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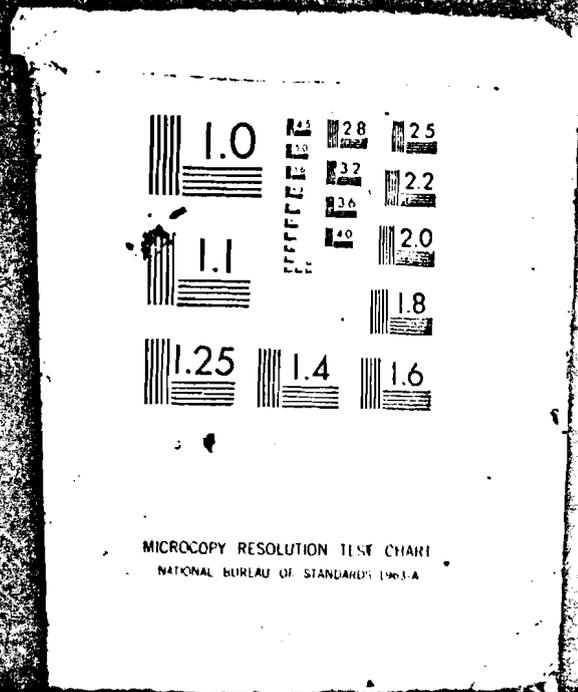
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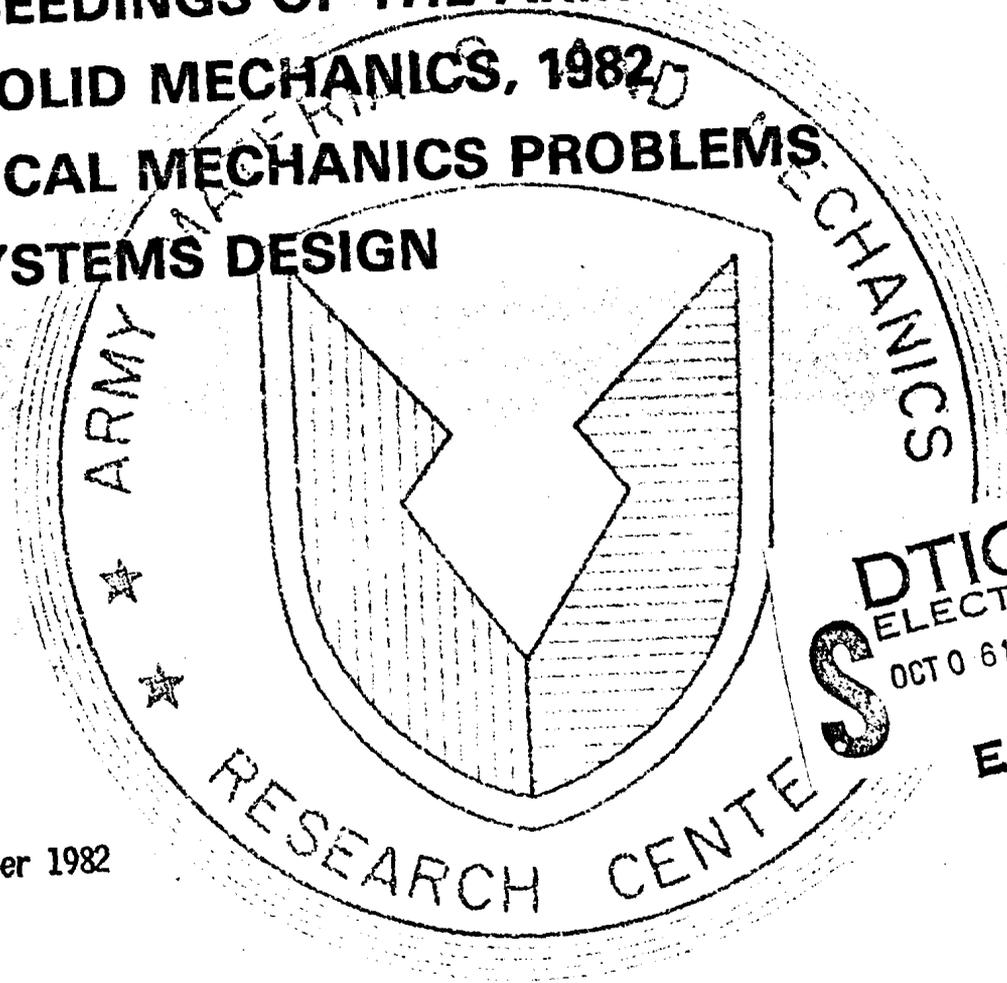


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**PROCEEDINGS OF THE ARMY SYMPOSIUM
ON SOLID MECHANICS, 1982
CRITICAL MECHANICS PROBLEMS
IN SYSTEMS DESIGN**



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(TITLE): Proceedings of the Army Symposium on Solid Mechanics, 1982 - Critical
Mechanics Problems in Systems Design, 21-23 September 1992,
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P000 017	Mechanics Problems in Composite Main Rotor Blade Design.
P000 018	An Efficient Method for Determining the "A" and "B" Design Allowables.
P000 019	Design and Fabrication of Low Cost Composite Compressor Blades.
P000 020	Cyclic Torsion of a Circular Cylinder.
P000 021	Determination of Proof Load Criteria for the F-14 Arresting Gear Hook Shank.
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PREFACE

The Army Symposium on Solid Mechanics, 1982 was the eighth in a series of biennial meetings sponsored by the Army Materials and Mechanics Research Center (AMMRC) in Watertown, Massachusetts. A Work-In-Progress Session(s) has been incorporated into these conferences since 1974 (called Ongoing Case Studies Session at the 1978 meeting). These sessions are comprised of a series of brief presentations and discussions of current, but not necessarily complete, research relating to the theme of the meeting. Abstracts of these presentations are published in a companion document to the regular proceedings; those presented at this 1982 symposium are published in AMMRC MS 82-5, dated September 1982. The transactions of earlier symposia are listed on page iv of this document.

Participation in these symposia has broadened with time. Starting with the 1972 meeting, papers have been solicited from in-house and contract researchers and designers for the Navy, Air Force, and other government agencies, in addition to those for the Army. The symposium committee has been expanded several times; its current membership is as shown on page v. These expansions were made in recognition of the fact that many mechanics research and/or design problems are not unique to a single service or government agency.

Essentially, these symposia are a vehicle for enhancing the responsiveness of mechanics research efforts for the design of advanced military systems. They also facilitate communications and coordination between and among researchers and designers having common military theme interests, whether they work for a government service or agency, industry, or at some university or research institute.

No endeavor of the magnitude of this 1982 symposium could have been successfully conducted without the enthusiastic cooperation and support of many individuals and organizations. We gratefully acknowledge:

The many authors, participants and session chairmen who made this conference such a success.

The manuscript reviewers from universities, industry and government organizations, for their diligence in carrying out a thankless task.

Brigadier General Church M. Matthews, Jr., Deputy Commanding General for Research and Development, of the U.S. Army Tank-Automotive Command in Warren, Michigan, who delivered a very interesting and relevant Keynote Address.

Finally, the staff of the Technical Reports Office of AMMRC for their unflagging efforts in the preparation and printing of numerous symposium materials.

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DESIGN AND FABRICATION OF LOW COST COMPOSITE COMPRESSOR BLADES

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ABSTRACT

A simplified technique for fabrication of low cost composite blades has been demonstrated. Sandwich construction was implemented and a two step fabrication technique was developed using a simplified composite design as a test vehicle. The approach used to design and fabricate full scale blades was duplicated using the test blade.

A finite element model was constructed and used to predict blade properties. Test blades were then fabricated using a two step squeeze molding technique. The method was to mold the foam core, release it, apply the skin material, and place the layered blade back into the same mold for curing. This would compress the core and apply pressure to the skin which is desirable during cure.

These test blades were tested to static deflection and frequency predictions to verify the finite element model. The close correlation between predicted and experimental results support the approach to the design and fabrication techniques applied here and indicate no problems during the eventual fabrication and testing of a full scale blade.

The preliminary composite design using sandwich construction and an aluminum root section resulted in a composite blade design which decreased the major loading by 82%, reduced the weight of the blade by 29%, and was easy to fabricate using the squeeze molding technique described. This reduction in blade weight would decrease the power requirements of the wind tunnel during operation.

The use of a composite design should greatly improve tolerance to impact damage and fatigue loading conditions found within the wind tunnel. The resulting increase in safe operation, decrease in cost of materials, fabrication, and operation of the tunnel, and the possibility of eliminating blade replacement due to reparability and enhanced fatigue life, support the effort to replace the metal compressor blades with those of a composite design using these low cost fabrication techniques.

INTRODUCTION

The fabrication of low cost composite blades has been a recent interest in the design and manufacture of composite windmill, helicopter rotor, and wind tunnel fan blades.

A study has been carried out to design and fabricate a composite replacement for an aluminum wind tunnel blade. This study was divided into several parts: design of a replacement compressor blade entailing an analysis of the present blade and its proposed composite counterpart, selection of materials and fabrication techniques, and verification of the design and fabrication method with test blades.

A concept for fabrication of such low cost blades has been developed using a foam core sandwich construction technique. This method entails a two step squeeze molding technique which utilizes a mold to form the foam core and uses the same mold to bond the composite skin to this core. This produces the finished blade with minimum effort and use of excess materials.

At the time this concept was being developed, NASA-Ames Research Center was investigating the possibility of designing and fabricating composite replacements for the solid aluminum fan blades for one of three wind tunnels in use at Moffett Field. Figure 1 depicts the compressor blade chosen for replacement. The reasons for implementing a composite design were (1) the blades may encounter moving objects (rocks, nuts, bolts) during operation and a composite design would have superior resistance to impact damage as compared to the solid metal blades, (2) a composite design would have better properties under the fatigue loading conditions encountered in the tunnel, (3) the composite blades would weigh less than their all metal counterparts, reducing the power requirements of the tunnel, (4) the blades would be easier to

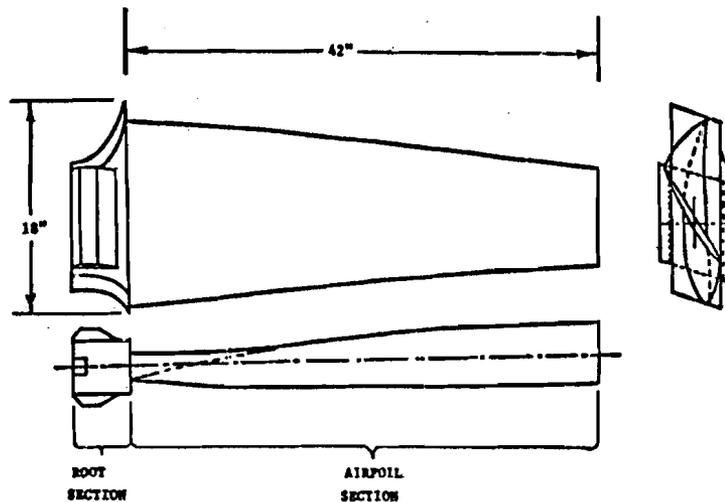


Figure 1. Compressor blade.

fabricate than the all metal blades and (5) with a composite design there exists the potential capability to tune the natural frequency of the blade by changing the fiber type and orientation. This would accomodate tunnel improvements which might present vibration problems with present blades.

Ease of fabrication and the desire to produce a viable replacement for the blades presently in use were considered to be important aspects of the design. When the squeeze molding technique had been chosen, two restrictions were placed on the design. These were that the fabrication method required a design of sandwich construction with a moldable foam core and a fibrous skin material (cloth or filament wound) and the aerodynamic shape of the blade was not to be changed.

Materials for the skin and core had to be chosen to produce the desired properties for the fabrication and design. Kevlar-epoxy was chosen as the skin material for its high impact resistance and excellent properties under fatigue loading. Polyurethane foam was chosen as the core material for its ease in molding and light weight.

The design criteria for the composite blade would be to approach the natural frequency of the present blade and its static stiffness (bending and torsional). Skin thickness, fiber orientation and the incorporation of graphite were variables involved in the design cycle.

After considering a general approach to the design and fabrication, the method of attaching the blades to the rotating hub was evaluated. This is an important aspect because the root is an area of high stresses and the design should be simple to facilitate ease of fabrication. For these reasons it was considered early in the design cycle.

The approach to the design and fabrication was then verified using a smaller simplified composite design.

Finally the design of the composite replacement was undertaken. The final proposed design resulted in an 82% decrease in the centrifugal loading and 29% reduction in the total weight of the blade.

QUALIFICATION OF THE FINITE ELEMENT MODEL

It was proposed to model the sandwich construction using the structural analysis program SAP4a(1). The sandwich design would be simulated using plate elements to model the skin and brick elements to model the foam core. This concept was supported by comparing results from a computer model of a sandwich beam with actual tests.

It was not known whether a finite element model of a foam core sandwich beam could be constructed tying a 3-D solid brick element (modelling the core) to a plate element (modelling the skin). There is a difference between these elements in that the brick has 6 degrees of freedom (x,y,z translation and x,y,z rotations) and the brick has only 3 degrees of freedom (x,y,z translation). Figure 2 illustrates these differences. To determine if this was a

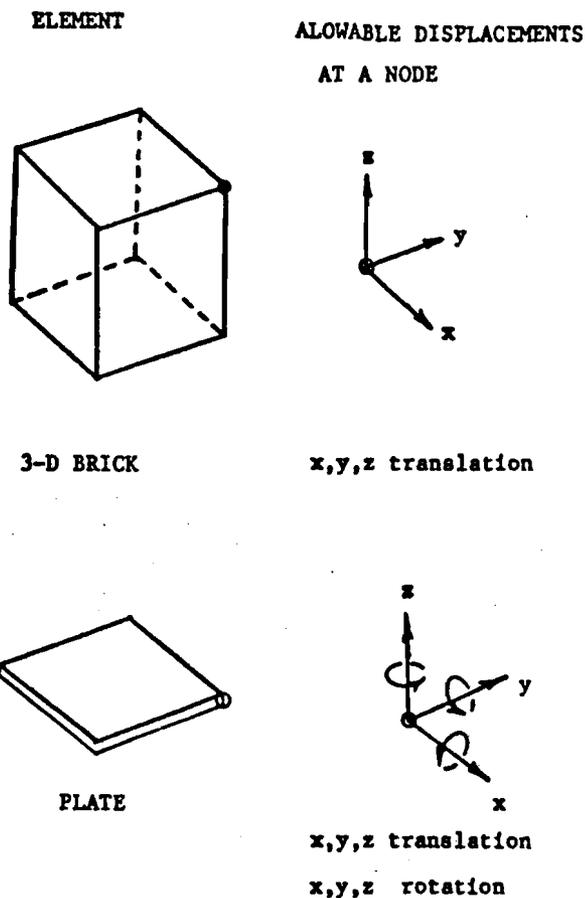


Figure 2. Allowable displacements for brick and plate elements.

viable method to model sandwich construction a finite element model of a 5 inch long cantilevered sandwich beam was constructed using the properties of the foam core and Kevlar skin used in the actual construction of the beam (Figure 3). The actual sandwich beam for comparison was constructed using a foam core 5 inches long with a 1 inch square cross section and epoxying a 0.033 X 1 inch layer of Kevlar to the top and bottom of the foam. The natural frequency of the sandwich beam was found by three methods which were used as a basis for comparison. The finite element model was used to predict the fundamental frequency initially. The second method was to calculate an effective EI for the beam and the use of handbook methods to predict the frequency. The third method was to measure the actual frequency by clamping the root section, placing an accelerometer on the end of the beam, exciting the beam and passing the output through a fast Fourier Transform analyzer.

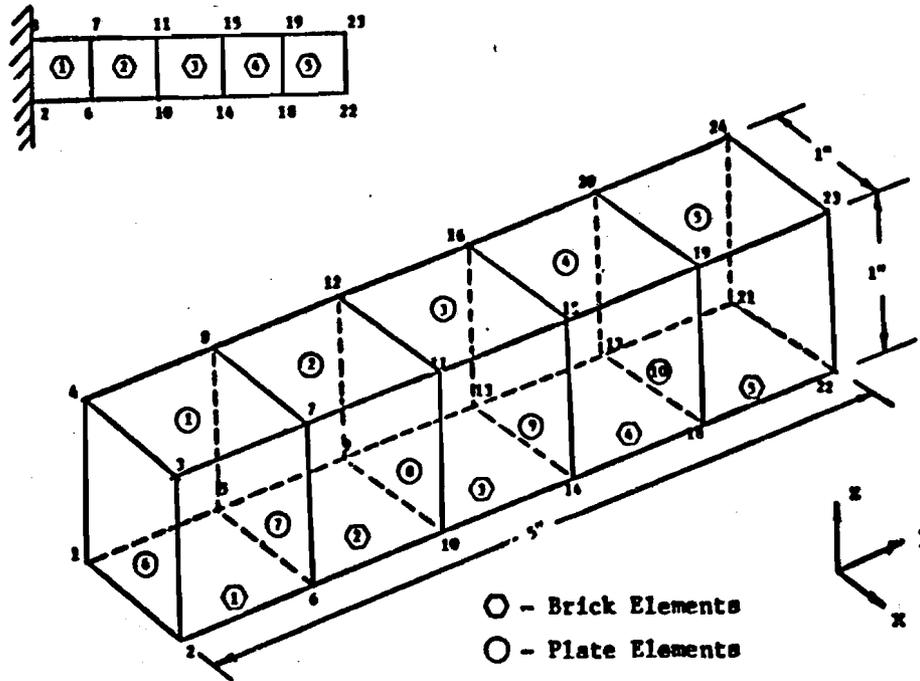


Figure 3. Finite element model of 5"-long test beam (sandwich construction).

The fundamental frequency predicted using the finite element model, 345 Hz, was much lower than the handbook prediction of 1312 Hz (Table I). This could be explained because the handbook does not consider the low shear stiffness of the foam core, which will decrease the overall beam stiffness and reduce the actual frequency.

TABLE I

Method	Frequencies of Sandwich Beam		
	Handbook	SAP IV	Measured
Frequency (Hz)	1312	345	350

The finite element model considers the low shear stiffness of the foam and was expected to predict the correct natural frequency. This conclusion was verified by experimentally measuring the fundamental frequency of the modeled beam. The actual frequency was measured as 350 Hz. This represents a 1.4% difference from the 345 Hz predicted by the computer model.

Thus it appears that combining the plate and brick elements presents no problems and may be used as a basis to model a sandwich beam.

ANALYSIS OF ALUMINUM COMPRESSOR BLADE

The 11 foot wind tunnel at NASA-Ames Research Center was elected to receive the first composite compressor blade. The primary reasons for its selection were that this tunnel receives the most use at Moffett Field and the compressor blades are 42 inches long and would fit easily into the autoclave at AMMRC during fabrication.

Surface coordinates for the solid aluminum blade were obtained and used to generate nodal coordinates for the model. A finite element model of the blade was constructed using 3-D solid brick elements. The structural program used was SAP 4a. The model contained a total of 229 nodes yielding 90 elements. Figure 4 shows a graphical representation of the model. In order to approximate the restrictions placed on the blade at the root during operation, displacement and rotational boundary conditions were imposed to simulate a cantilevered beam.

STATIC ANALYSIS

Two static analyses were performed on the model to determine the static stiffness of the solid aluminum blade for comparison to the composite design.

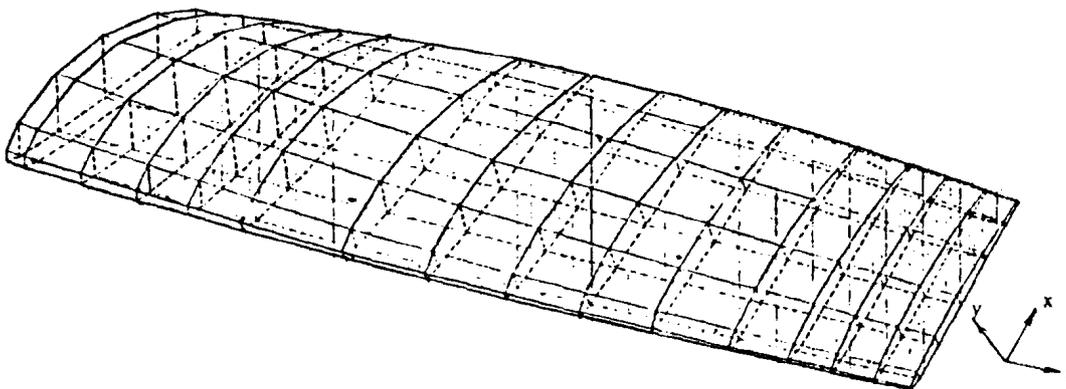


Figure 4. Finite element model of 42" wind tunnel compressor blade.

A one pound distributed load was placed on the end of the blade to determine its static bending stiffness. Next a twisting load was applied to the tip (+1 pound on one corner and -1 pound on the other corner of the tip). Deflections for these two case loads were obtained and shown in Figures 5.a and 5.b.

DYNAMIC ANALYSIS

A modal analysis was also performed using this model to predict the fundamental natural frequency, its harmonics, and the associated mode shapes. These frequencies are tabulated in Table II and the mode shapes and associated frequencies are shown in Figures 6 a, b, c, d.

EXPERIMENTAL MODAL ANALYSIS

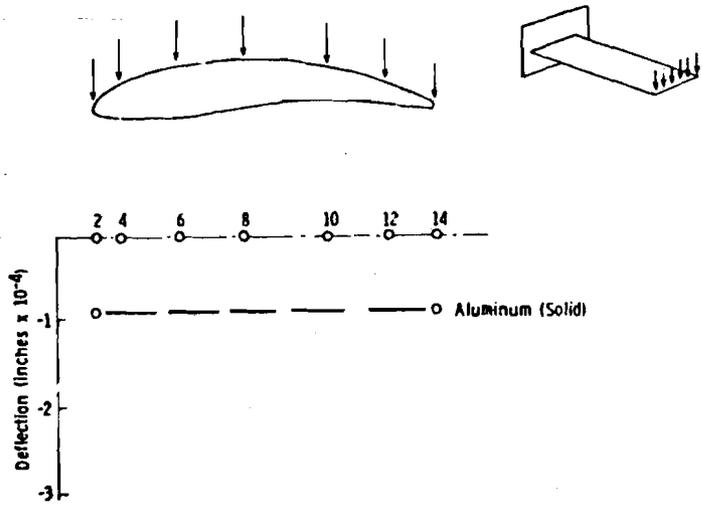
The actual natural frequency, harmonics and associated mode shapes of the aluminum blade were determined by an experimental modal analysis. This was performed on the aluminum blade by restraining the root section in a mechanical testing machine under compression, placing an accelerometer on the tip, exciting the blade, and running the accelerometer output directly into a Fast Fourier Transform Analyzer. This determined the range of frequencies to be matched with the composite design and also provided a check of the accuracy of the computer model.

Attachment of the root section in the machine was critical. First testing was carried out using a servohydraulic system (Tinius Olsen). Erroneous results were obtained leading to suspect the system hydraulics may have caused interference in the frequency measurements. Further analysis was performed using a mechanical screw type testing machine (Instron 1127) which produced a more rigid grip of the root section. Total restraint of the root section was accomplished by "shimming" the fixture so that clamping pressure could be distributed over the entire root section.

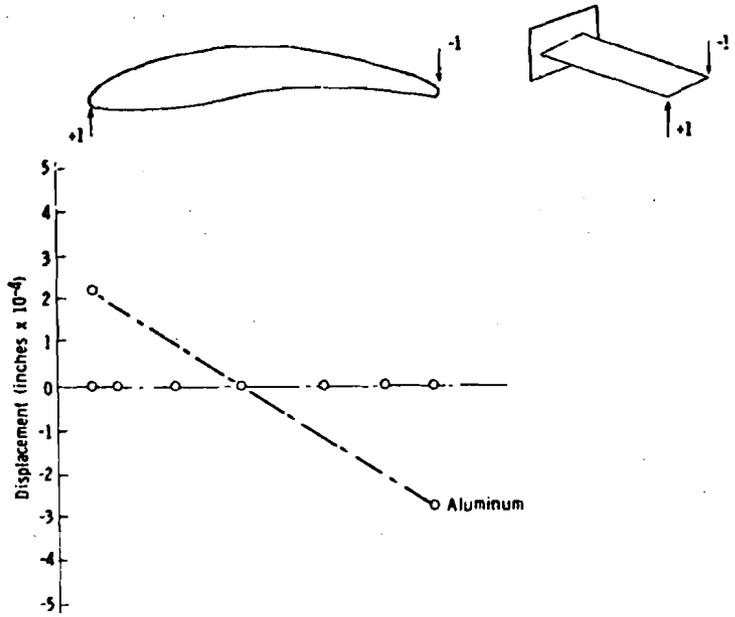
TABLE II

Comparison of Blade Frequencies-
Predicted and Experimental

Mode	Frequency (hz.)		
	Al.(FEA)	Composite(FEA)	Measured(Al.)
1	51.5	69.62	55
2	158.7	209.9	155
3	266.4	304.1	305
4	340.9	---	395
5	426.5	---	555



a. Relative tip deflection versus material for distributed unit load at tip.



b. Twist at tip for twisting load applied at tip.

Figure 5.

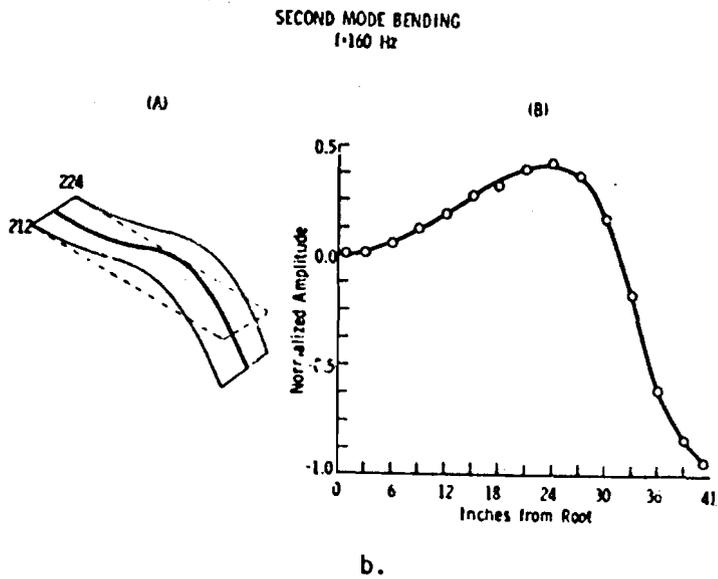
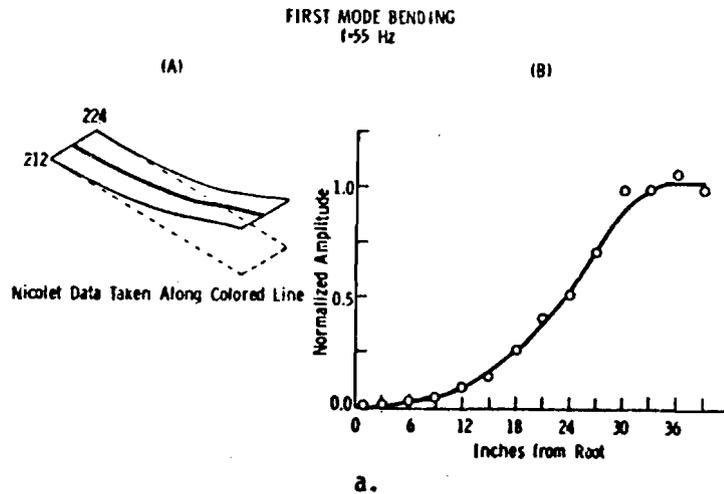
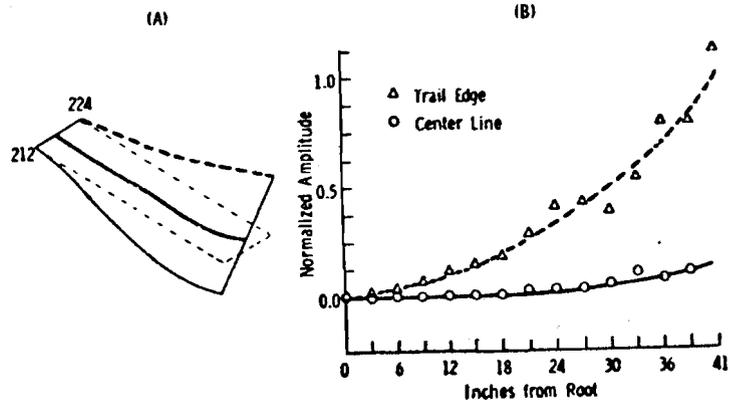


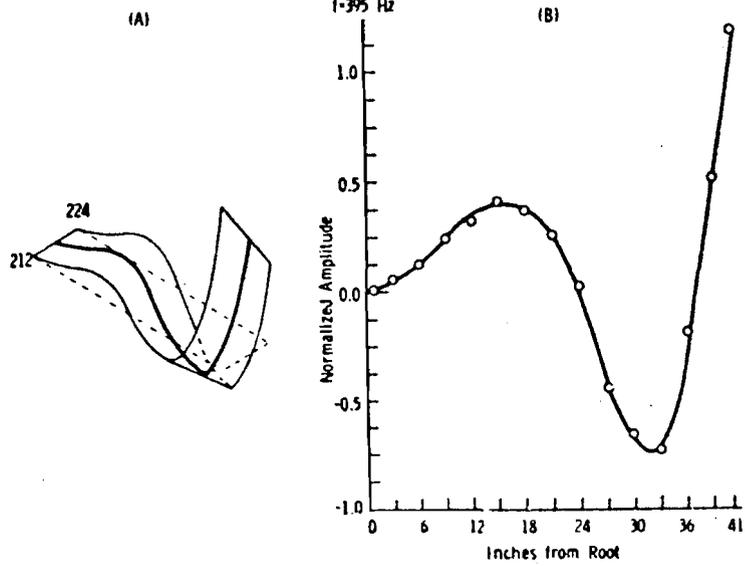
Figure 6. Mode shapes obtained from (A) Finite Element Model, and (B) Nicolet Frequency Analyzer.

FIRST MODE TORSION
f=305 Hz



C.

THIRD MODE BENDING
f=395 Hz



d.

Figure 6. (Cont.)

Frequencies obtained in the modal analysis were related to the clamping pressures. Natural frequency and harmonics were measured at various clamping pressures. Frequencies increased with clamping pressure until levelling off between 15,000 and 20,000 pounds. For the final analysis a clamping pressure of 20,000 pounds was chosen.

Mode shapes were obtained using the same FFT analyzer and the same method of root retention. The approach used to measure the mode shape was to place the transducer at various intervals along the length of the blade. The blade was excited by striking the tip with a hammer and recording the frequency spectrum from the accelerometer. This was repeated four times at each transducer location.

MATERIALS AND DESIGN

Presently the wind tunnel compressor blades are made by milling the shape out of a billet of solid aluminum. In an effort to simplify design and fabrication a preliminary design using sandwich construction was chosen for the composite blade. This method produces very strong and stiff structures which are simple in design and easy to fabricate. Sandwich construction consists of a lightweight core material "sandwiched" between two relatively stiffer and/or stronger outer layers. This skin provides strength and stiffness. The skin is bonded to the core to maintain stiffness and to prevent buckling and skin vibrational modes. Polyurethane foam was chosen as the core material because it is easy to use and has good chemical resistance (it is insoluble in the solution used for cleaning and dewaxing the core material).

The wind tunnels in question are of the racetrack type (air is recirculated) and parts (nuts, bolts, etc.) lost from the model being tested are encountered by the moving compressor blades. This presents a problem for solid metal blades because the objects may cause nicks, initiating crack growth and resulting in possible catastrophic failure. A composite blade will not fail catastrophically (without warning). When a blade is damaged the operator would have time to stop the machine before further damage could occur. If by chance a blade were released the sandwich construction would be so light that there would be minimal damage to surroundings.

Kevlar was chosen as the skin material for two reasons; it has superior resistance to impact damage and excellent properties under fatigue loading conditions³. For these reasons it is chosen as the major constituent in most composite helicopter blades.

The static stiffness of the blade became an important factor in the design, therefore, unidirectional graphite fibers were incorporated into the design. Graphite fibers have a much higher stiffness than Kevlar, resulting in an increase in the overall stiffness of the blade. Graphite could be added together with Kevlar to form a hybrid composite skin to obtain the mutually beneficial properties of a high degree of stiffness associated with high strength and toughness.

The resin chosen as the matrix material for the composite skin was EPON 828 with Jeffamine T-403 hardener. This resin was chosen for the preliminary design because it can be cured at room temperature overnight or at high temperature (200°F) for one hour. This would eliminate the need for an oven for initial fabrication of test blades. A high cure temperature is associated with a high glass transition temperature which is desirable because of the elevated temperature encountered in the 3 stages of the wind tunnel compressor. The temperature ranges from 150°F in the first stage to approximately 180°F in the third stage. To maintain the stiffness of the blade, the glass transition temperature of the resin must be above the operating temperatures.

FABRICATION AND TEST OF COMPOSITE VERIFICATION BLADE

The proposed fabrication method consisted of a two step squeeze molding technique molding the foam core in the first step and bonding the skin to this core using the same mold in the second step. Because this was a relatively new technique for the fabrication of blades, the approach was perfected using a simplified composite design as a test vehicle. A finite element model of the test blade was constructed, and used to predict the static stiffness of the blade and its natural frequency. The blade was then constructed and tested to these same criteria and compared with the theoretical predictions.

ROOT DESIGN

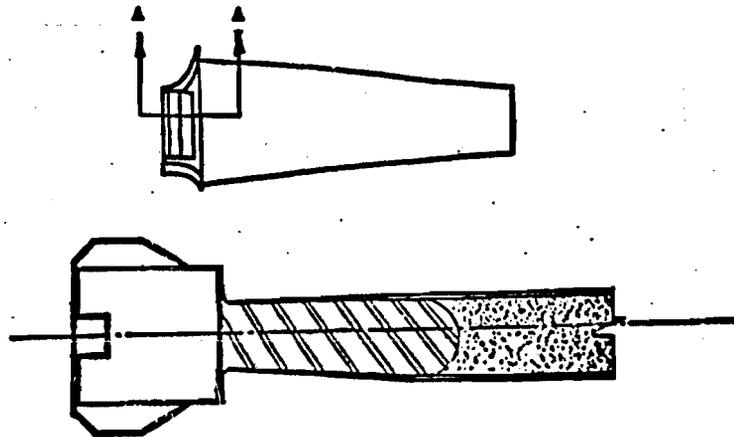
A solid aluminum root insert was chosen as a method for attaching the blade to the hub. The solid aluminum root insert obtained from the original blades (Figure 7a) provided the unique opportunity of direct comparison of the performance of aluminum vs. composite for blades apart from the root design. The only difference in the design is the blade section itself. It also offers ease of construction of the new blade in that the complicated root section can be molded into the blade in one step during fabrication. Also the method of restraining the root section for the modal analysis of the blade could be duplicated.

When the 42 inch blade (11 ft. tunnel) was chosen as the blade to be replaced, the solid root insert was chosen as the prototype for several reasons. It could be easily molded into the blade, and presented a direct comparison of old and new designs.

This type of solid insert was used in the fabrication of the test blade to duplicate the eventual manufacture of the full scale compressor blade. Figure 7b shows the design used for root end of the test blade.

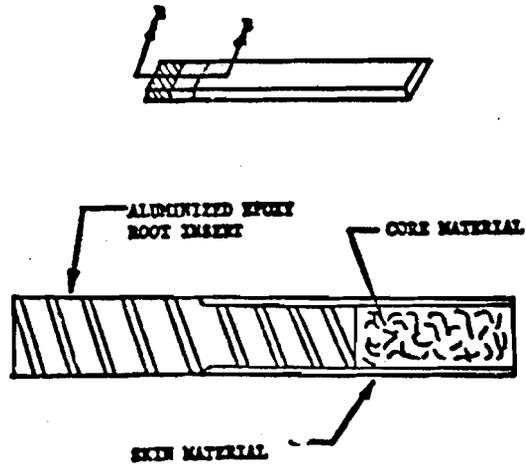
FABRICATION OF TEST BLADE

Verification of the proposed construction method was accomplished using a 36 inch long composite blade design of trapezoidal cross section (Figure 8). The mold for this blade was constructed using a two 3/8 inch thick aluminum plates held apart by aluminum spacers which have a 45° bevel cut along one side.



SECTION A-A

Figure 7a. Solid aluminum root insert for composite blade.



SECTION B-B

Figure 7b. Solid epoxy root insert for composite test blade.

The mold was held together with 27 1/4-20 steel bolts. the top aluminum plate was removable to provide access into the mold and could be tightened down with nuts to provide clamping pressure during blade fabrication.

To simulate fabrication of the composite compressor blade the test blade was constructed using a Kevlar epoxy skin, polyurethane foam core, and aluminized epoxy root insert. The epoxy root insert provided simulation of the aluminum insert in the compressor blade while decreasing the time required for its fabrication (machining) because it could be cast in place right in the mold. The trapezoidal shape of the blade was chosen for two reasons; it was a slightly more complex shape than a simple box beam, lending itself to a better comparison to the behavior of the aluminum blade, and beveling the edges allowed for easy release from the mold during fabrication.

A finite element model of this test blade was constructed using the finite element program SAP 4a. A total of 180 three dimensional, isoparametric elements (eight node bricks) were used to simulate the polyurethane foam core. The skin of the sandwich was modelled using 420 orthotropic plate and shell elements whose properties were determined using the program lay-up. The root insert was modelled using the properties of the aluminized epoxy for the first four rows of brick elements in the root section. Boundary conditions of restricted rotations and displacements were placed on the nodes at the root to parallel the attachment of the blade to the hub as a cantilevered beam.

To determine the static stiffness of the blade using this model a 4.5 pound point load was placed hanging from the tip of the blade. A static deflection of 0.134 inches was predicted.

A modal analysis was performed to predict the fundamental frequency, and associated model shape. This frequency was predicted to be 32.37 Hz for first mode bending.

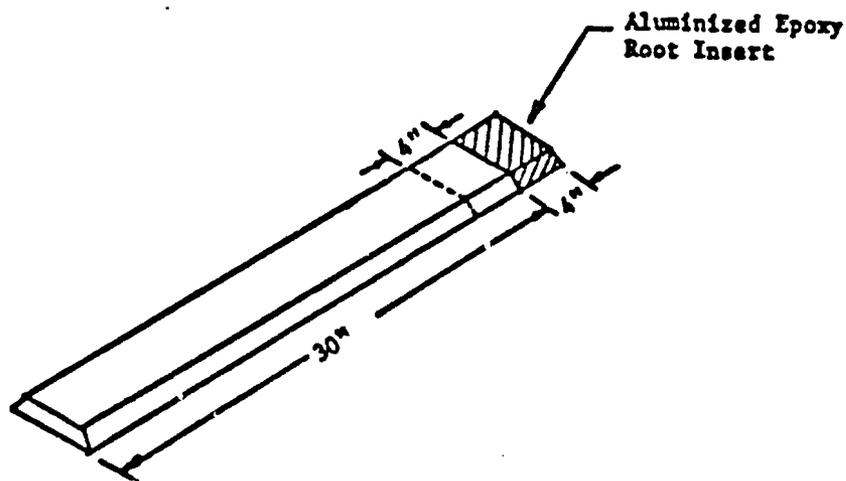


Figure 8. Fabrication test blade.

A new technique was proposed for construction of the blade. The approach was to mold the foam core, release it from the mold, apply the fabric skin around the foam and finally place the blade back in the same mold to cure. Since the blade is the thickness of the skin larger than the mold, when the mold is closed the foam core is compressed. This allows for ease of fabrication and also applies pressure to the skin which is desirable during cure.

Mold release for the foam (Carnuba wax) was first applied to the mold. Polyurethane foam (General Latex 16-F-2702) was mixed thoroughly in a 1:1 proportion and poured into the mold which was then closed. Foam density could best be controlled by the volume of liquid foam poured into the mold. After the foam was cured (about 3 hours) it was released from the mold. The section of the foam to be replaced by the epoxy root was removed by cutting it off. The foam core was dewaxed, epoxy mold release (PVA) applied to the mold, the core placed back into the mold, and the cover was closed. Aluminized epoxy was poured into the open end of the mold and allowed to cure overnight. After

curing, the foam core and insert were removed in one piece. The skin also covers the root insert and since the epoxy was not compressible like the foam 0.1 inch was required to be milled out around the section.

A quasiisotropic lay-up ($0^{\circ}/90^{\circ}$ and $+45^{\circ}$) was chosen for the skin because it lends itself to the orthotropic plate element and the use of woven material. Cloth was used to facilitate ease of fabrication of the initial design. In the fabric the fiber orientation is $0^{\circ}/90^{\circ}$ making it possible to obtain a quasiisotropic lay-up with two layers. The pattern for the skin was laid out on the cloth and cut with the fiber directions $0^{\circ}/90^{\circ}$ and $+45^{\circ}$ both of woven roving. One layer of $0^{\circ}/90^{\circ}$ satin weave Kevlar was used for the outer surface as a surfacing mat. The cloth was laid out on a table and the epoxy (EPON 828, 100 parts and Jeffamine T-403, 49 parts) was applied with a brush. The wet cloth was then laid up on to the core material, placed into the mold, and the mold was closed. The mold and blade were then placed in an oven at 200°F for 1 1/2 hours. It was then removed from the oven and allowed to cool for several hours. The mold was then opened and the blade removed from the mold.

EXPERIMENTAL TESTING AND ANALYSIS

Testing of the blade was carried out in the same manner to be performed on the full scale compressor blade. Retention of the test blade was accomplished by holding the root section in a mechanical testing machine under a compressive load of 5000 pounds. These conditions were maintained throughout all phases of testing.

While retaining the blade under a load of 5000 pounds as mentioned above, a point load of 4.5 pounds was hung from the tip of the blade on the centerline and the resulting deflection was measured by a dial indicator placed 1 inch behind the load.

A static deflection of 0.126 inches was measured when the load was applied. This represents a 6% difference from the predicted deflection of 0.134 inches.

TABLE III
MODAL ANALYSIS OF TEST BEAM

METHOD	FREQUENCY(Hz)
Finite Element Model	32
Experimentally Measured	30

An experimental modal analysis was performed on the test blade to verify the frequency prediction of the finite element model.

Using the same experimental techniques as used for the aluminum blade, the first mode frequency and associated mode shapes were determined for the test blade. Figure 9 shows the predicted (32 Hz) and experimental (30 Hz) frequencies and their associated mode shapes for the first mode. These frequencies differ by 6.6%.

Deviations of only 6% for the deflection and 6.6% for the natural frequencies indicate that the analytical methods used are a viable approach to the design of the composite blade.

COMPOSITE BLADE DESIGN

The design and fabrication of the composite compressor blade was undertaken in the same manner as the composite test blade. A finite element model

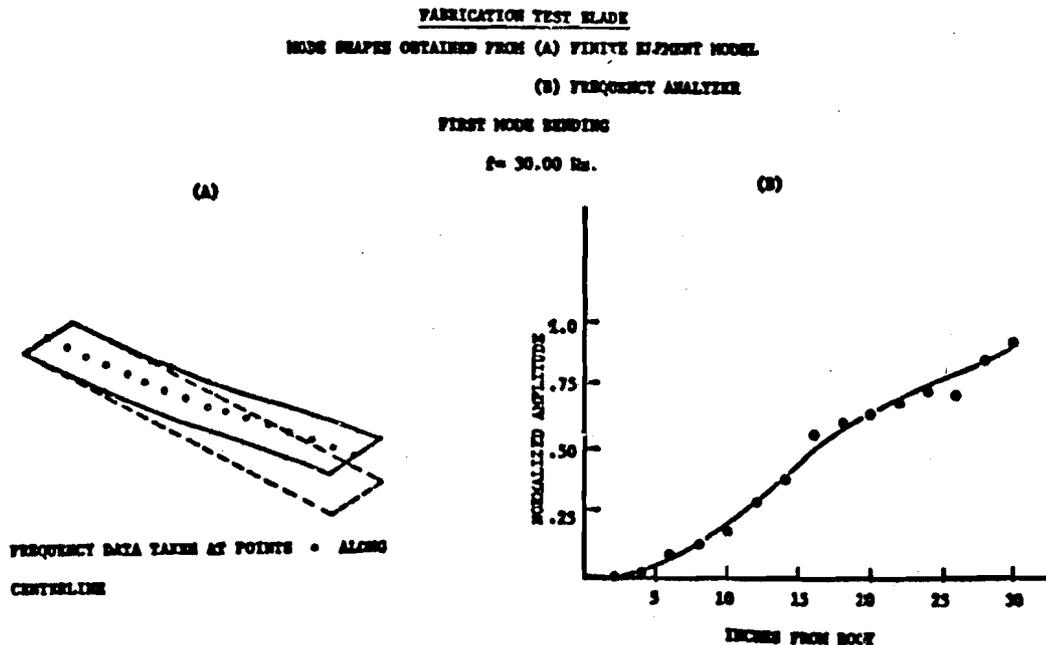


Figure 9. Modal analysis of test blade.

was constructed to evaluate the designs. Skin thickness, fiber orientation and material type were all adjusted to approach the natural frequency and static stiffness of the compressor blades presently in use.

A finite element model of the composite blade was constructed using SAP 4a. The foam core was modelled using eight node solid brick elements. Four node isoparametric plate elements (orthotropic) were used to simulate the composite skin. The root insert was modeled using eight node brick elements with aluminum properties. As in the metal blade, the same boundary conditions of restricting all displacements and rotations at the root were applied to the composite blade. The blades presently in use in the tunnel presented no problems within the present operating range so it was desirable to approximate their frequency response.

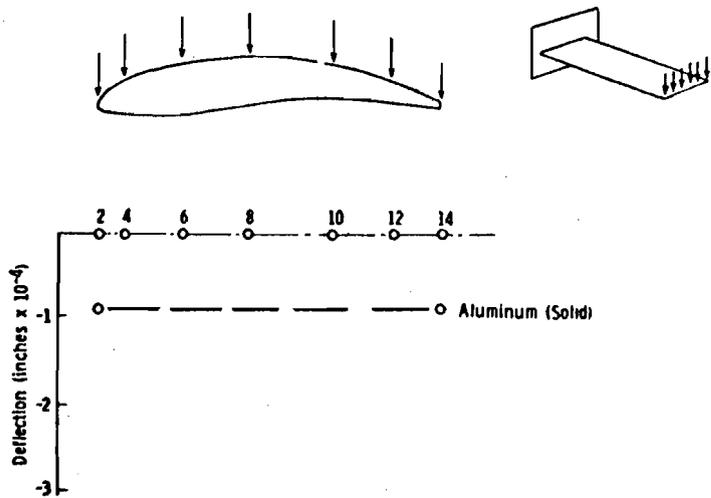
Results from the modal analysis of the computer model of the composite blade indicated that approaching the frequency response of the aluminum blades would present no problem. The results are displayed in Table II.

It was also necessary to approach the static stiffness of the aluminum blade because distortion of the aerodynamic shape of the blade would decrease its efficiency and also high bending stiffness would eliminate blade contact with the stators while the tunnel was in operation. Since matching the frequency response of the aluminum blade posed little problem, the limiting design criteria became static stiffness. For this reason different lay-ups, skin thicknesses, and material combinations were experimented with and their effect on overall stiffness of the resulting blade was observed.

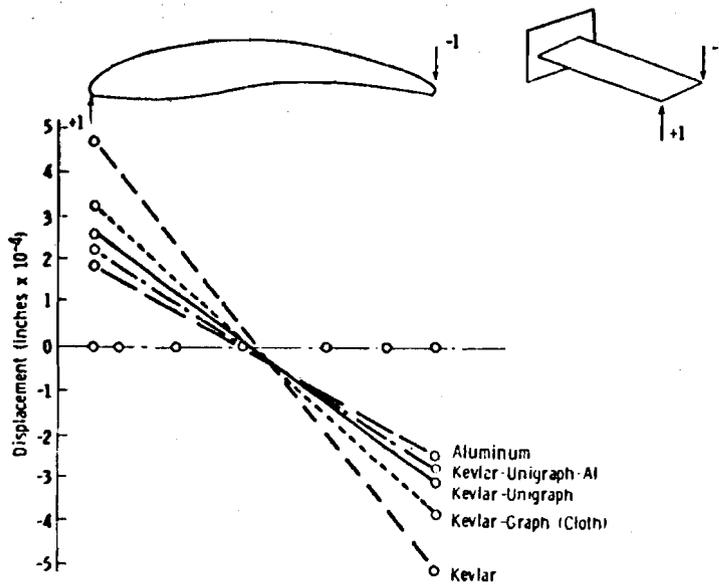
Cloth was chosen in the preliminary design for its ease of lay-up. A quasiisotropic lay-up $(0/90, +45)_2$ was chosen as the lay-up orientation to produce uniform skin properties. A final skin thickness of 0.15 inches of quasiisotropic Kevlar was chosen with 20% unidirectional graphite placed at the midplane of the lay-up in the radial direction. The iteration process to determine skin thickness vs. deflection is shown in Figures 10a and 10b, for lateral and torsional deformations respectively. The aluminum blade was approximately 30% stiffer in static deflection than the composite design for the prototype blade.

DETERMINATION OF CENTRIFUGAL LOADING

A preliminary calculation of centrifugal loading was performed using a lumped mass method. Using this method the centrifugal load at the root of the composite blade spinning at a speed of 700 RPM was predicted to be 16,447.97 pounds as opposed to 93,420.22 pounds for the aluminum blade. The weight of the airfoil section of the composite blade was calculated to be 9.97 pounds and for the aluminum design, 57.262 pounds, an 82.6% reduction. Although the composite design reduced the weight of the airfoil section 82.6%, because of the solid aluminum root insert the overall weight of the blade was reduced only 29%. A root section for the aluminum blade was obtained and the weight was added to the airfoil section to predict the total weight of the individual blade. These weights were 64.88 pounds for the composite blade and 90.97 pounds for the aluminum blade. The predicted weight of the aluminum blade represented a 3%



a. Relative tip deflection versus material for distributed unit load at tip.



b. Relative twist at tip versus material for twisting load applied at tip.

Figure 10.

error from the actual weight of the aluminum blade which was measured to be 88.1 pounds. This reinforces the lumped mass method for calculating the centrifugal loading.

SUMMARY

The design and fabrication of a low cost composite replacement for the solid aluminum compressor blades of the transonic wind tunnel at NASA-Ames Research Center has been demonstrated.

The techniques used were verified using a simplified composite design as a test vehicle. The approach to be used to design and fabricate the full scale compressor blade was duplicated using this test blade. A finite element model was constructed and used to predict blade characteristics. Test blades were fabricated using an innovative two step squeeze molding technique. These test blades were utilized to initially test and perfect this fabrication concept. The experimental blade was tested and predicted blade properties were compared with those found experimentally. The tip deflection under a static point load of 4.5 pounds applied on the end of the blade was predicted to be 0.134 inches and was measured to be 0.126 inches. The natural frequency of the blade was predicted to be 32.68 Hz and was measured to be 30.00 Hz.

The close correlation between predicted and experimental results support the approach to the design and fabrication techniques applied here and indicate no problems during the eventual fabrication and testing of the full scale compressor blade.

The design of a composite replacement to the solid aluminum wind tunnel compressor blade was undertaken next. Finite element methods were utilized to analyze the existing aluminum design and to predict the properties of the composite replacement. The frequency response and static stiffness were to be the criteria for the design of a replacement.

Since the existing blades posed no vibrational problems within the present operating range of the tunnel it was desirable to match their frequency response of the aluminum blade with the composite design; however, a problem existed in developing the equivalent static stiffness. In the final design, unidirectional graphite was incorporated into the Kevlar skin to increase the static stiffness, resulting in a hybrid composite skin of 20% unidirectional graphite and 80% Kevlar cloth.

Theoretical centrifugal stress calculations were performed on the aluminum and composite blades using a lumped mass method. These loads were reduced 82.4% due to the decrease in weight of the composite design. Using this method, the total weight of the aluminum blade was predicted to be 90.9 pounds as opposed to the actual weight of 88.1 pounds, a 3% error. Since loading is a function of the square of the rotating speed, which dominates the calculation, the error in the centrifugal loading prediction should be even less.

The preliminary composite design using sandwich construction and an aluminum root section resulted in a composite blade design which decreased the major loading by 82%, reduced the weight of the blade by 29%, and was easy to

fabricate using the squeeze molding technique described. This reduction in blade weight should decrease the power requirements of the wind tunnel during operation.

The use of a composite design would greatly improve tolerance to impact damage and fatigue loading conditions found within the wind tunnel. The resulting increase in safe operation, and decrease in cost of fabrication support the effort to replace the metal compressor blades with those of a composite design.

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