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Study of Spider Silk Composite Material and its Analysis for Aerospace Applications

Mayank Sharma[1], Megha Tangri[2], Sudhir Chaturvedi[3], Vishal Sethi[4] and Siddharth Rai[5]

[1,2,3,4,5]UPES, Dehradun
E-mail: [1]mayanksharma2690@gmail.com, [2]meghatangri@gmail.com, [3]schaturvedi@ddn.upes.ac.in, [4]007vishalsethi007@gmail.com, [5]siddharthroy@hotmail.co.in

Abstract—*Aerospace industry relies heavily on composite materials. Whether it is an aircraft or space craft, every designer desires to choose a material with high strength to weight ratio. Composite materials are those hybrid materials which are developed by the combination of more than one material to get desired properties. Today we find a lot of variety in composite materials, like basic composites, Fiber Reinforced Composites, Particle Reinforced Composites, Sandwich Panel, Metal Matrix Composites, and Ceramics Matrix Composites. Fiber Reinforced Composites are widely used in the industry for their ability to bear tensile load, and are particularly used in designing skin of the aircraft. Composites are non-magnetic materials and hence, do not interfere with the magnetic compass of the aircraft and so are ideally used for designing the panels and other cabinet parts. The main motive of this paper is to find its compatibility and other applications of this material in aerospace industry.*

Spider silk is the only natural fiber which is used to trap insects, that is this fiber can easily bear impact loads. This fiber has the property of getting elongated to 500% of its original length which gives it strength to bare tensile loads. This fiber is extremely elastic which helps this fiber to regain its shape. This fiber is mixed with the matrix material, Epoxy and a laminate is formed having Epoxy as a matrix material and Spider Silk as reinforced material and it is optimum for the Aerospace industry This paper contains the estimation of the reduction in weight of the window panes with the introduction of Spider Silk material through computational analysis in NASTRAN PATRAN.

1. INTRODUCTION

Aerospace industry has dramatically shifted towards the usage of composite materials. Recently Pratt & Whitney has developed turbine blades which are entirely made up of composites. The new aircrafts of Airbus and Boeing which are coming in market are more focused on composite materials and they have large percent of the structure made up of composites. Composite materials are those materials which are made up of different materials which do not mix with each other, yet come together and perform as a single material. Depending upon the conditions and the output needed from the material, different constituents could be used which comes together to give the desired properties of the composite materials. The main specification of the composites used in Aerospace industry are light weight, high strength, joint ability, bulk production and should be cheaply available. Study of materials which could be used in composites without affecting the desired properties namely tensile strength, weight, modulus of elasticity, poisons ratio and shear strength was carried out. This paper deals with the introduction of the spider silk as a reinforcement material to the composites with Epoxy as a matrix material. Spider silk due to its natural implementations as insect catcher is naturally evolved fiber to bear impact loads, have high tensile strength, toughness and elongation properties. The model under consideration selected is a fuselage window. Two models are being created in NASTRAN/PATRAN software where one of the model is made up of the conventional material (acrylic) and the second model is made up of this new composite material. Both the materials are exposed to same boundary conditions and same pressure conditions and then the stress and strain developed on these two models are compared.

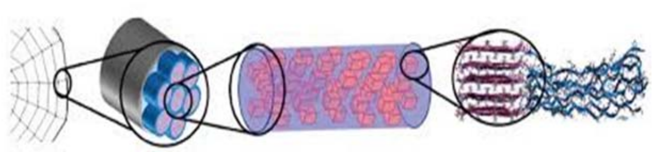

Fig. 1: Spider silk webs are made from intricately designed fibers displaying a hierarchical structure all the way from the fibers themselves (left) to the atomistic scale (right)

2. PROPERTIES OF DIFFERENT MATERIALS CONSIDERED

Acrylic Material: Materials were searched and different materials which are being used for the manufacturing of the window of the fuselage were studies and the most common of them was taken as conventional material for the analyses.

Spider Silk Material: These properties could easily be compared to Kevlar, steel, aluminum and other materials which are used in composites. Carbon coated spider-silk nanotubes are a step forward in properties than spider silk. The best advantage of spider silk used in composites is that as the temperature falls the properties get improved. So, the young's modulus will increase as the aircraft moves from runway towards its cruising altitude.

Table 1: Spider silk and Acrylic Material Properties.

Properties	Acrylic	Spider-silk
Young's Modulus, E(Mpa)	4185.1177	12710
Poisson's Ratio, ν	.35	.3
Tensile Yield, ty (Mpa)	58.6	300
Tensile Ultimate, tu(Mpa)	110.3	450

Table 1: Epoxy Matrix Material Properties.

Properties	Epoxy
Tensile Modulus EL (GPa)	44.6
Poisson's ratio	0.262
Shear Modulus GLT (GPa)	3.49
Shear Modulus GLZ (GPa)	3.77
Shear Modulus GTL (GPa)	3.04

3. CALCULATION OF COMPOSITE MATERIAL PROPERTIES

3.1 Formula Used

1. Young's modulus of Elasticity along x-axis

$\mathbf{E_l = E_m + V_f(E_f - E_m)}$ (Equation 1)

2. Young's modulus of Elasticity along y-axis

$\mathbf{E_b = \frac{E_f E_m}{E_f - V_f(E_f - E_m)}}$ (Equation 2)

3. Shear stress in xy – plane

$\mathbf{G_l = \frac{G_f G_m}{G_m V_f + G_f V_m}}$ (Equation 3) Equation 1

4. Total Cross sectional area of fiber in lamina

$\mathbf{A_f = \left(\frac{\pi}{4}\right) d^2}$ (Equation 4)

5. Cross sectional area of lamina

$A_l = L * B$ (Equation 5)

6. Cross sectional area of matrix

$\mathbf{A_m = L_m * B_m}$ (Equation 6)

7. Number of fibers Equation 2

$n = \frac{T_m}{T_l}$ (Equation 7)

8. Volume fraction of matrix material

$\mathbf{V_m = 1 - V_f}$ (Equation 8)

3.2 Geometry Specifications

Length of lamina (L) = 100mm

Breath of lamina (B) =0.006mm

Length of matrix (L_m) =100mm

Breath of matrix (B_m) =10.033mm

Diameter of fiber (D_f) = 0.003 m

Diameter of fiber with coating (d_f) = 0.0035mm

Cross sectional area of fiber (a_f) :

$$(a_f) = \left(\frac{\pi}{4}\right) D_f^2 = 7.065 * 10^{-6} mm^2$$

Let the spider silk fiber form lamina with epoxy as a matrix material. Diameter of fiber is 0.003mm and we apply a coating of Epoxy as 0.0015mm on top and bottom. Therefore the thickness of lamina becomes 0.006mm. Distance of 0.0005mm is left between two consecutive fibers along the length. So together with the fiber and the distance left between two fibers we are left with a unit comprising of fiber and a space adjoining it, having a length of this unit cell as 0.0035mm.

3.3 Calculating the number of fibers in lamina running unidirectional

Number of fibers *in Laminate*, $n_f = \frac{L}{d_f}$

Number of fibers in laminate

$n_f = 28572$

Total cross sectional area of all fibers in laminate is given as, $A_f = n_f * a_f$

Therefore, $A_f = 20.20 mm^2$

Cross sectional area of laminate (A) =L*B

Therefore, $A = 0.6 mm^2$

3.4 Calculating Volume fraction of fibers material in lamina

Volume fraction (V_f) = $\frac{A_f}{A}$

Therefore, $V_f = 0.3366$

Using [8] we get

$$V_m = 0.6633$$

Calculating young's modulus of lamina:

The value of Epoxy/spider-silk lamina is:

$$E_f = 12.71 * \frac{10^3 N}{mm^2}$$

$$E_m = 45 * \frac{10^3 N}{mm^2}$$

From equation 1, we get $E_l = 34.13 * \frac{10^3 N}{mm^2}$

From

Young's modulus of Elasticity along y-axis

$\mathbf{E_b} = \frac{\mathbf{E_f E_m}}{\mathbf{E_f - V_f(E_f - E_m)}}$ (Equation

we get

$$E_b = 24.256 * \frac{10^3 N}{mm^2}$$

Since, lamina is 2D-othotropic material, therefore it has same young's modulus in x and z direction, which implies

$E_b = E_h$.

3.5 Calculating shear stress of lamina

G_{12} = shear stress in xy − plane

$G_f = 2.38$ GPa

$G_m = 3.49$ GPa

Using 2)

3. Shear stress in xy – plane

Gl=GfGmGmVf+GfVm (Equation 3) Equation 1, we get $G_{12} = 3.016$ GPa

Similarly,
G_{23} = shear stress in yz − plane

$G_f = 2.38$ GPa

$G_m = 3.17$ GPa

Using 2)

3. Shear stress in xy – plane

Gl=GfGmGmVf+GfVm (Equation 3) Equation 1, we get $G_{23} = 2.851$ GPa

G_{31} = shear stress in zx − plane

$G_f = 2.38$ GPa

$G_m = 3.04$GPa

Using 2)

3. Shear stress in xy – plane

Gl=GfGmGmVf+GfVm (Equation 3) Equation 1, we get $G_{31} = 2.78$ GPa

3.6 Values calculated for lamina

(i) $V_m = 0.6634$
(ii) $V_f = 0.3366$
(iii) $E_l = 34.13 * \frac{10^{\,3} N}{mm^2}$
(iv) $E_b = 24.256 * \frac{10^3 N}{mm^2}$
(v) $G_{12} = 3.016$ GPa
(vi) $G_{23} = 2.851$ GPa
(vii) $G_{31} = 2.78$ GPa

4. METHODOLOGY

4.1 Designing and Meshing:

i. For designing the model software CATIA V5 and for giving properties and analysis, PATRAN/NASTRAN software were used

ii. Firstly a model design was created in CATIA, which was later on imported to PATRAN and meshed as shown in Fig1.

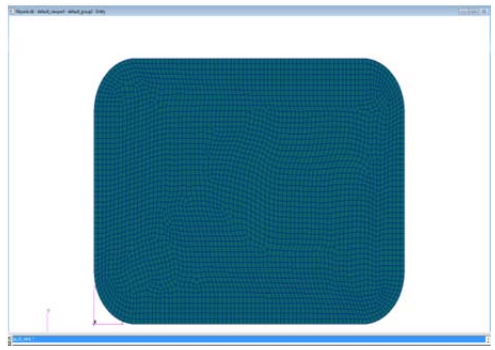

Fig. 2: Shown is the basic model of an aircraft window pane.

4.1 Adding Material and Properties

(i) Using the calculations shown above for a lamina of Epoxy/Spider-silk was declared as material in PATRAN software as 2D orthotropic material and with the decided characteristics. The material values have already been calculated for E_{11}, E_{22}, γ_{12}, G_{12}, G_{23}, G_{31}.

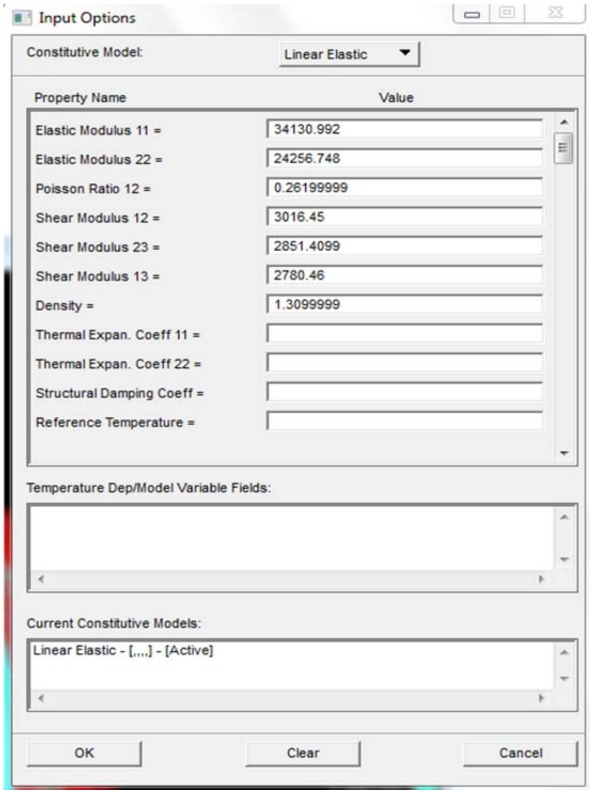

Fig. 3: Declared values for Epoxy/Spider-silk laminate.

(ii) After declaring the material for the model, our next task is to create the composite with decided thickness of the lamina and in proper orientation for better results.

(iii) After calculating the thickness of each lamina, it was clear that for the whole model we need to create 1673 layers of lamina piled up together in proper orientation.

(iv) Then properties for the model were declared, deciding the material to be used and the vector orientation of the material in all three axes.

4.2 Boundary Conditions and Loadings

(i) Next task is to create the boundary layers and to apply the required loading on the model.

(ii) Since the window pane of an aircraft cabin is fixed, therefore the boundary conditions of the model were given to be fixed, that is there is no translational and no rotational motion in the model edges as shown in Fig. 4.

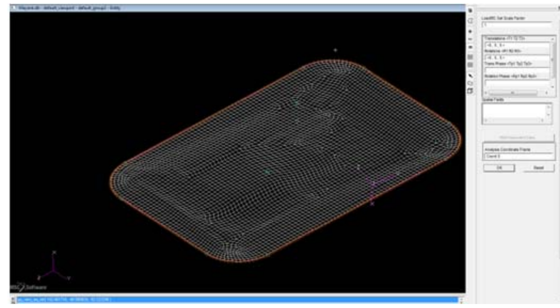

Fig. 4 : Boundary conditions defined on the edge nodes

(iii) Then loading on the model was declared.

(iv) Since window pane doesn't go through the much of the forces, therefore the forces acting on the window pane were neglected.

(v) Due to pressurized cabin, the difference between the inside pressure and atmospheric pressure was taken as the net applied from inside towards outside of the model.

4.3 Analysis

(i) At this point, all the inputs needed have been given and now we have to analyze for the compatibility of the model with this new material.

(ii) The parameters which have been used to decide if the proposed material is better than the conventional material are as follows:
   a. Deflection caused in the model,
   b. Stresses developed in the model

(iii) The analyses of the model were done and the deflection and stress analyses were requested as output requests as in Fig.5

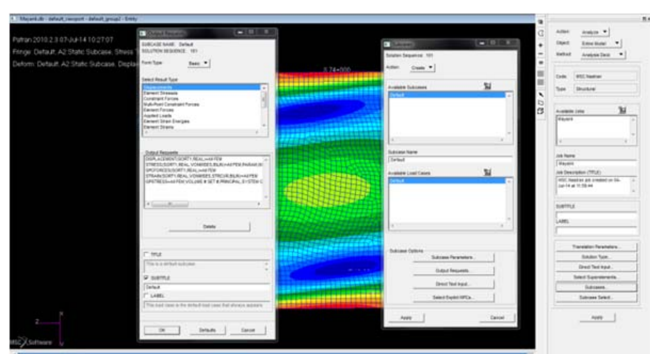

Fig. 5: Output requests and the "XDB" file.

4.4 Results

(i) After attaching the file thus obtained we got the required results

(ii) Same procedure was followed for the conventional material also, except that the material declared in conventional case was isotropic

(iii) Properties given were homogenous in nature and thickness was given to the model as a whole.

5. RESULTS AND DISCUSSIONS

To a same model two different materials were assigned and analyzed. The first was the conventional (Acrylic) material and the other was a composite made of a lamina (Epoxy/spider-silk). Both the models were analyzed for same boundary conditions and same pressure loading applied on them. The results obtained were as follows:

(i) The first parameter used to analyze the results is the displacement under applied loading for same boundary conditions.

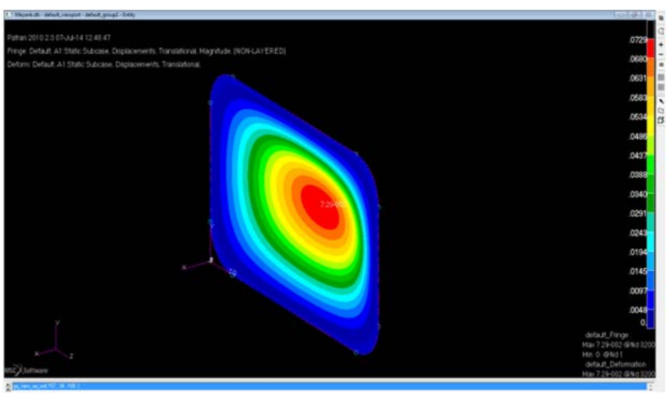

Fig. 6: Displacement in the model (acrylic material) due to pressure applied.

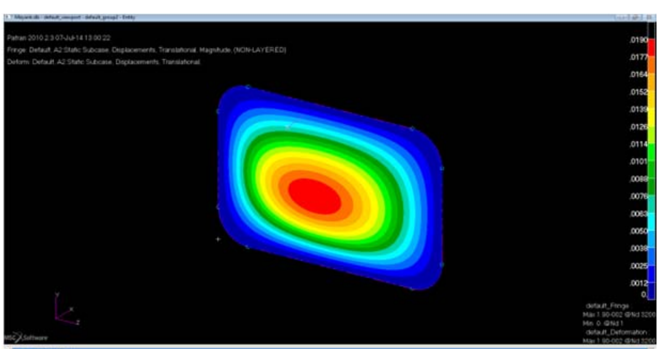

Fig. 7: Displacement in the model (Epoxy/Spider-silk) due to pressure applied.

It is clear from the above results that the composite is much more stiffer. The deflection in the body structure of the model under same pressure loading and same boundary conditions have reduced. Further this also implemends that the new material has given more strength to the structure to withstand the presasure loading with ease.

(ii) Another parameter to check for the given material is the stress tensor results. These results will tell us how the material develops stress under the same pressure loading and same boundary conditions. The results thus obtained from the analyses of both the models are as under.

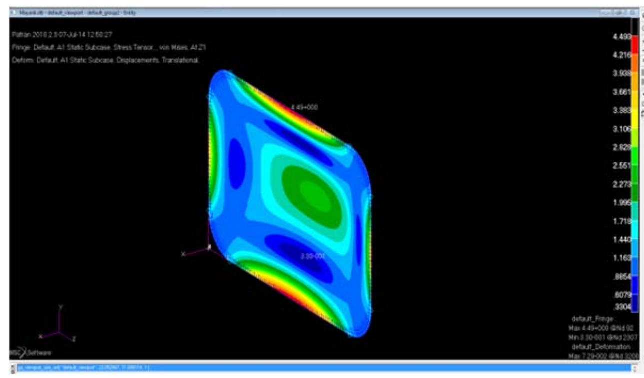

Fig. 8: Stress concentration in the model (Acrylic material) under uniform pressure loading.

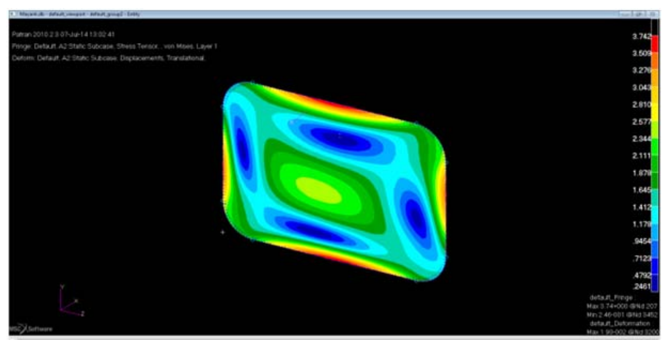

Fig. 9: Stress concentration in the model (Epoxy/Spider-silk) under uniform pressure loading.

It is clear from the above results that the stresses developed in the models are less in case of new material (Epoxy/spider-silk composite). Thus the new material handles stress well. Both maximum and minimum value of the stress concentration is reduced thus increasing the life of the component and reducing the fear of failure during flight.

6. CONCLUSION

After analyzing the results thus obtained from the project, it is clear that Epoxy/Spider-Silk composite is better material to be used in structures. Lesser thickness of new material can withstand the same load as compared to Acrylic, thus saving the weight. This is a great advantage of using this new material.

Moreover this new material has many more advantages like good conductive properties and so can be used to serve more than one purpose, like designing a circuit running throughout the fuselage, thus increasing the conductivity and side by side providing more strength to the structure.

But before all this could be achieved there are certain underlying challenges, the most significant being that this silk has not been successfully obtained for bulk production. Many companies are trying to produce this fiber artificially but no significant achievements have been made. Further, the silk is irregular and thin. These physical properties make working with this silk a challenge.

7. FUTURE WORK

The production of the fiber is the major challenge in our way at present. In near future we are determined to inject the spider silk producing glands in bacteria and other microorganisms, to generate the bulk production of the fiber.

The working with this fiber is also a complex process due to its irregularity. Recently a technique called “post-spin” has been developed by the scientists to bring this silk into regular form so that its workability could be increased. These kinds of techniques are future needs for working with this fiber.

Carbon nanotubes/coated spider silk are a step forward in this. The carbon coated spider silk nanotubes are much more superior to spider silk itself. The conductivity of the silk after coating increases several times with mechanical properties also enhanced to large extends.

8. ACKNOWLEDGEMENTS

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List and number all bibliographical references in 9- point Times, single-spaced, at the end of your paper. When referenced in the text, enclose the citation number in square brackets, for example [2-4], [2, 5], and [1].

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