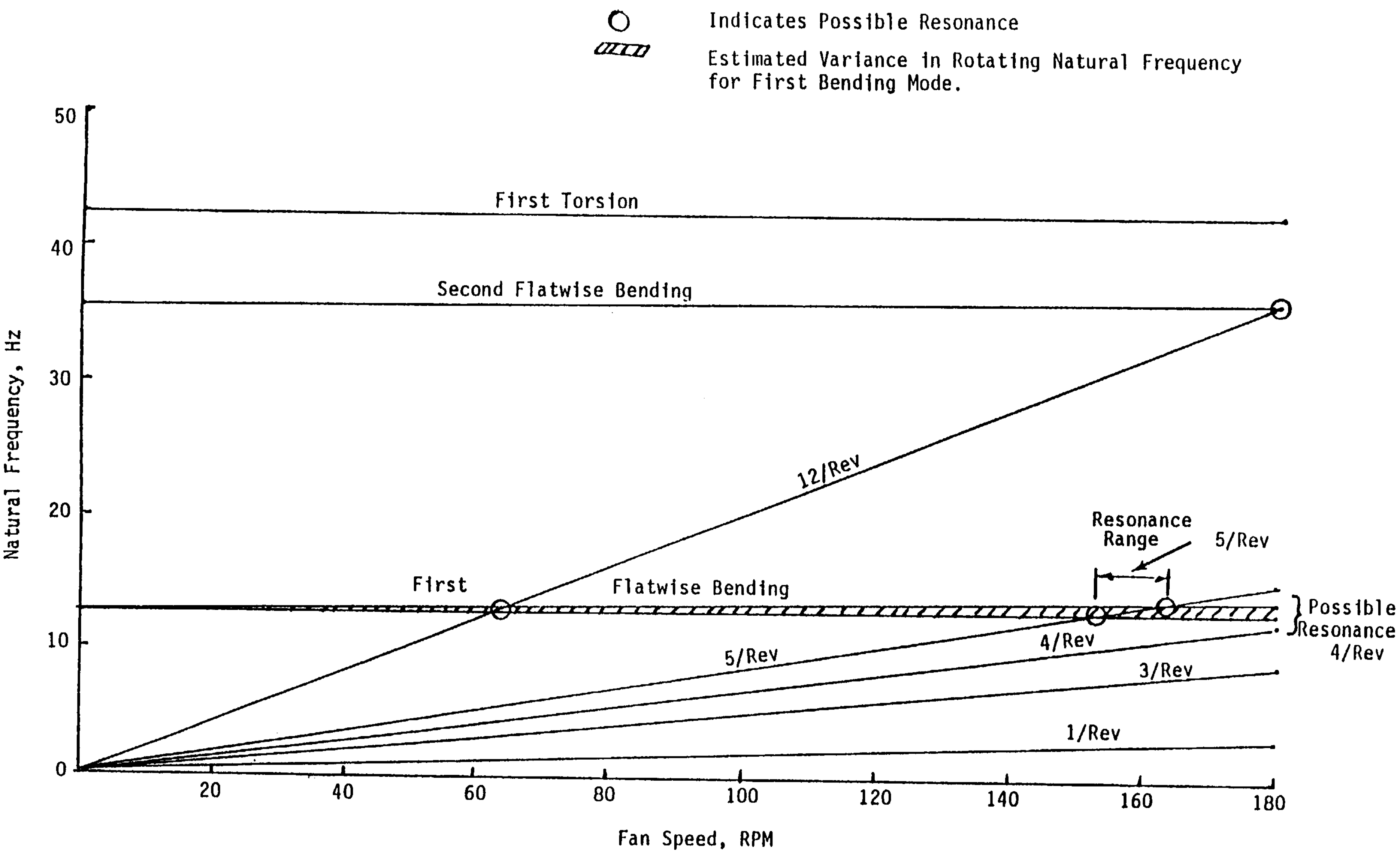
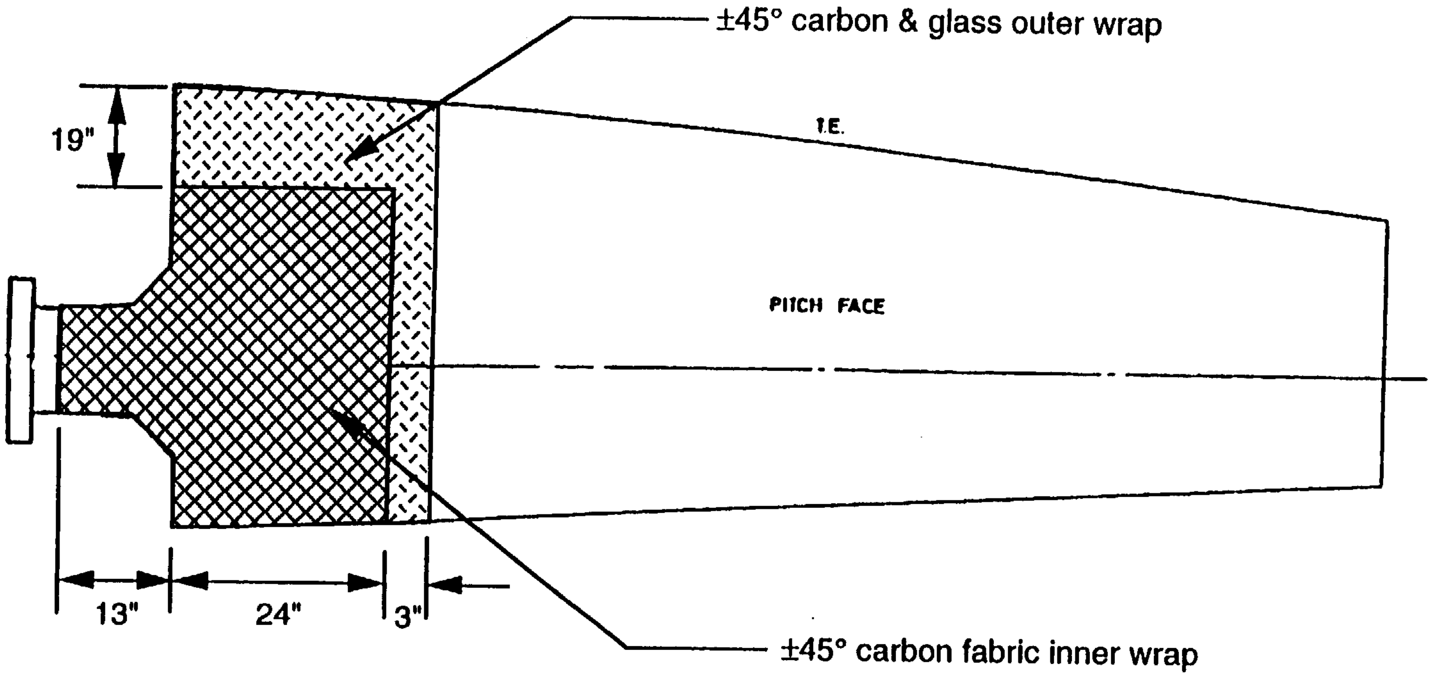


Figure 6. Estimated interference (Campbell) diagram for NFAC blades taken from reference 3.



NFAC BLADE REPAIR ILLUSTRATION

Figure 7. Fan blade assembly repair illustration.

Figure 8. Photo of carbon composite inner wrap (patch) installed on blade and metal cuff.

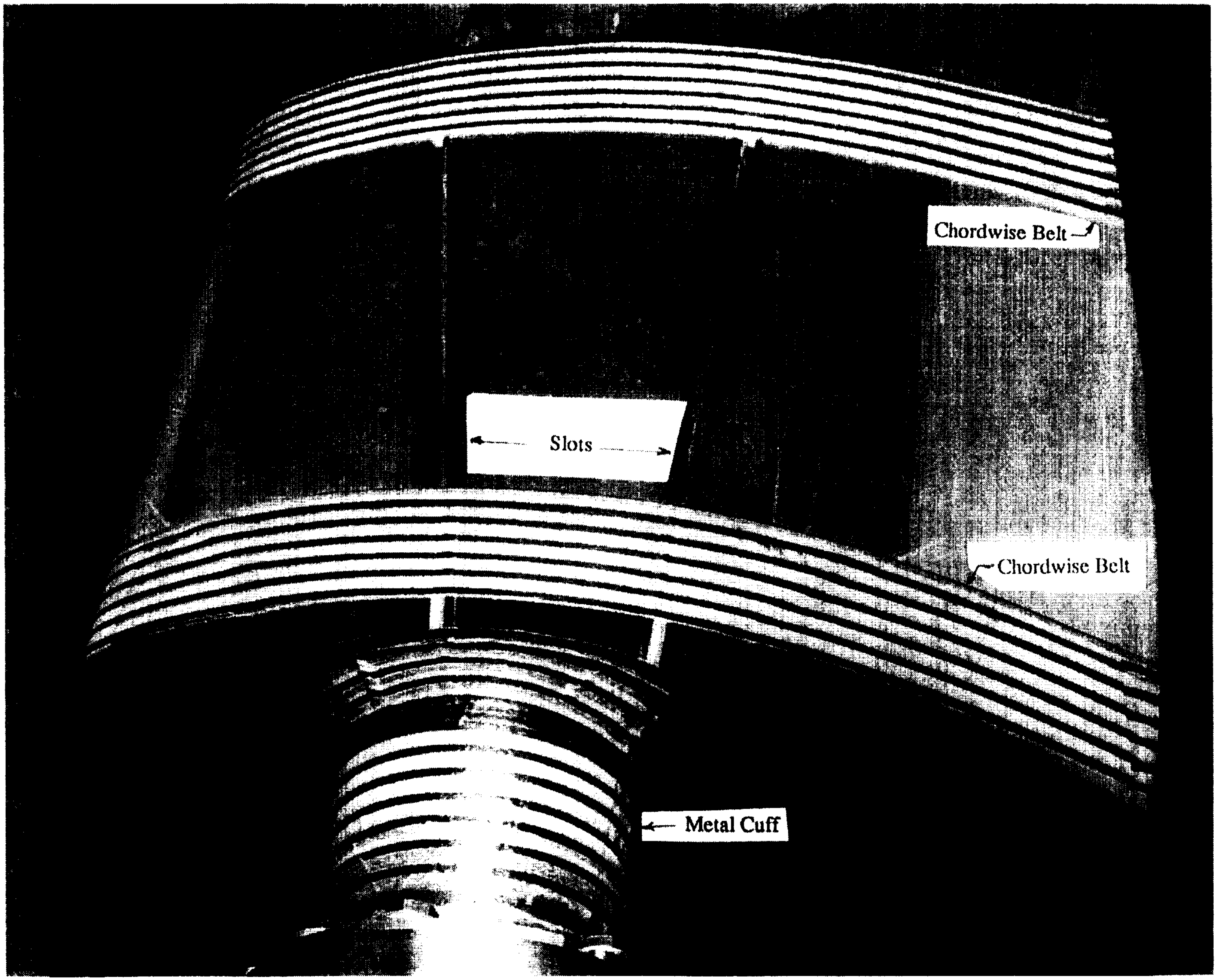


Figure 9. Photo of repaired blade upper surface illustrating overwrap of blade and metal cuff with chordwise.

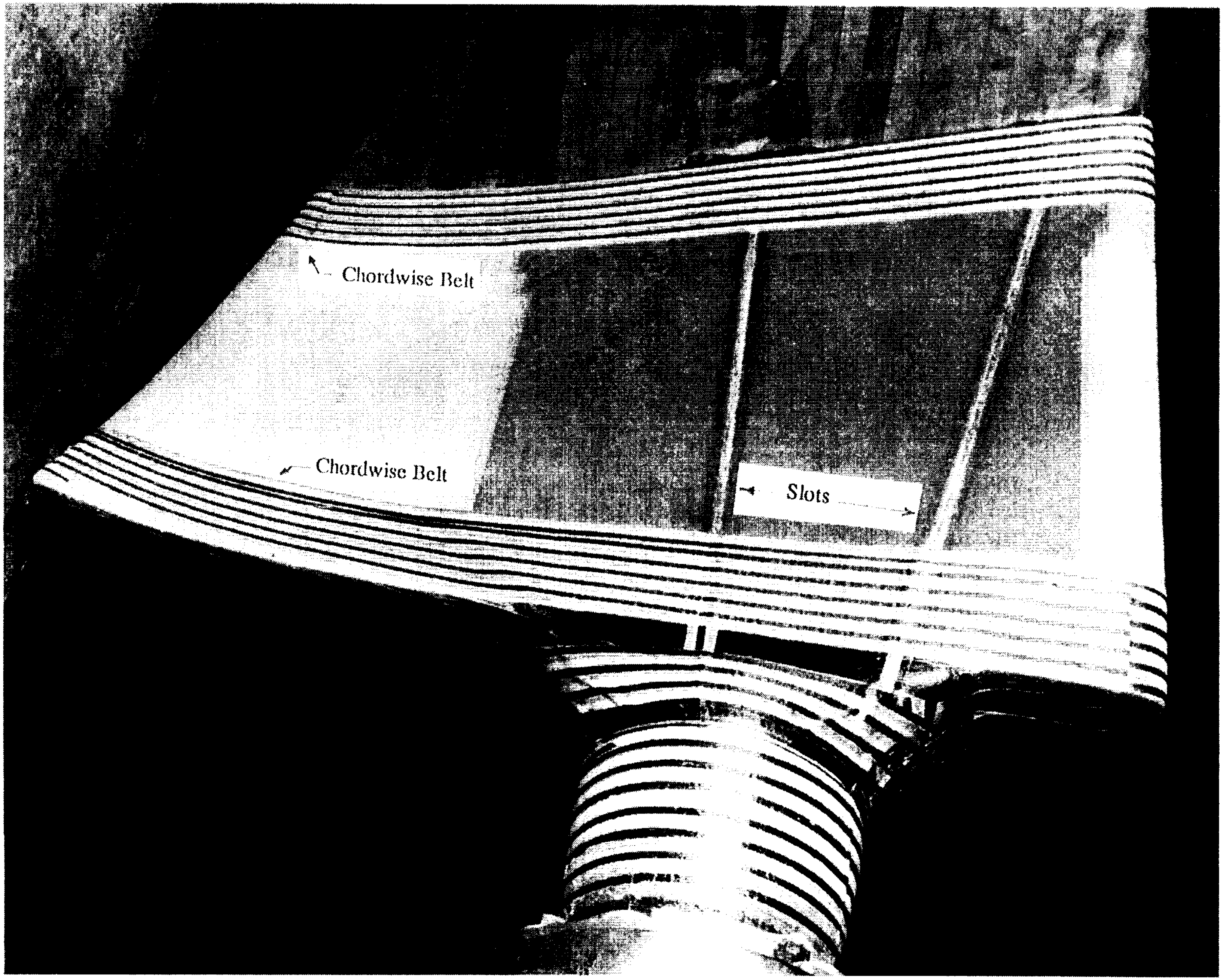


Figure 10. Photo of repaired blade lower surface illustrating overwrap of blade and metal cuff with chordwise belts.

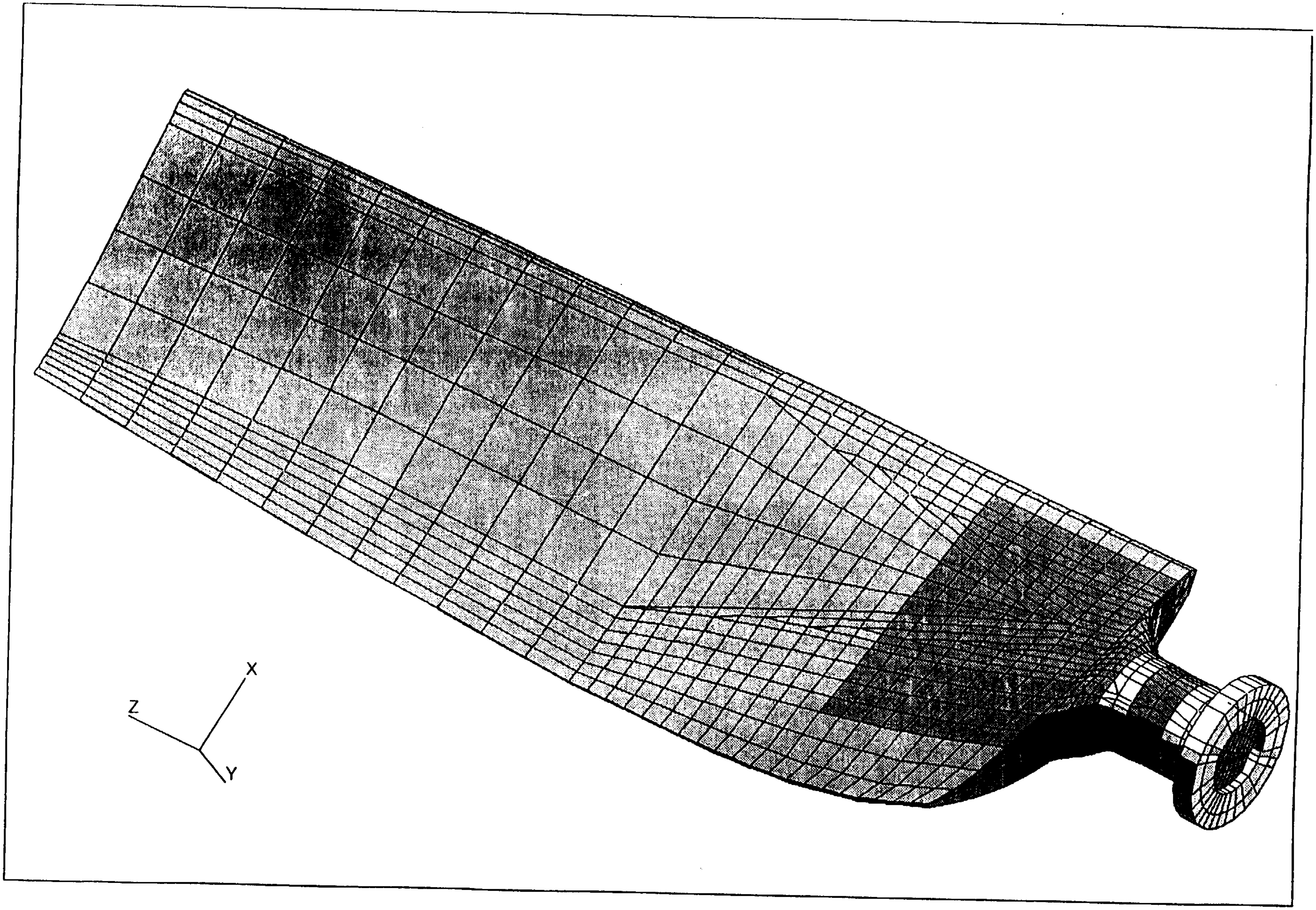


Figure 11. Finite element model of repaired blade assembly.

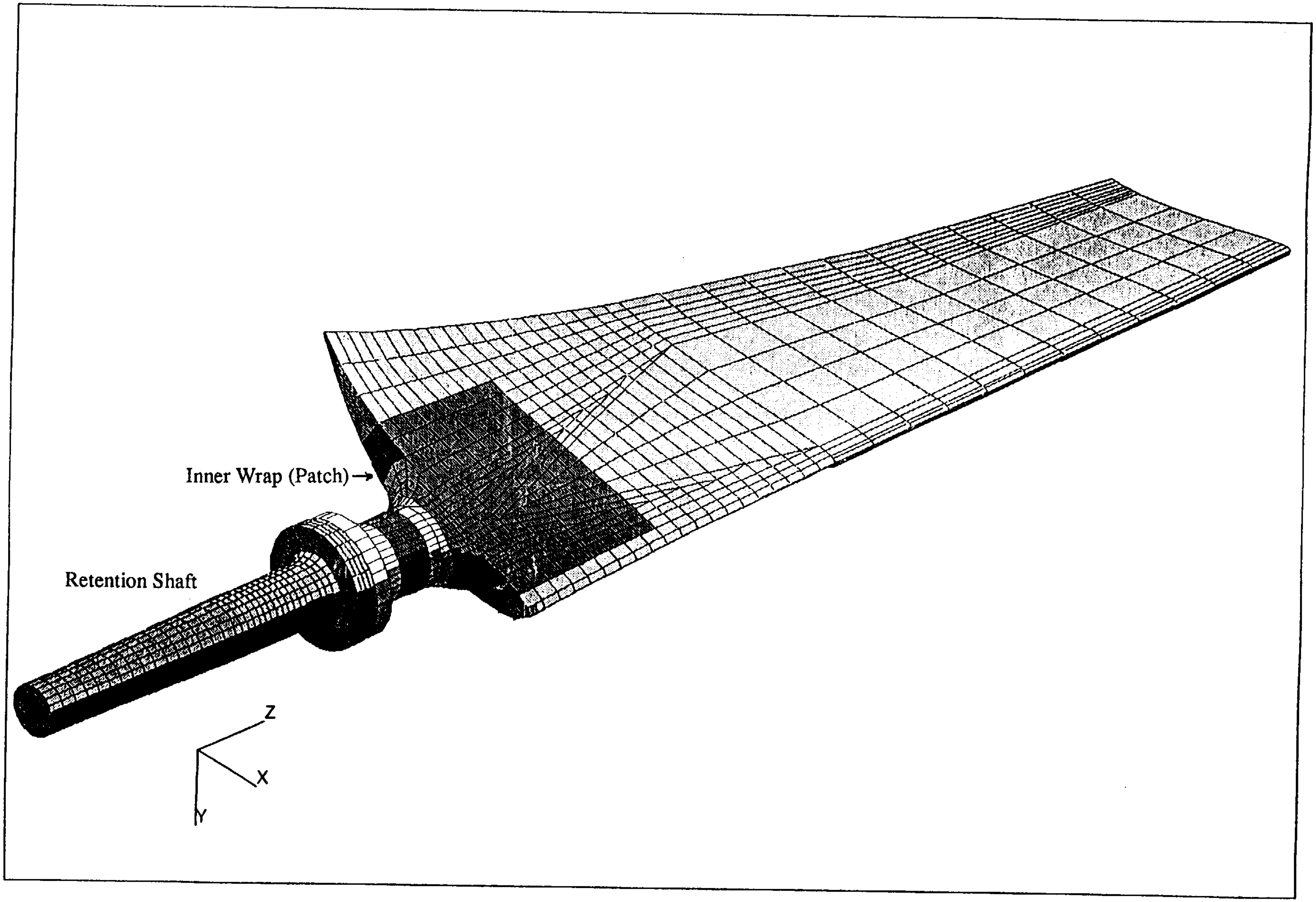


Figure 12. Finite element model of repaired blade assembly with retention shaft.

Thermal Expansion Properties

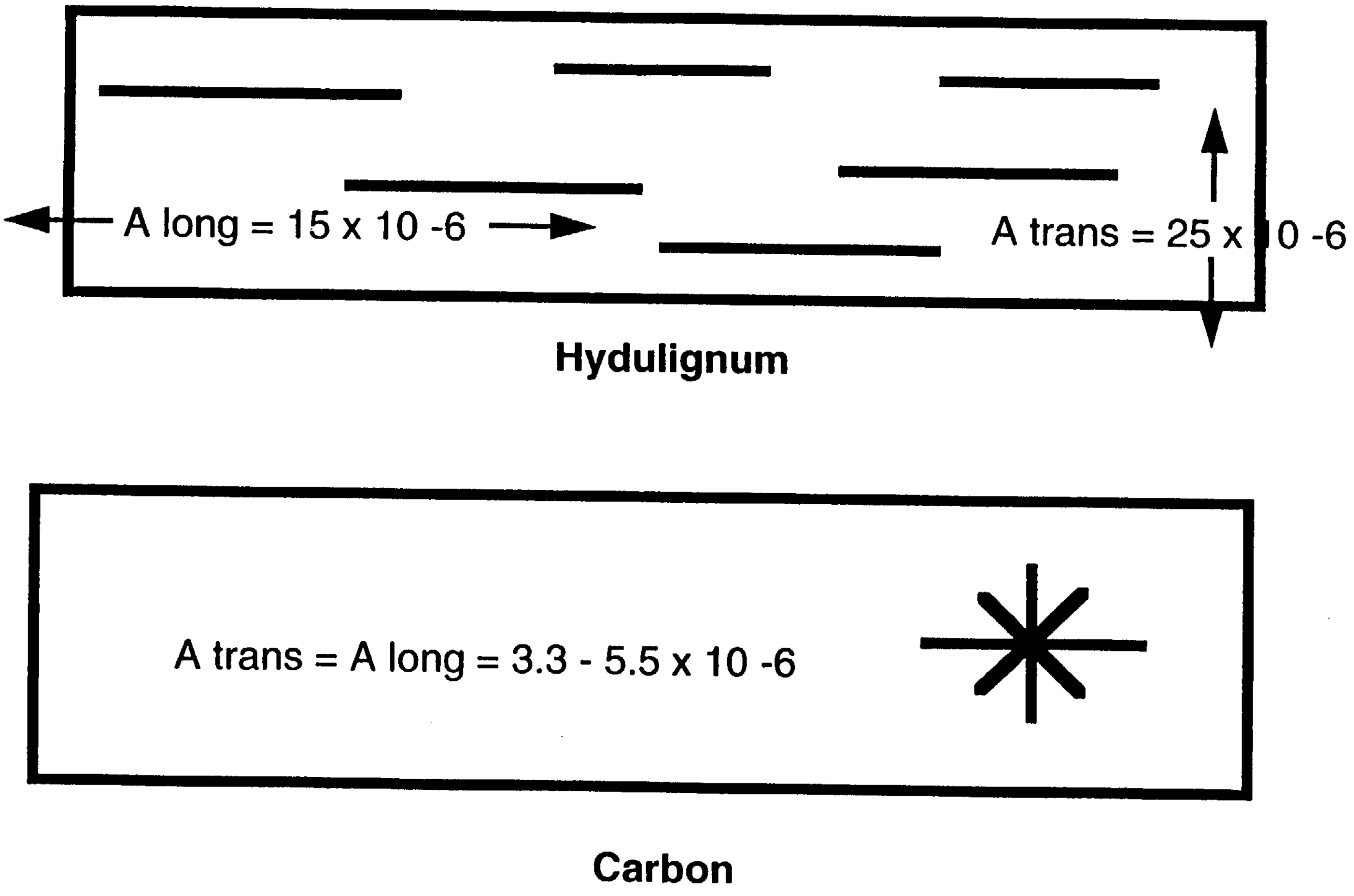


Figure 13. Thermal expansion properties of Hydulignium and carbon composite materials.

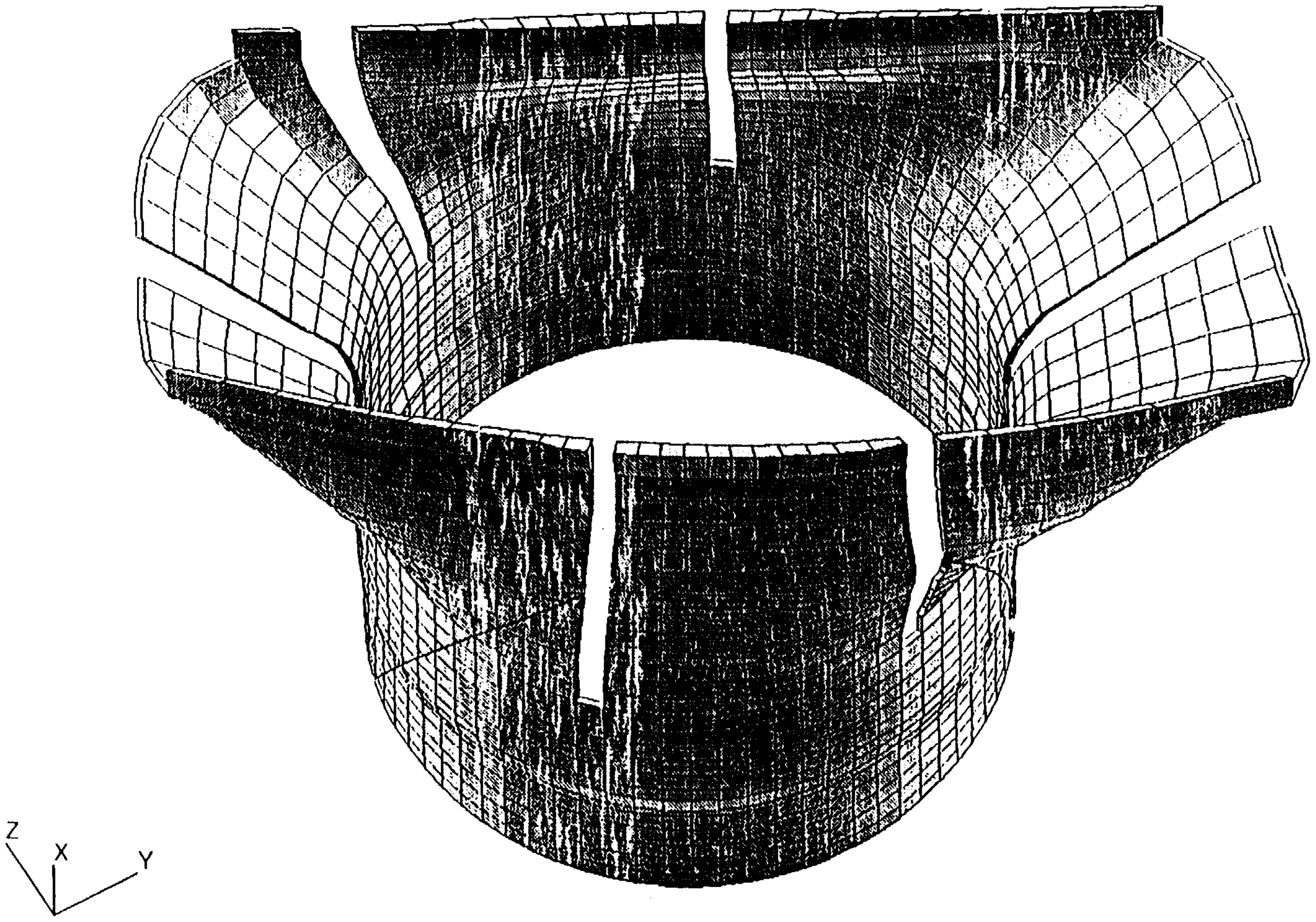


Figure 14. Finite element mode illustration of blade repair overwrap with slots.

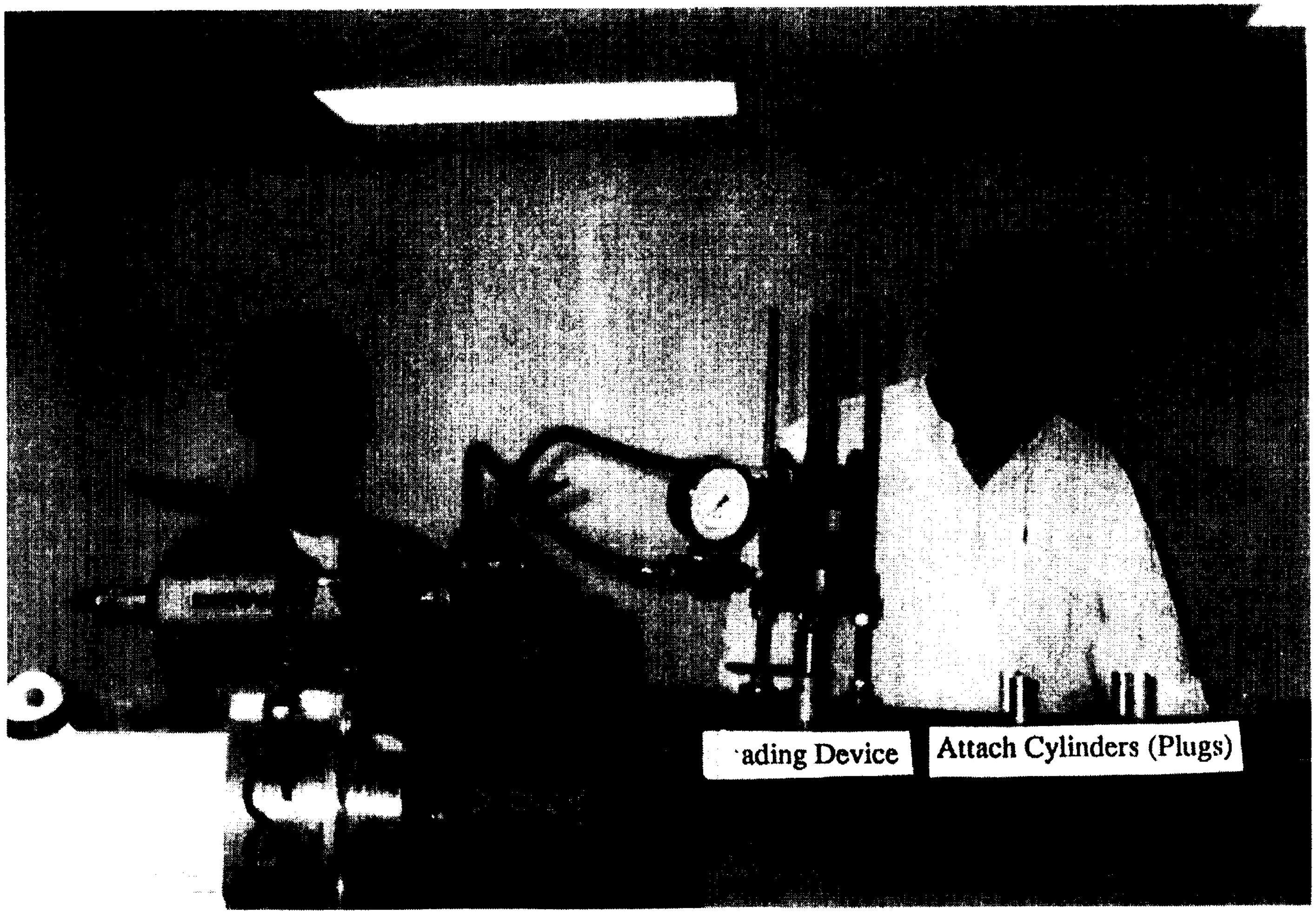


Figure 15. Photo of pull test rig installed on blade 120.

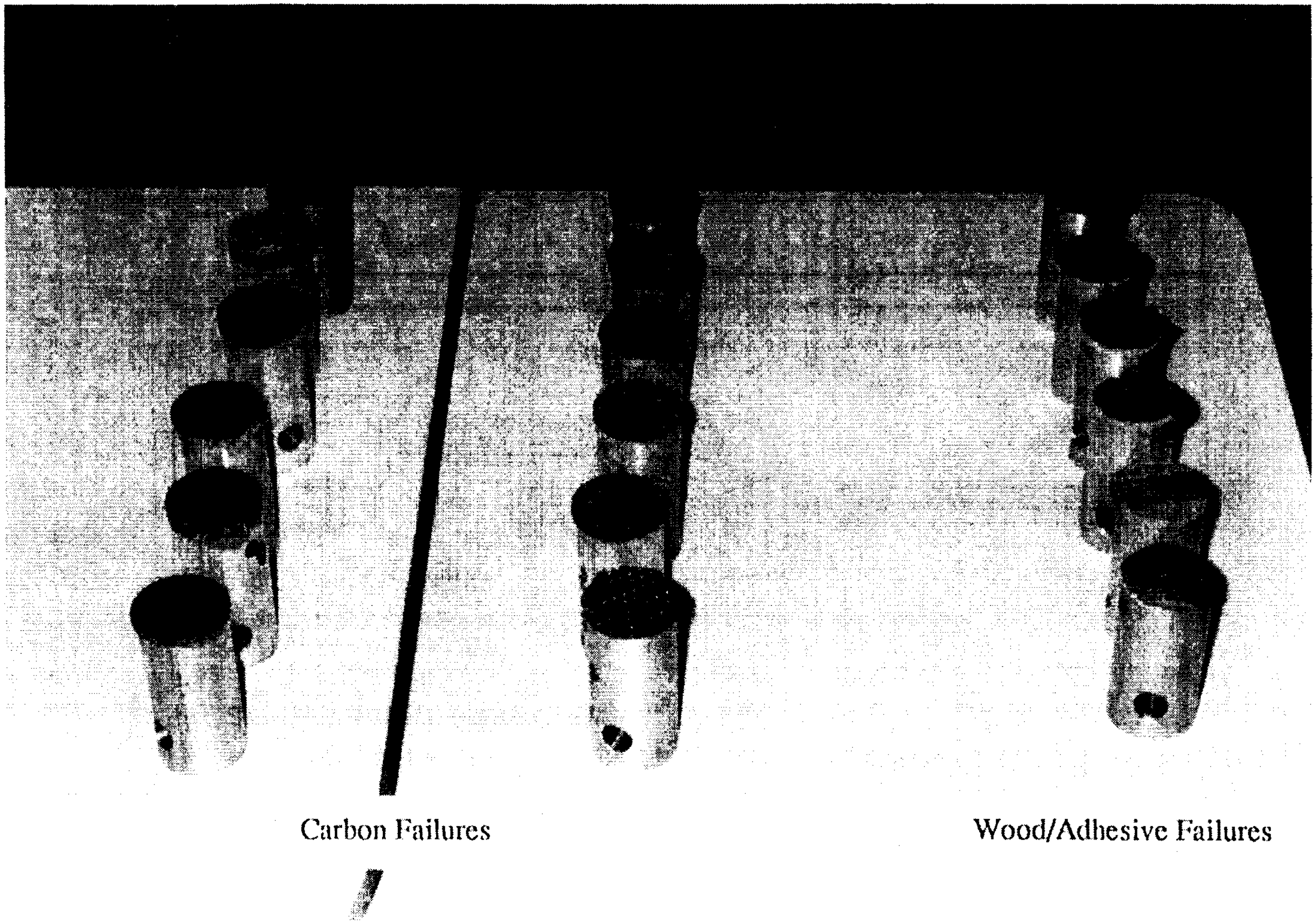


Figure 16. Photo illustrating pull test plugs from blade 120 test bed.

Full Scale Fatigue Test of Repaired NFAC Blade
Test Apparatus

- steady, centrifugal loading applied axially at blade tip (induces no moment)
- moments, shear, and torque applied through a load transverse to the blade at a single point
- temperature environment simulated using heated air forced through an insulated chamber

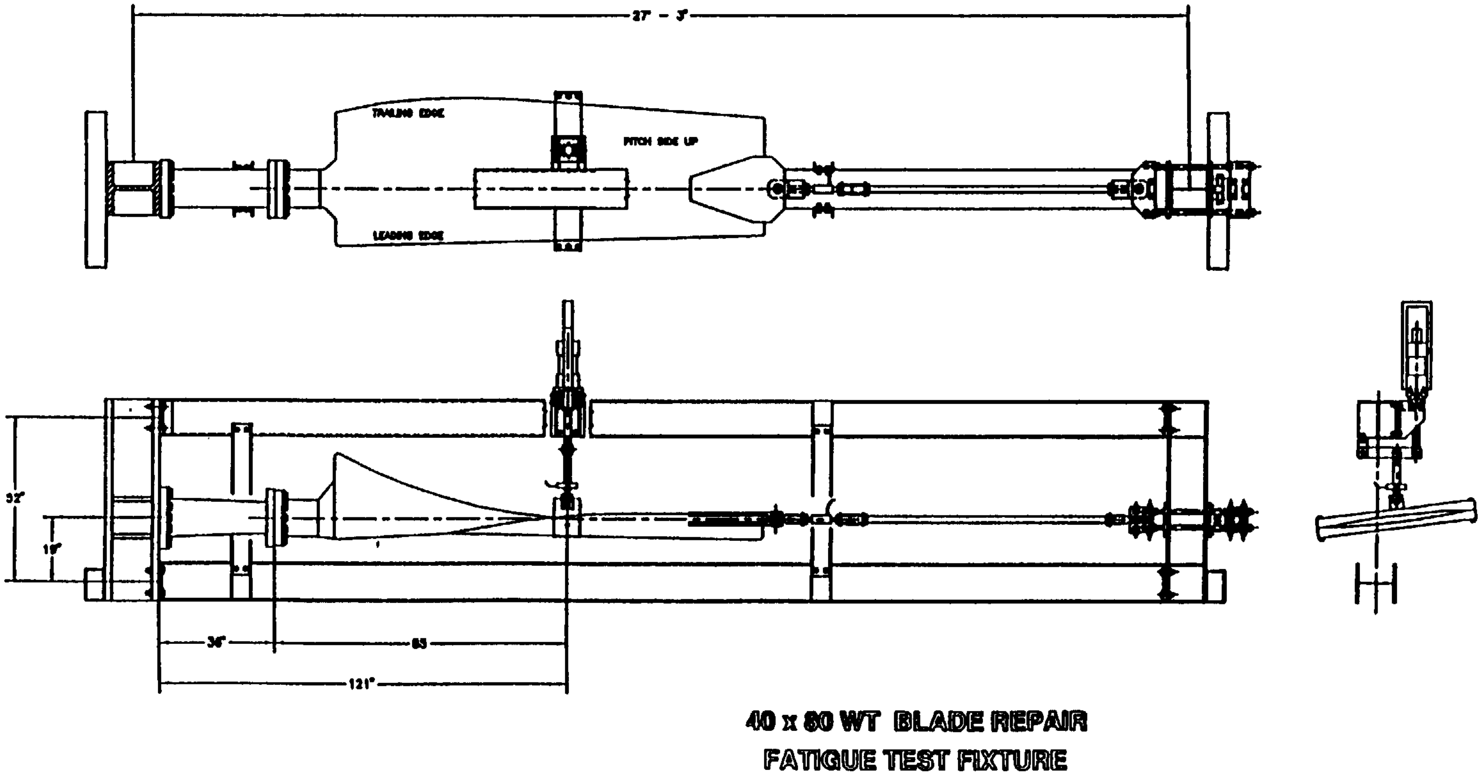


Figure 17 Fatigue test fixture.

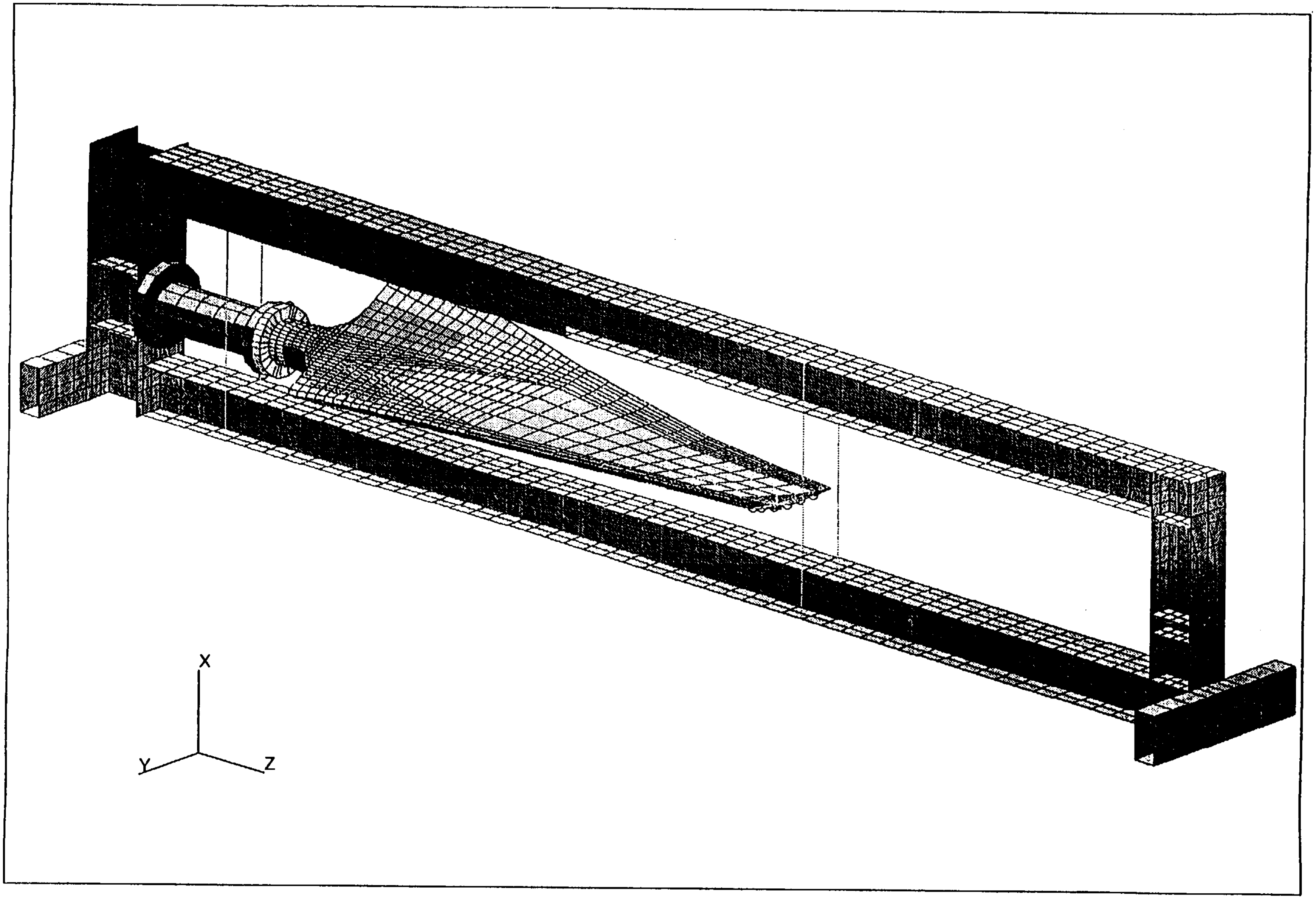


Figure 18. Finite element model of NFAC blade installed in fatigue test fixture.

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13. ABSTRACT (*Maximum 200 words*)

This report describes the principal activities of a technical review team formed to address National Full Scale Aerodynamic Complex (NFAC) blade repair problems. In particular, the problem of lack of good adhesive bonding of the composite overwrap to the Hyduliginum wood blade material was studied extensively. Description of action plans and technical elements of the plans are provided. Results of experiments designed to optimize the bonding process and bonding strengths obtained on a full scale blade using a two-step cure process with adhesive primers are presented. Consensus recommendations developed by the review team in conjunction with the NASA Ames Fan Blade Repair Project Team are provided along with lessons learned on this program. Implementation of recommendations resulted in achieving good adhesive bonds between the composite materials and wooden blades, thereby providing assurance that the repaired fan blades will meet or exceed operational life requirements.

14. SUBJECT TERMS
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