Wind Blade Composite Design, Manufacturing and Experimental Testing

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Abstract *— The design and manufacture of composite material sandwich type blade is presented. Stainless steel rods and ribs, are the internal structure, core is foam, between ribs. The skin is a laminate of fiber glass and a matrix of epoxy, with a laminae staking sequence of -45°, 45° and 90 °, 0 ° up to six layers.*

Three point bending test, shows that the blade can withstand approximately 200 lb, impact results showed that the blade is damaged with energy 33.849 J, resulting in delamination and cracking of the fiber and crazing of the matrix. Cantilevered results showed that the blade can support only 8 lb. A new design of the blade support is presented to avoid critical damage.

Key Terms *— Composite Blade, Design, Manufacturing, Testing Materials.*

INTRODUCTION

Composites products is an alternative manufacture new products, new method of manufacturing or new industries for the country. Knowledge of efficient properties, replace metal parts, design and including low production cost.

This research aims to build blades for a wind turbine using fiber glass-epoxy laminate, vacuum methods of manufacturing and available materials. Following this objective, these blades are constructed according to the parameters of an aircraft normal wing, such as the metal component as ribs and rods. These materials will be designed and investigated based on its original wing form, where they will be evaluated using the equipment available at the Engineering Materials Laboratory, Mechanical Engineering Department.

COMPOSITE BLADES

The selected laminate to form the skin of the blade comprises several laminae stacked and bonded in longitudinal, transverse direction (0° and 90°) directions. Laminae at +/- 45° directions, provide a material with quasi-isotropic characteristics [1]. The fibres at 45° provide the ability to carry shear loads and, together with the 0° and 90° plies, lead to laminate whose properties vary little with direction, permitting simplified stress analysis based on conventional isotropic methods [2].

Structural Failures

The composite blade was subjected to three point bending test, cantilever beam and impact test, using the equipment available at the Materials Engineering Lab. The blade was tested until failure to study the failure mode. The blade will function as a cantilever beam, the critical failure mode is how the blade is attached to the frame, and the method selected is using the threaded rod as a bolted joint. The resistance to impacts depend upon the ability of a structure to convert the impact energy into strain energy. The greater the strain to failure, the greater the impact can be tolerated.

Even when the impact damage is barely visible, the incurred micro-damage may have a significant effect on the laminate strength and durability [3]. The impact energy can be absorbed at any point of the laminate, well away from the point of impact, and by means of various laminate level failure mechanisms including front face indentation (indicative of local matrix crushing and local fiber breakage) [3], internal laminar delamination, back face splitting and fiber peeling

[2]. Matrix cracking is and delamination was identified as failure modes.

WIND BLADE DESIGN, PROPERTIES AND MANUFACTURING

Initially the internal structure is design, following inserting the foam and composite material.

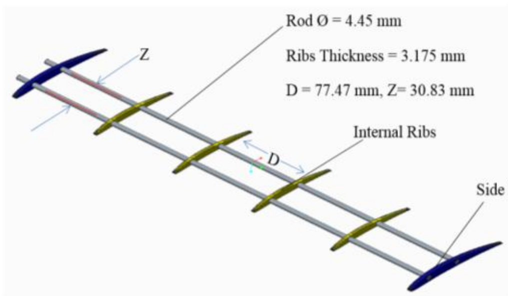

Figure 1
Stainless Steel Threaded Rods and Ribs, Form the Internal Structure of the Blade

The proposed blade is similar a sandwich composite structure. The skin is a fiber glass fabric-epoxy laminated, the core is foam [4]. Figure 1 represents Ribs, are stainless steel plates and front and rear spares are stainless steel threaded rods [5].
Threaded rods function as spare and support the blade components. Fiber glass is economical, strong material and easy available, this material will form the skin of the blade. There are 6 layers components and directions of (-45°, 45°) and (90°, 0°), the staking sequences are (±45°, 90°, 0°, ±45°, 0°, 90°,±45°,90°, 0°) see Table 2.
Components blade material properties are the followings using Table 1.

Table 1
Material Properties

Material	Density (kg/m^3)	Yield Tensile Strength (MPa)	Young's Modulus (GPa)	Coefficient of Thermal Expansion ($10^{-6}/K$)	Strain to Fail (%)
Fiber Glass E-Glass	2620	3450	81	5	4.9
Stainless Steel	8000	720	200	17.2	2
Foam	25	0.345	0.006	N/A	12
3M Epoxy (Resin)	1410	0.088	0.00497	6.69	6.6

Blade Construction

A modified airfoil was developed, this modification was from airfoil NACA 4515. Changing the shape to obtain greater lift coefficient [6]. This optimization was realized in a past investigation using Finite Elements Programing, Optimization parameters and Profili [7]. Using Finite Element method is extremely important in design, were the stresses and failure is anticipating at desired loads Figure 2.

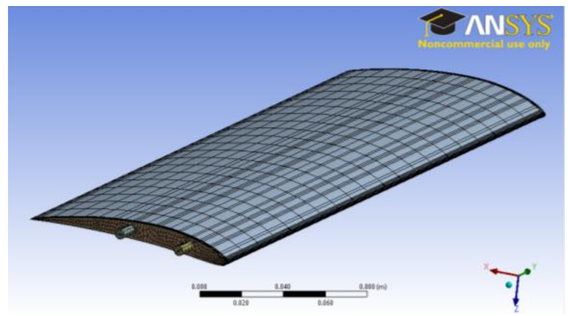

Figure 2
Mesh Nodal Analysis Blade using ANSYS ®

The following Figure 3 represents the airfoil nomenclature:

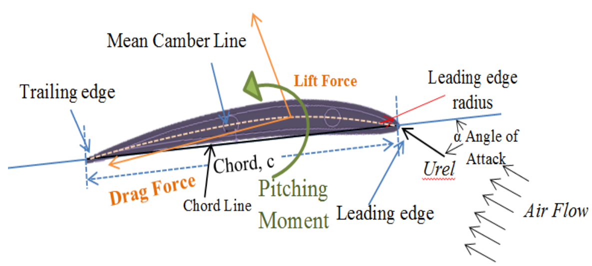

Figure 3
Airfoil Design Shape Nomenclature

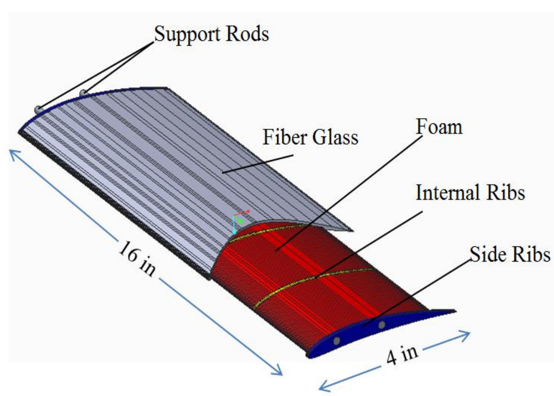

Figure 4
Blade Design

Blade Components and Main Dimensions

The threaded stainless steel rods are used as spare to locate and support the internal ribs and at the attachment bolt to the support. The ribs are two types Figure 4.

- Internal ribs define the entire airfoil
- External ribs define the limits blade border

Foam FormulaR® [4] define the skin blade and fill the blade core see Figure 5.

The skin fabric is 3M fiber Glass [8] and the matrix is epoxy. The Blade Skin is the main structure and provide the toughness and stiffness to the blade. The method of fabrication was hand wet lay-up, with a vacuum to extract internal air cavities using polyethylene bags see Figure 6. Note that in the blades the internal ribs will leave a space for fiber glass-epoxy laminate skin. There will have a distance of 0.05929 in for fiber glass layer see Figure 5 and Table 2 layers directions.

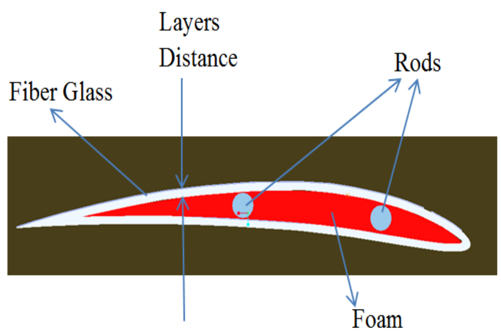

Figure 5
Sandwich Blade Design, including the Fiber Glass Layers Distance of 0.05929 in.

The fabrication method is as follow: After the metal threaded rods and ribs are in position, gaps between ribs filled with the shaped foam, the Fiber Glass mat will be placed to form the shell of the blade in the proper staking sequence impregnated with the epoxy resin. In the final step, vacuum to eliminate air cavities (see Figure 6).

Figure 6
Vacuum Process 1 Blade Covered, 2 Vacuum Chamber and 3 Vacuum Centrifugal Pump

Laminate Staking Sequency

The behavior of a multidirectional laminate is a function of the laminae properties, i.e. their moduli, thickness, angle orientations and the stacking sequence of the individual layers [9]. Table 2 is a detailed manufacturing sequence of layers.

Table 2
Fiber Layers Level

Layer	Fiber Orientation Angles
6	0,90
5	45,-45
4	0,90
3	45,-45
2	0,90
1	45,-45

Blade surface is sanded due to only one surface is smooth. Next apply a damp cloth to remove debris, and applied a coat of paint Figure 7.

Figure 7
Finishing Blade

EXTERNAL FORCE

Cantilever Beam Method is used to approximate forces in each blade. The shear and momentum diagrams (Figure 8) [6] calculated is as follow:

Ra

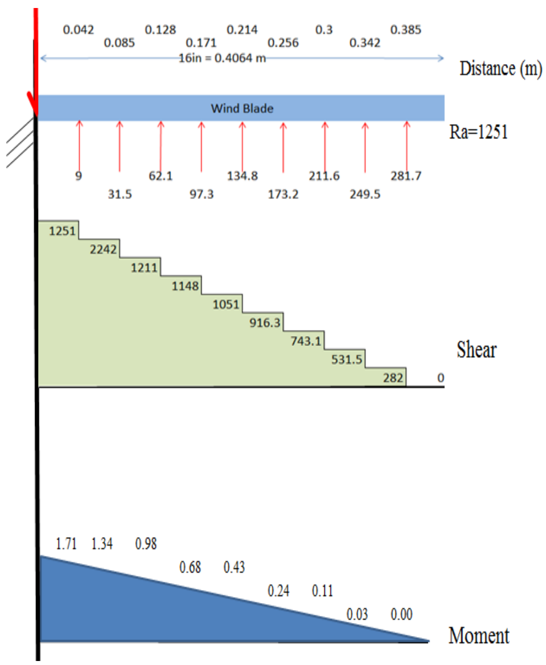

Figure 8
Conditional Blade Shear and Momentum

RODS FAILURE CRITERIA

Using the maximum shear and moment values from the previous diagrams for Figure 9.

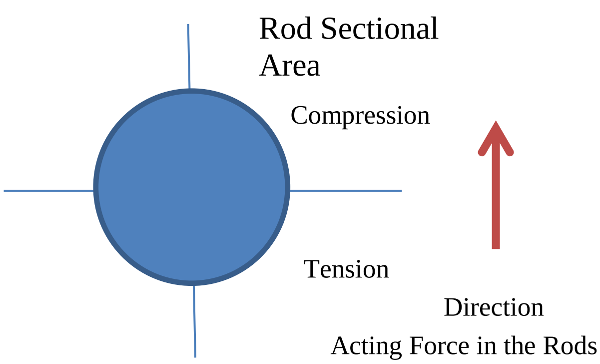

Figure 9
Blade Shear and Momentum

Rod radius = 0.0047625 m = 3/16 in

Using the total moment is 6N-m see Figure 8,
I = 2.52e -11 m^4 moment of inertia acting in the rods.
Applying Distortion Energy Failure criteria at the rods and Threaded Rod properties from Experimental Test the actual design does not support the expected loads and a new design will be proposed at the corresponding section.
To obtain preload force the threaded graphical linear test was selected see Figure 22. Approximately 1000 lb. = 4448.22 N of force there in the elastically limit (3). Using from Reference [10], obtain the Diameters and areas of coarse-pitch and fine pitch metric thread. Nominal Major Diameter d = 5mm and Pitch = 0.8 and Tensile Stress Area = 14.2 mm^2 [10].

Checking Preload Stress (1)

$$\sigma pl = \frac{Fi}{At} = \frac{4{,}448.22\ N}{1.42\ exp - 5} = 313.25\ MPa \qquad (1)$$

Tr=Torque required for raising the load, or tightening a screw or bolt (2), this yields [10].

$$Tr = \frac{Fdm}{2}\left(\frac{l + \pi f dm\ sec\alpha}{\pi dm - fl sec\alpha}\right) \qquad (2)$$

Fi=4,448.22 N per bolt, d_m = d-0.6495p [10] (3)

d_m= the thread depth middle and width are the same and equal to half the pitch.
d_m=4.188 mm, dr=5mm,
d_m and dr are the mean diameter and nominal major diameter l = np, l = number of threads at the pitch, n = threads, p = pitch = 0.8, n=2.Using Equation 4 calculate the screw friction.

$$f = \frac{l}{\pi\ dm} = 0.1216, \text{ screw friction} \qquad (4)$$

α=15°, thread angle
Substitute values into the Equation (2) to knowing the nut torque needed to support the blade.
T_r =2.3297 N.m.
The T_r = 2.3297 N.m is the torque required to produce yielding in the threaded rod.

BENDING, CANTILEVERED AND IMPACT TESTING

The blade was experimentally tested by three point bending test, cantilever beam test and impact drop test. The equipment available at the Engineering Materials laboratory was used to test the blade under room conditions of temperature and humidity.

Bending Test

Preliminary design of laminates for bending is based on carpets plots of Flexural Strengths for Laminates [6]. Figure 10 represents the schematic bending test.

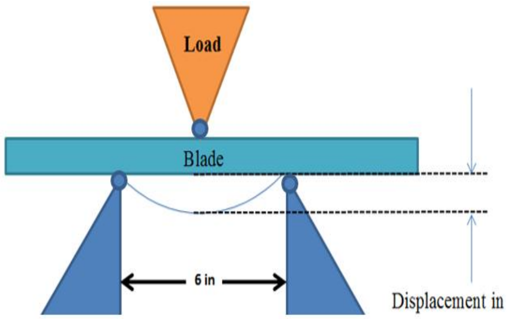

Figure 10
Three Point Bending

- Test #1: Bending Parameters:
  - Test Parameters on the UTM AST Machine®
  - Setting load = 2,000 lb.
  - Maximum displacement 2 in, after this length the machine stop.
  - Crosshead Velocity 0.2 in/min.
  - Blade parameters
  - Blade max thickness is 0.54 in.
  - Blade width 4.547 in.
  - Span = 6 inch.
- Bending test # 2 Parameters:
  - AST Machine®
  - Maximum setting force was 1,000 lb.
  - Velocity of 0.5 in/min.
  - Wing max thickness is 0.54 in.
  - Wing width 4.547 in.
  - Maximum displacement 2 in, after this length the machine stop.

Figure 11 represents bending test 2 overpassing the elastic limit.

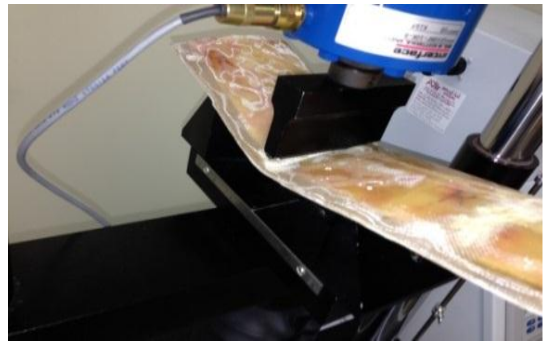

Figure 11
Bending Test 2 Acting Force at 240 lb.

Graphical Tests

Two bending test were measure providing the elastic limits of the fiber glass skin and blade rods.

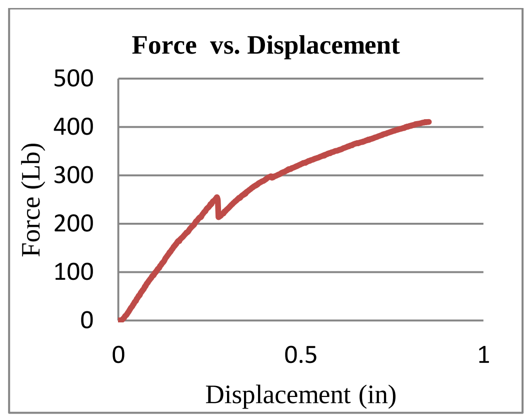

Figure 12
Force vs. Displacement Bending Test 1

- First Trial Bending Test 1 (Figure 12):
  - First trial maximum displacement was 0.88in.
  - At 233 lb. crushing of the matrix. Localized damage at the contact point between the mechanism to apply the load and the upper surface of the blade. Matrix crazing, matrix cracking and fiber debonding damage are identified at this point. This failure is associated at the type of loading of the test. No damage was observed in the opposite side of the skin or in the metallic structure. The displacement of first crush is approximately 0.3 in.

- At 401 lb. the load application was turned off to review the damage at the blade. After the force was removed at the point in contact between the mechanism of load application and the blade debonding of the laminate was observed, this damage if the load was a distributed load probably will not be observed. By the First Ply Failure criteria, and the method used the load of 233 lb is the maximum load that the blade support without damage.

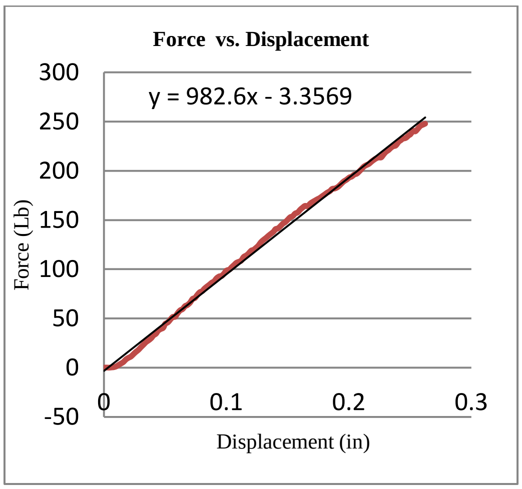

Figure 13
Force vs. Displacement Bending Test 1 (Linearity)

First test indicates linearity at maximum of 233 lb.; Figure 13 and 15 show a similitude in the elastic range.

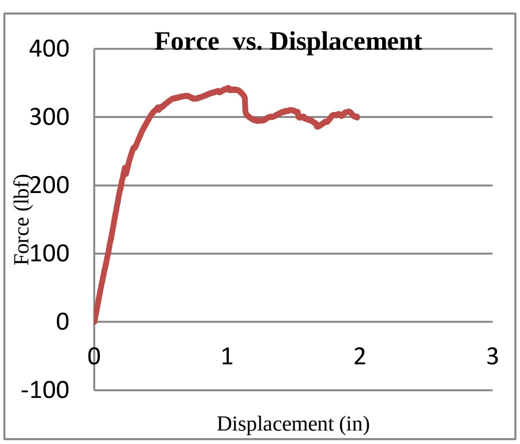

Figure 14
Force vs. Displacement Bending Test 2

- Second Trial Bending Test 2 (Figure 14):
  - At 207 lb. crushing of the matrix. Localized damage at the contact point between the mechanism to apply the load and the upper surface of the blade. Matrix crazing, matrix cracking and fiber debonding damage are identified at this point. This failure is associated at the type of loading of the test. No damage was observed in the opposite side of the skin or in the metallic structure. The displacement of first crush is approximately 0.21 in.
  - At 231 lb similar values comparing to test 1, failure of the skin was observed, crushing of the composite laminate. The load damage values for both experiences are similar, the blade load limit is determined at 230 lb.
  - At 203 lb. is the limit of elastic behavior. After this load interaction between the composite skin and the metallic frame is observed.
  - At 300 lb. complete failure of the upper skin of the blade is observed and the load is supported by the lower skin interacted with the metallic frame.
  - At a load of 341 lb. and a displacement of the crosshead of 1.04 inch deboning and delamination of the skin is observed and the load is support only by the interaction between the fabric and the metallic frame. The blade has lost the shape.
  - The limit load of design is 200 lb, due to the resolution of the ATS UTM machine.
  - By the First Ply Failure criteria, and the method used the load of 200 lb. is the maximum load that the blade support without damage.

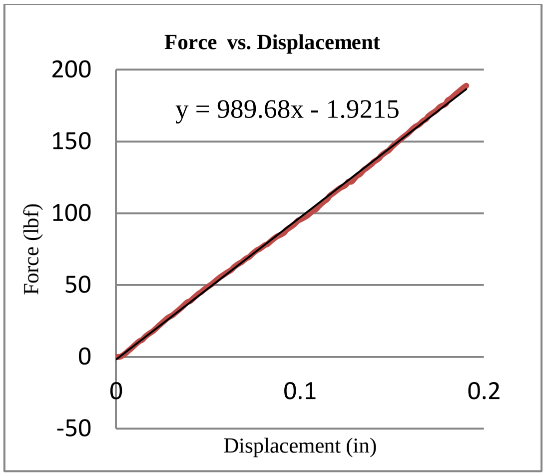

Figure 15
Force vs. Displacement Bending Test 2 (Linearity)

Elastic stress linearity at second bending stress is 191 lb. at 0.18in, low in comparison to bending test 1 of 250lb at 0.26 in.

Impact Test

The most dangerous consequences of the impact loading is an internal delamination in the laminate [7].

The sequence of impact is as follows (Figure 16):

Four site of impact near the leading edge to determine the influence of the core as damping material to absorb energy. Two test near the trailing edge where only the skin is present.

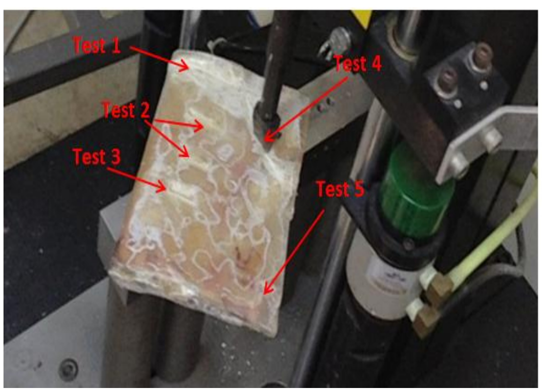

Figure 16
Impact References

- During Impact Test:
  - One blade was cutting in three pieces to realize the impact test, machine used Instron Dynatup 920®.
  - Initially the impact test was measured close to leading edge.
  - Test 1 not completely holed the blades but debonding it, result in internal crack.
  - Test 3 the energy in this point crush the matrix blade, not holed all layer in the blade surface.
  - Test 2 and 3 penetrated the layers (holed the blade, Figure 17), the impact energy is presented in Table 3.
  - Evaluating Test 4 and 5, near the trailing edge, delamination results complete separation of the laminae. Three layer could take off with the hand, the other internal three layers reminded intact.

Evaluating Energy before and after the impact

Kinetic Energy =Potential Energy, (5)

$$\frac{1}{2}mv^2 = mgh \quad (5)$$

Resolving for v,$v = \sqrt{2gh}$

Impact Test Results

This test initially were measure at the front of the blade and finally in the back borders see Table 3.

Table 3
Impact Test Data

Test	Weight (kg)	Height (cm)	Velocity (m/s)	Energy (J)	Impact Side
1	13.02	45	2.97	57.42	Surface Front
2	13.02	40	2.80	51.04	Surface Middle
3	13.02	35	2.62	44.69	Surface Middle
4	13.02	26.5	2.28	33.84	Side Border back
5	13.02	40	2.80	51.04	Side Border back

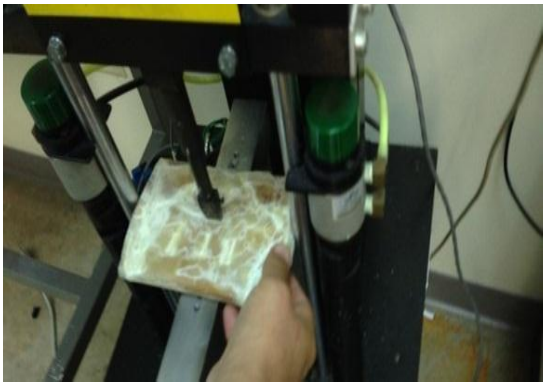

Figure 17
Impact Test # 4

Cantilevered Test

Figure 18 shows the cantilever schematically description.

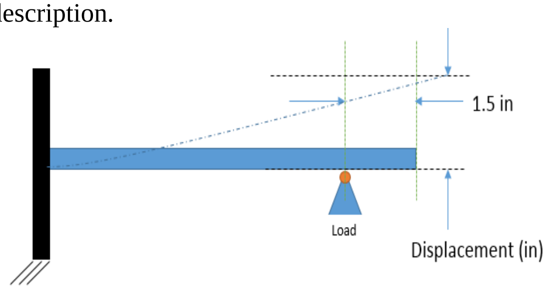

Figure 18
Cantilever Beam Test

- Parameters:
  - Machine used Applied Test System Inc. Allen Bradley series 600®
  - Maximum Force 1000 lb**.**
  - The maximum displacement (deflection) was 2.5 in.
  - In test # 1 the maximum cantilevered load applied was 28 lb.
  - The blade results damages at the support holes, with a minimum delamination effects (see Figure 19 and 20), with angle deflection screw of 17°.
  - Little cracks and delamination was produce in the support layer walls due to the cantilevered loads.
  - The cantilevered test # 2 deflection ending of 3 in, 8 lb max.
  - Conclusion from the cantilever beam test.

The method of support the blade must be modified. From this test at operational loads the blade will fail at the support.

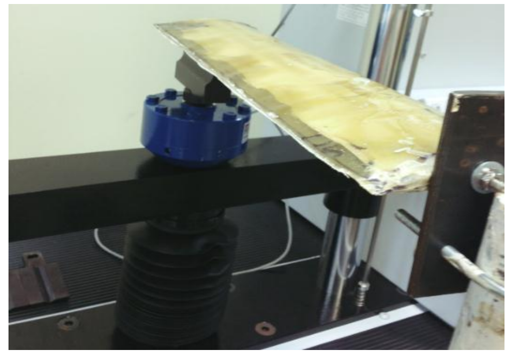

Figure 19
Cantilevered Test

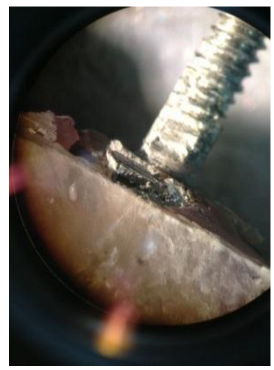

Figure 20
Damage in the Screw and Delamination is Produced in the Cantilevered Test (Front Screw)

Screw Tension Test

Screw test is important to obtain stress resistance properties Figure 21, 22 and 23.

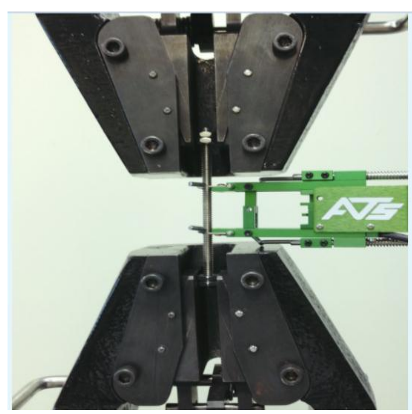

Figure 21
Screw Tension Test using ATS Machine

Graphical Results Tension Test

Tension test is one of various technics to obtain the mechanical properties materials that are important in design.

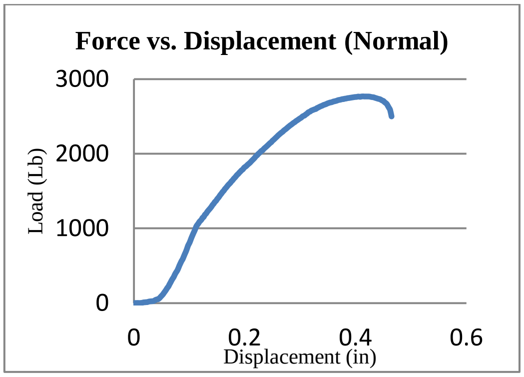

Figure 22
Force vs. Displacement Threaded Test

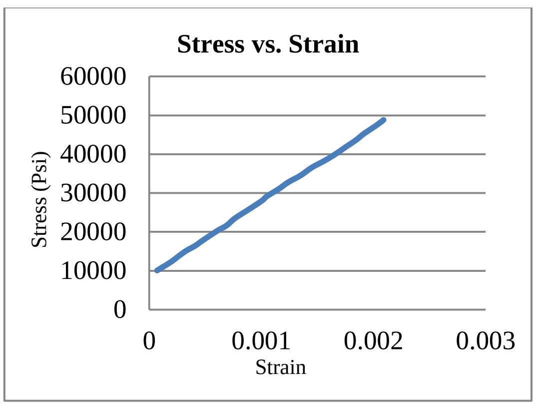

Figure 23
Force vs. Displacement Threaded Test 1

RESULTS ANALYSIS

The composite blade manufactured using the hand wet lay-up method does not provide dimensional accuracy and repeatability. The surface require rework to maintain the airfoil along the blade. The above problems are solved using molds to manufacture the blade Figure 24. Honey comb will substitute the foam to increase the stiffness of the blade.

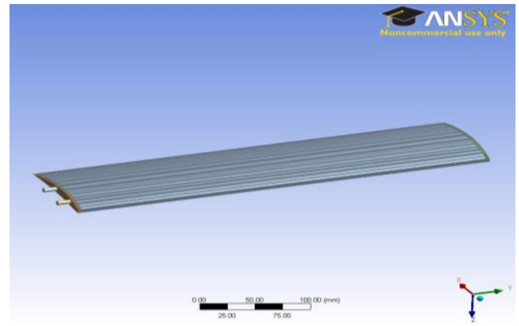

Figure 24
Blade Design starting Analysis in ANSYS®

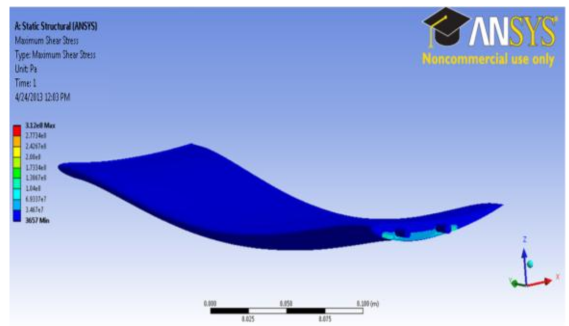

Figure 25
Blade Design Deformation using ANSYS®

Using finite elements analysis programing the blade support 200 lb. without reaching the plastic limit. Evaluating the three point bend test resulting 200 lb is the elastic limit. The bend test allow to study the failure modes in the blade. Crushing in the contact surface of the blade and the mechanism to apply the load was the first mode of failure, this failure is associated at the method of test and to simulate the pressure distribution of the wind, other type of load must be used, but provide information about the linear range of the component that supports of 200 lb. Level of stress of 10.4 MPa at the composite materials, that is in the linear range of the fiber glass used Figure 25.

The cantilever method provide a method to test the behavior of the support mechanism. A new model of support is proposed to improve the actual threaded rod fail at a bending moment of 1.44 N.m.

The Impact test shows that manufactured blade present different types of failure at the leading edge and the trailing edge. At the leading each the foam core, increase the toughness of the section, crushing is the mode of failure and at the leading edge delamination is the failure mode.

Additional alternative are design and manufacture the ribs using composite material and increase their thickness. Honey comb to replace the foam, it's disintegrated in the manufacture process reacting with the resin hardener. New design of the support frame to support the operating load as was demonstrated in the cantilever beam test, the new design is presented in Figure 26.

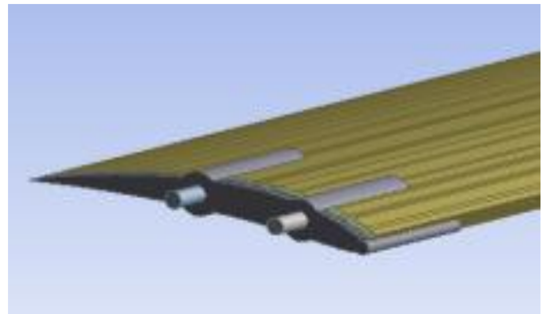

Figure 26
Future Design for Cantilevered Effort Resistance
(Finite Element Method Must Analyzed After Select Design)

CONCLUSION

The hand wet lay-up manufacturing blade method produce defects, which cannot be upgraded without using mold transfers resin method. During the manufacturing process irregularities are presented like thickness profile are not continuous. The foam will be replaced with honeycomb to evade internal cavities in the blade, the foam is disintegrated causing a reaction with the hardener. The blade profile will be improve using a mold, the mold use avoid defects and internal air cavities. The blade was subject to 3 types of test, bending, and impact and cantilever test. Bending test elastic limit were approximately 200 lb that induce 10.4 MPa in the composite skin. By Impact test, the energy to produce delamination is 33.85 J. Delamination in the trailing edge blade border result in a complete 3 layers delamination at the lower skin side. At the upper surface near the leading edge and the center of the blade, hole result from the impact, and internal delamination around the hole. Cantilever support not work the test properly, because its base not was rigid, at maximum deflection of 28 lb, at 2.5 in of maximum displacement, causing rods support plastic deflection of 17°. The blade will not support the operational loads Figure 8, of 281 lb. Figure 26 represent a possible alternative solution to resist cantilevered loads of 281 lb. the frame will be modified. This blade modification will be a future blade improvements, with the additional internal parts.

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