



Failure and Thermal Examination of Hybrid Materials for a Propeller shaft in Aerospace Applications

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Abstract: Hybrid materials are an attractive option in case of aerospace and aviation applications since they are exceptionally strong. The current study presents the failure analysis of the hybrid material in ANSYS software. The main aim of this study is to check the suitability of the MATLAB results obtained from the previously selected composite material comprising of carbon steel + epoxy + S glass + T700 fibres using ANSYS software by creating a solid three-dimensional meshed model of the shaft. Layerwise shaft theory and finite element analysis have been employed for developing the model. The thermal analysis, delamination and buckling failure studies are conducted and found that increasing the thickness of the material will increase its load withstandability. The load failure point is found to be 8.4mm from the delamination studies. From analysis it was understood that the chosen composite material could be used for the propeller shaft of an aircraft.

Keywords: Composite material, ANSYS, delamination, buckling, layer-wise shaft theory

I. INTRODUCTION

The leverage of using composite materials is that the design of the structures and the composite materials can be modified to withstand the applied load. To modify the designs one has to understand the stress, strains and the displacements produced by this type of loading (Hamstad, 1986).

The composite materials which are under stress will experience different damage mechanisms like delamination, buckling, matrix cracking, phase debonding, etc. (Davies, 1997). The composite can be damaged at any point; hence many studies have been conducted to understand the development in these damages since it is an important factor that has to be taken into account by the engineers while using the composite materials in different structural applications. The detection of damage is necessary for the efficient utilisation of the composite materials.

Revised Manuscript Received on 30 July 2019.

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Retrieval Number: B2518078219/2019©BEIESP

DOI: 10.35940/ijrte.B2518.078219

Journal Website: www.ijrte.org

Kessler, (2002) carried out a survey experimentally and analytically on the different methods through which the damages in composite materials can be detected, and inferred that the method of frequency response is reliable to detect even the smallest damage in a composite structure. Degrieck, (2001) presented a review of the fibre-reinforced polymer composites which were subjected to fatigue loadings. Alfano, (2001) conducted finite element analysis (FEA) of delamination in laminated composites by using interface elements and interface damage law. The interaction model is used in case of mixed mode delamination. Camanho, et al., (2002) proposed a decohesion element which could be used at the interface of solid finite elements which modelled the initiation of delaminations. Bolotin, (1996) reviewed the researches in the mechanics of internal and surface delaminations. The paper also presented a study on the buckling which is usually caused when delamination occurs near the surface. This usually happens in cases of composites which are under compression and tension. Many studies use finite element analysis or ANSYS software to carry out the delamination studies. Some of the authors concentrated on the design method for composite material while others concentrated on the studies related to damages in composite materials. This paper is a continuity of the previous work which carried out a comprehensive analysis of different composite materials to determine the best suitable composite material for a propeller shaft in aerospace applications. It was concluded from the previous work that low carbon steel + S glass + epoxy + T700 fibres is best suitable for the propeller shaft for aerospace application. This paper analyses the composite material in ANSYS software in order to check the suitability and load withstandability for the propeller shaft in aerospace applications. A 3D model for the shaft is generated and it is then meshed for further analysis. The buckling, delamination and thermal analysis of the structure is conducted to understand the suitability of the proposed composite material.

II. LITERATURE REVIEW

Sancho, (2006) explored different possibilities to calculate the 3D stress in composite structures. Finite element analysis and classical laminate theory are the techniques proposed for the calculations since they give accurate results with the minimal use of computer resources.



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The evaluation of stress distribution at singular points of the materials is done with the proposed methods.

Once this is done the possible faults due to the onset of delamination is checked using fault criteria. Badie et al., (2011) examined the influences the stacking sequence and orientation angle had on the torsional stiffness, buckling, failure modes of composite tubes. The exhaustive life of the composite drive shaft was predicted using finite element analysis, and from the results, it was inferred that natural frequency and fibre orientation were inversely proportional. The experiments also showed that orientation angles of ± 45 degrees experienced higher torsional stiffness and higher load carrying capacity. Impact test of low velocity was conducted on graphite epoxy laminates which have different thicknesses (Caprino et al., 1999). From the study, it was concluded that the force needed for the commencement of delamination increases with respect to the power law. Observations also suggested that shear stress is the main reason for delamination and it is calculated with the help of Hertzian law. A study on the stability of a composite drive shaft with respect to its torsion was conducted by Shokrieh et al., (2004). Torsional instability poses as a hindrance in the transfer of torque by the shafts. Buckling torque behaviour is studied using finite element method. The author also studied the effect of increased torque on the natural frequency of torsion in the composite shaft. Wettergren, H. L. (1997) studied the effect of Eigen-frequencies which were a result of the variations in the thickness of delamination in rotors of the composite shaft. The studies showed that in the case of small delaminations the effect of eigenfrequencies increased linearly with increase in delamination length. Comparative analysis of experimentally measured torsional buckling in graphite/epoxy loads and the theoretical values proves that the values are in good agreement, but the theoretical predictions slightly overestimate in case of critical loads. But the study of damage tolerance carried out in this study is in the primary stage since it deals with only the residual strength of the tubes and not on the actual ballistic impacts. Bauchau et al., (1998) conducted an experimental study of bending fatigue of composite drive shafts. The fabrication of the hybrid shafts is achieved using the technique of filament winding. The external composite layers are constructed using glass fibre and epoxy. The studies proved that increasing the number of composite layers and also a change in stacking sequence enhanced the fatigue strength. Sino, et al. (2008) assessed the dynamic instability of the rotating composite shaft which was damped internally. This research developed simplified homogenized beam theory (SHBT) and its results was compared with equivalent modulus beam theory (EMBT), modified EMBT and layerwise beam theory (LBT). The parametric study showed that the instability thresholds were sensitive to the laminate parameters. But this method does not consider the coupling effects by non-symmetrical stacking. Kaviprakash, (2014) examined the effects of stacking sequence and orientation angles on the different characteristics of the composite shaft like its frequency, buckling, torsional stiffness. The study evaluated the

appropriateness of the material to use it for automotive transmission. The drive shaft was analysed with the help of ANSYS software to reduce the weight of the shaft exposed to tension and buckling. Alwan, (2010) studied the dynamic behaviour of the composite shafts emphasising on the estimation of damping in the shafts. The Eigen-frequencies of the shafts were estimated by

modal testing. The results are analysed and compared with analytical and FEM results. Rotational laser vibrometer is used for the analysis of torsional vibration in the shafts.

A numerical and experimental study is conducted on E-glass-carbon/epoxy, carbon/epoxy and E-glass/epoxy shafts subjected to impact loadings to understand their surplus torsional properties (Sevkat, 2013). The studies revealed that at energy levels of 5, 10, 20, 40 J there was an impact on the shafts. It was found that resistance to the impact was highest in case of carbon reinforced shafts whereas it was the lowest in glass reinforced shafts that of hybrid shafts was between the two. Glass reinforced shafts had the best ability to absorb the energy while it was in case of carbon shaft and that of hybrid shafts was between the two. Maheta et al., (2015) developed a method for designing and evaluating a driveshaft used in automobile applications. The design process was carried out using the finite element modelling in ANSYS software. It was inferred that the Kevlar/epoxy composite had maximum strength and it was observed that at 90 degrees the fundamental frequency was the best when compared to other angles. Gayen et al., (2017) formulated and validated a finite element (FE) model for a functionally graded (FG) shaft which had multiple cracks. The developed model is utilised in the study of the effect of power-law gradient on various factors such as relative location, index, temperature gradient, orientations and depth of the cracks on the dynamic behaviour of the cracked FG shaft. The stability analysis of rotating composite shaft with internal damping was conducted by Arab et al., (2015). A Euler–Bernoulli shaft finite element is formulated with the help of equivalent single layer theory (ESLT). Various parameters like stacking sequences, instability thresholds, fibre orientations are evaluated. Comparison of the obtained results with the results of the existing methods proved that the method can be effectively used for assessing the stability. Arab et al., (2017) conducted studies for the dynamic analysis of rotating shafts with laminations. The paper proposed a new finite element model for the shaft based on the shaft and layerwise theories. The results showed that the proposed theory can be efficiently utilised for dynamically analysing the

III. RESEARCH METHODOLOGY

This work is a continuation of the previous work in which it was determined that low carbon steel + S glass + epoxy + T700 fibres is the best suitable composite material for the propeller shaft for aerospace application. The further analysis of this composite material is carried out with the help of ANSYS software.



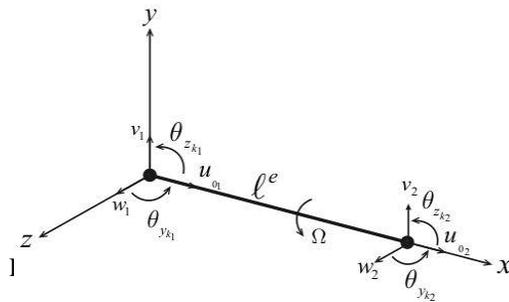
A solid 3D model of the composite shaft is modelled, meshed then the buckling, delamination and thermal analysis is done to justify that low carbon steel + S glass + epoxy + T700 fibres is the best suitable composite material for the propeller shaft of the two seater aircraft.

A. Layerwise shaft theory

Figure 1 illustrates a laminated shaft with P orthotropic layers. The shaft which is laminated is modelled using the layerwise shaft theory (LST). The assumptions made are

- The material at each layer has the property of linear elasticity
- All the layer are uniformly thick
- At each interface the layers perfectly bond together.

shafts. It was also found that the shear-normal coupling, stacking sequences and fibre orientation had a powerful impact on the dynamic behaviour of shafts.



The generalised displacement field is approximated using the equation (2)

$$\{d^e\} = [N] \{d_i^e\} \tag{2}$$

The global form of contribution of the E finite elements is expressed as

$$\sum_{e=1}^E \left(\sum_{k=1}^P \int_{A_k^e} \int \int \{\delta x^e\}^T [N]_k^T \rho_k [N]_k \{d^e\} dA_k^e dx^e + \sum_{k=1}^P \int_{A_k^e} \int \int \{\delta x^e\}^T [N]_k^T \rho_k \Omega [N]_k \{d^e\} dA_k^e dx^e + \sum_{k=1}^P \int_{A_k^e} \int \int (([B]_k^e \{\delta d^e\})^T) \underline{Q}_{11k} [B]_k^e + ([B]_k^e \{\delta d^e\})^T k_s \underline{Q}_{16k} [B]_k^{\gamma\phi} \{\delta d^e\})^T k_s \underline{Q}_{16k} [B]_k^e + ([B]_k^{\gamma\phi} \{\delta d^e\})^T k_s \underline{Q}_{66k} [B]_k^{\gamma\phi} \{\delta d^e\})^T k_s \underline{Q}_{55k} [B]_k^{\gamma\phi} \{d^e\} dA_k^e dx^e \right) = 0 \tag{3}$$

The variables {d^e} are integrated in the domain l^e and at each local level of the finite element approximation is assumed.

B. Finite element Modelling

The shaft element has two nodes as illustrated in figure 1. The degree of freedom of the element with P layers for each node is (3+2P). u, v, w → displacements, the slopes about the y and z axis is denoted by theta_yk and theta_zk for the kth layer where k ∈ {1...P}. The linear interpolation functions of the finite element defined in the natural coordinate system is given by

Where

$$N_1 = \frac{1-\xi}{2} \quad \text{and} \quad N_2 = \frac{1+\xi}{2} \tag{1}$$

N1 and N2 is utilized in interpolating the variables inside the domain of finite element. xi coordinate coincides in the x direction.

$$[J]_k = \int_{A_k^e} [N]_k^T [N]_k dA_k^e \tag{6}$$

[G^e(Omega)] → elementary gyroscopic matrix which depends on rotational speed Omega given by

$$[G^e(Omega)] = \sum_{k=1}^P [G^e(Omega)]_k = \sum_{k=1}^P \int_{A_k^e} [N]_k^T [H(Omega)]_k [N]_k dx^e \tag{7}$$

Where the gyroscopic inertia matrix [H(Omega)]_k depends on rotational speed Omega is given by

$$[H(Omega)]_k = \Omega \int_{A_k^e} [N]_k^T \rho_k \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix} [N]_k dA_k^e \tag{8}$$

$$[K^e] = \sum_{k=1}^P [K^e]_k = \sum_{k=1}^P \left([B]_k^e \int_{A_k^e} [D]_{11k} [B]_k^e + [B]_k^e \int_{A_k^e} [D]_{16k} [B]_k^{\gamma\phi} + [B]_k^{\gamma\phi} \int_{A_k^e} [D]_{16k} [B]_k^e + [B]_k^{\gamma\phi} \int_{A_k^e} [D]_{66k} [B]_k^{\gamma\phi} + [B]_k^{\gamma r} \int_{A_k^e} [D]_{66k} [B]_k^{\gamma r} \right) dx^e \tag{9}$$

Where [B]_k^e = [B-hat]_k^e [N], [B]_k^{\gamma\phi} = [B-hat]_k^{\gamma\phi} [N], [B]_k^{\gamma r} = [B-hat]_k^{\gamma r} [N] are the deformation matrices of the finite element. (10)

And D_ij is given by

$$D_{11k} = \int_{A_k^e} [Z]_k^e \underline{Q}_{11k} [Z]_k^e dA_k^e \tag{11}$$

$$D_{16k} = \int_{A_k^e} [Z]_k^{\gamma\phi} \underline{Q}_{16k} [Z]_k^{\gamma\phi} dA_k^e \tag{12}$$



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$$\sum_{e=1}^E (\{\delta d^e\}^T [M^e] \{d_i^e\} + \{G^e(\Omega)\} \{d_i^e\} + \{K^e\} \{d_i^e\}) = 0 \quad (4)$$

$[M^e] \rightarrow$ element matrix given by

$$[M^e] = \sum_{k=1}^P [M^e]_k = \sum_{k=1}^P \int_{A_k^e} [N]_k^T [J]_k [N]_k dx^e \quad (5)$$

Inertia matrix $[J]_k$ is given by

$$\{d^e\}_i = [R^e] \{d\} \quad (16)$$

From equations (4) and (16) the following relation is obtained

$$\{\delta d_i\}^T [M] \{d_i\} + \{\delta d_i\}^T [G(\Omega)] \{d_i\} + \{\delta d_i\}^T [K] \{d_i\} = 0 \quad \forall \{\delta d_i\} \quad (17)$$

Where

$$[M] = \sum_{e=1}^E [R^e]^T [M^e] [R^e] \text{ is the assembled mass matrix given by} \quad (18)$$

$$[G(\Omega)] = \sum_{e=1}^E [R^e]^T [G^e(\Omega)] [R^e] \text{ is the assembled gyroscopic matrix} \quad (19)$$

$$[K] = \sum_{e=1}^E [R^e]^T [K^e] [R^e] \text{ is the assembled stiffness matrix} \quad (20)$$

The global semi-discrete equations of motion of the rotating composite shaft are given

$$[M] \{\ddot{d}_i\} + [G(\Omega)] \{\dot{d}_i\} + [K] \{d_i\} = \{0\} \quad (21)$$

global equation for the force vector is given

$$\{F\} = [K]\{u\} \quad (22)$$

by

- $\{F\}$ = Global Force Vector
- $[K]$ = Global Stiffness Matrix
- $\{u\}$ = Global Displacement Vector

Strain is given by

$$\hat{D}_{66_k} = D^T = \int_{A_k} [Z]_k^{\gamma\phi} k_s Q_{66_k} [Z]_k^\epsilon dA^e \quad (13)$$

$$D_{66_k} = \int_{A_k} [Z]_k^{\gamma\phi} k_s Q_{66_k} [Z]_k^{\gamma\phi} dA^e \quad (14)$$

$$D_{55_k} = \int_{A_k} [Z]_k^{\gamma r} k_s Q_{55_k} [Z]_k^{\gamma r} dA^e \quad (15)$$

Equation (16) gives the relationship between degrees of freedom $\{d_i^e\}$ and elemental degrees $\{d_i\}$

The shearing strain along xy direction is given by

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial x} \quad (25)$$

$$\text{Stress is given by } \sigma = D(e - e_0) = D(Bu - e_0) \quad (26)$$

Where B = Stress-Strain Relationship and D = Strain-Displacement Relationship

Weighted residual methods

General procedures,

$$(27)$$

Where w_i = Weight function, D = Domain, R = Residual

Point collocation method:

$$\int_D (\delta(x - x_i) R(x; a_1, a_2, a_3, \dots, a_n)) dx = 0 \text{ and}$$

$$R(x; a_1, a_2, a_3, \dots, a_n) = 0 \quad (28a)$$

Subdomain Collocation Method:

$$\int_D (R(x; a_1, a_2, a_3, \dots, a_n)) dx = 0 \quad (28b)$$

The Least Squares Method:

$$\int_D (R(x; a_1, a_2, a_3, \dots, a_n))^2 dx = 0 / \min$$

$$(28c)$$

Galerkin's Method:

$$\int_D (N_i(x) R(x; a_1, a_2, a_3, \dots, a_n)) dx = 0$$

$$(28d)$$

Stress strain relationship is given by

- Stress, σ (N/mm²) =
- Young's Modulus, E (N/mm²)
- x Strain, e



The strain displacement relationship is given

$$e = \frac{du}{dx} = \frac{u - u_1}{x_2 - x_1} \quad (23)$$

$$\text{Strain, } \{e\} = [B] \{u\}$$

Where, $\{e\}$ = Strain Matrix, $[B]$ = Strain – Displacement Matrix, $\{u\}$ = Degrees of Freedom

$$\text{Stress, } \{\sigma\} = [E] \{e\} = [D] \{e\} = [D] [B] \{u\}$$

Where

$$[E] = [D] = \text{Young's Modulus}$$

$$\text{Strain energy, } U = \int \frac{1}{2} \{e\}^T \{\sigma\} dv \quad (32)$$

The stiffness matrix is given by

$$[K] = \int [B]^T [D] [B] dv \quad (33)$$

Where, $[B]$ = Strain - Displacement relationship Matrix, $[D]$ = Stress - Strain relationship Matrix

$$\text{Equation for Force Vector is given by } \{F\} = [K] \{u\} \quad (34)$$

$\{F\}$ = Element Force Vector, $[K]$ = Stiffness Matrix, $\{u\}$ = Nodal Displacements

for the correct prediction of the results obtained is shown in figure 4.

$$\text{Equation for Force Vector is given by } \{F\} = [K] \{u\} \quad (34)$$

$\{F\}$ = Element Force Vector, $[K]$ = Stiffness Matrix, $\{u\}$ = Nodal Displacements

IV. RESULTS AND ANALYSIS

The failure analysis of the composite shaft material is done in ANSYS software. First the geometrical model is generated, then it is meshed so that the shaft can be analysed. A solid 3D modelled shaft is generated using the ansys design modular as shown in figure 2. The dimensions of the shaft are shown in figure 3.

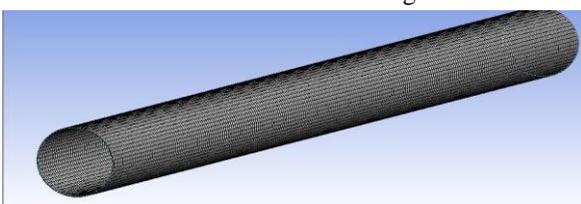


Figure 2. Solid 3D model of the shaft

by

$$\text{Strain } \{e\} = \frac{du}{dx} \quad (29)$$

For 1D problem, displacement is the field variable

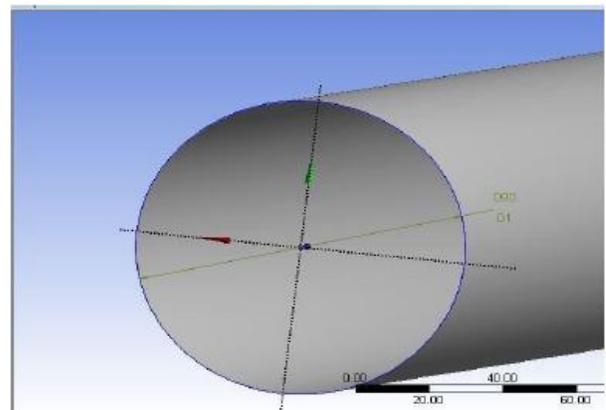


Figure 3. Dimensions of the shaft

Meshing of the composite shaft is achieved with the help of meshing tool. A fine mesh which is sufficient for the correct prediction of the results obtained is shown in figure 4.

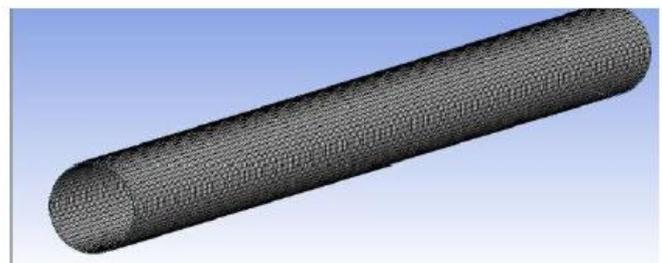


Figure 4. Meshed composite shaft

Once the meshing is done the failure analysis of the shaft based on buckling failure and delamination failure criteria is carried out. For the analysis three different thicknesses of the carbon, steel and glass are used. The values are tabulated in table 1.

Cases	Carbon (t)	Steel (t)	Glass (t)
Case 1	0.5mm	2.32mm	0.5mm
Case 2	0.75mm	1.82mm	0.75mm
Case 3	1mm	1mm	1mm

Table I: Different values of thickness considered for analysis

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A. Buckling Failure

Buckling occurs when the structures are under compressive stresses. In this study the complete shaft geometry is considered to analyse the maximum load it can take beyond which buckling failure occurs. From ansys a load multiplier is obtained which specifies the maximum load the shaft can take. The load multipliers obtained from ansys for the different cases are tabulated in table II.

Cases	Load multiplier
Case 1	5.05
Case 2	3.19
Case 3	1.76

Table II: Load multipliers obtained for the three cases of Table I

B. Delamination Failure

Delamination is one of the failure mechanisms in composite materials. The repeated stresses causes the layers to separate and form a mica-like structure with different layers and there is a significant loss in the mechanical strength. For delamination only a part of the shaft is considered and the results obtained are tabulated in table III.

Cases	Elemental Load (N)
Case 1	82.59
Case 2	110.59
Case 3	147.65

Table III: Load withstandability for the considered cases

C. Thermal analysis of composite shaft:

Under ambient temperature conditions the shaft does not develop any stresses. the aircraft is flying in air, there is a temperature drop of 10-15 degrees and therefore the shafts experience thermal stresses. Hence the thermal stresses are analysed for the shaft. The stresses developed at such conditions is tabulated in table IV.

Cases	Deformation Value (mm)	Stress Developed (MPa)
Case 1	0.24835	31.7650
Case 2	0.24648	32.1600
Case 3	0.25961	32.5230

Table IV: deformation and stress developed by the three cases mentioned in Table I

The graphs in figures 5-7 show a plot of the deflections caused for the different loads applied to the three different cases considered. Figure 8 shows the point at which delamination occurs. The peak point in the figure 8 is the load failure point.

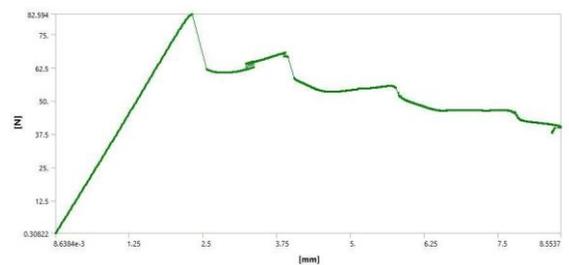


Figure 5. Plot of deflection versus Load for case 1

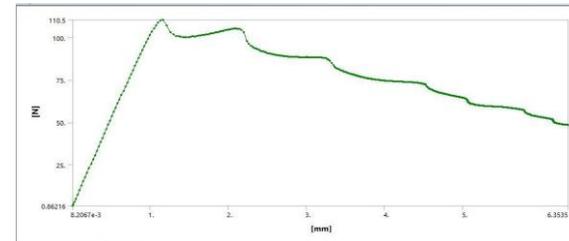


Figure 6. Plot of deflection versus Load for case 2

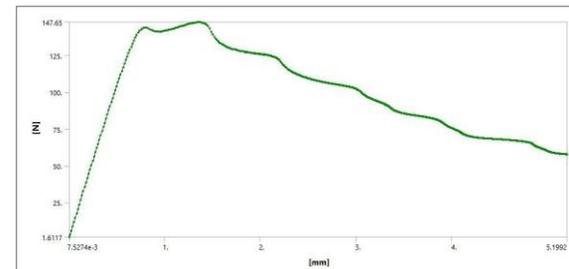


Figure 7. Plot of deflection versus Load for case 3

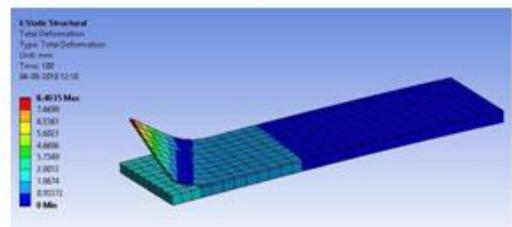


Figure 8. Failure due to delamination.

V. CONCLUSION

From the previously conducted study, it was determined that low carbon steel + epoxy + S glass + T700 fibre is the best suitable hybrid material for the propeller shaft of a two-seater aircraft. This study satisfies the conditions for the suitability of the results obtained from Matlab (from the previous study) in ANSYS software.



The failure analysis was carried out for the composite shaft in ANSYS by creating a solid meshed 3D model of the shaft. The analysis was done for three cases of carbon, steel and glass considering three different values of thickness. From the results, it is concluded that higher the thickness of the hybrid material, higher is its load withstanding capability. The point at which failure occurs due to delamination is also determined from the software.

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