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Effect of fiber-matrix volume fraction and fiber orientation on the design of composite suspension system

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Abstract. The suspension is one of the most essential parts of the vehicle whose main purpose is to absorb the energy transmitted by the bump to the vehicle. It also helps to maintain the surface contact of wheels with the road for better stability, ride and comfort. Carbon-epoxy composites are being extensively used in the automobile industry due to its high strength and specific stiffness. The main objective of this work is to identify the suitability of unidirectional carbon fiber for the design of composite suspension system by considering the effect of fiber-matrix volume fractions and fiber orientation. Double-wish bone type suspension system was considered for analysis. The control arms in the suspension system which are generally made up of Low Carbon Steel were replaced by Unidirectional carbon fiber. The strength of the composite material depends on the amount of fiber and matrix content which are indicated by fiber-matrix volume fractions. Fiber orientation also plays an important role in the design of composite materials since the direction of maximum strength depends on it. Various fiber-matrix volume fractions are considered and the material properties in each case are found by conducting tensile and compression testing on UTM. Thus from the experimental data the volume fractions with better mechanical properties are chosen. The suspension model was modelled in UG-NX and finite element analysis (FEA) was performed using ANSYS 18.1. The mechanical properties found experimentally were considered for analysis. For various fiber orientations, analysis was carried out and the optimum orientation is found.

Keywords Composite analysis, Double wishbone suspension system, Fiber orientation, Fiber-matrix volume fraction, Finite element analysis.

1. Introduction

Composite structures are being extensively used in automobile industry, especially for the components which are critically stressed such as suspension arms, chassis, gear box, aerodynamic devices and brake disks [1]. Carbon-epoxy fibers are generally preferred for highly stressed components over other composite materials due to its superior material properties such as high specific strength, specific stiffness and almost limitless formability.



Unlike the isotropic materials, the composite layers have in general three planes of material symmetry. The mechanical properties such as tensile, flexural, compression and impact strength depends on the fiber orientation, fiber-resin ratio and number of laminates [3]. In this paper the investigation is carried on the effect of fiber-matrix volume fraction and fiber orientation on the design of composite suspension system. The suspension system selected in this paper is double-wish bone suspension which is widely used in the commercial vehicles.

2. Material selection

2.1 Fiber material

The fiber material selected in this paper is Uni-directional carbon fiber which is a transversely isotropic material i.e. the material have one property in the X-direction and another property in Y-direction and Z-direction. The carbon fibers are generally composed of carbon atoms having diameter of about 6-10 micrometer. Generally, carbon fibers are derived from polyacrylonitrile (PAN) and from petroleum, also known as coal pitch. But PAN based carbon fibers are commonly used.

2.2 Epoxy resin

Epoxy resin refers to a type of reactive pre-polymer and polymer containing epoxide groups. It is cured by curing agent called “hardener”. Most common hardener used for epoxy resins are amines, phenols, acid anhydrides, thiols and alcohol. The properties of the epoxy resin is tabulated in the below.

Table 1. Properties of epoxy resin

S.No	Parameters	Value
1	Density in g/cm ³	1.2
2	Young's modulus in Mpa	3780
3	Poisson's ratio	0.35
4	Shear modulus in Mpa	1400
5	Tensile strength in Mpa	54.6
6	Compressive strength in Mpa	108
7	Shear strength in Mpa	29



Figure 1. Unidirectional carbon fiber

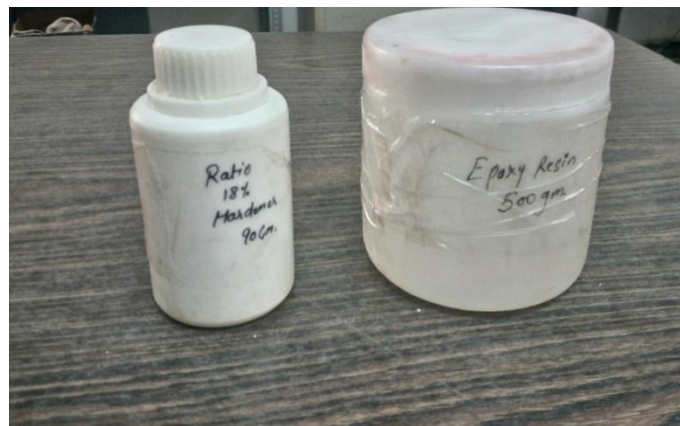
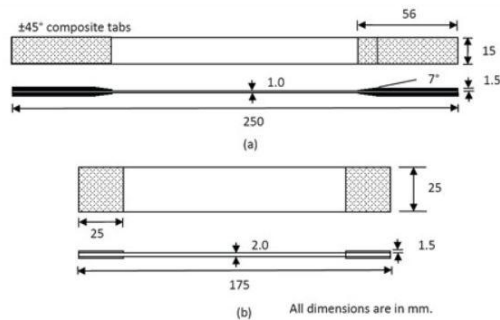
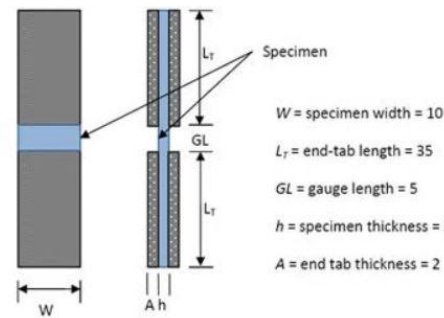


Figure 2. Epoxy resin and hardener

3. Specimen preparation for testing on UTM

The standard specimens with various fiber-matrix volume fractions for tensile and compressive testing are prepared by using the ASTM D3039 and ASTM D695 respectively.

**Figure 3.** Dimensions of tensile specimen**Figure 4.** Dimensions of compression specimen**Figure 5.** Tensile specimen (Longitudinal)**Figure 6.** Tensile specimen (Transverse)**Figure 7.** Compression specimen

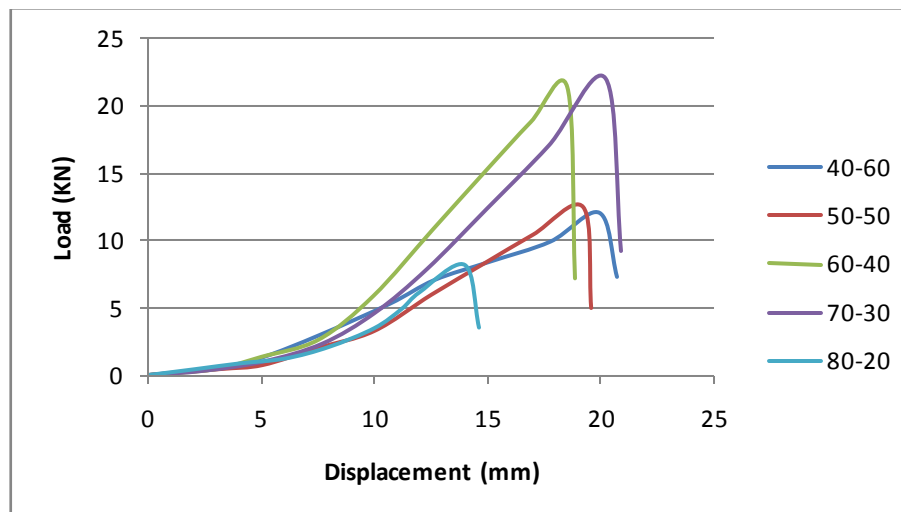
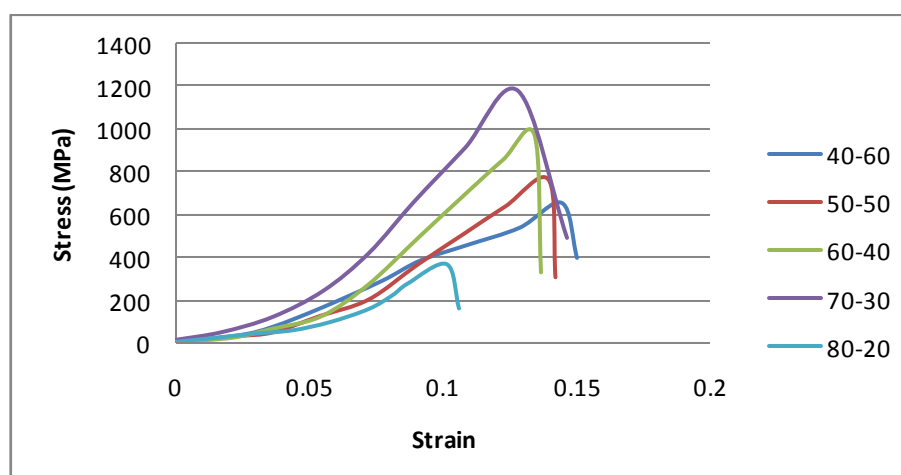
Wet hand layup technique was used for preparing the test specimen. The various fiber-matrix volume fractions were maintained by taking appropriate amount of epoxy, hardener and fiber on weight basis. Table 2 shows the amount of fiber, matrix and hardener used for longitudinal tensile test specimen. Similar calculation was also carried out for transverse tensile test specimen and compression test specimen.

Table 2. Amount of fiber and matrix used to prepare test specimen

Fiber-matrix volume fraction	Volume of fiber (cm^3)	Volume of matrix (cm^3)	Mass of fiber (gm)	Mass of epoxy	
				Epoxy (gm)	Hardener (gm)
40-60	1.5	2.25	2.625	2.87	0.6318
50-50	1.875	1.875	3.281	2.398	0.5265
60-40	2.25	1.5	3.94	1.918	0.4212
70-30	2.625	1.125	4.59	1.439	0.3159
80-20	3	0.75	5.25	0.959	0.306

4. Experimental set up

The universal testing machine having load capacity of 400 KN is used for testing the specimen in tension and compression. The strain rate is kept constant and the load is applied until the specimen is failed. The test data was obtained from the digital logger connected to the UTM through a computer. The output of the test is load Vs displacement graph. The tensile strength was calculated from the obtained graph and is tabulated in table 3.

**Figure 8.** Experimental setup**Figure 9.** Tensile testing**Figure 10.** Compression testing**Figure 11.** Load v/s displacement graph for longitudinal specimen**Figure 12.** Stress v/s strain graph for longitudinal specimen.

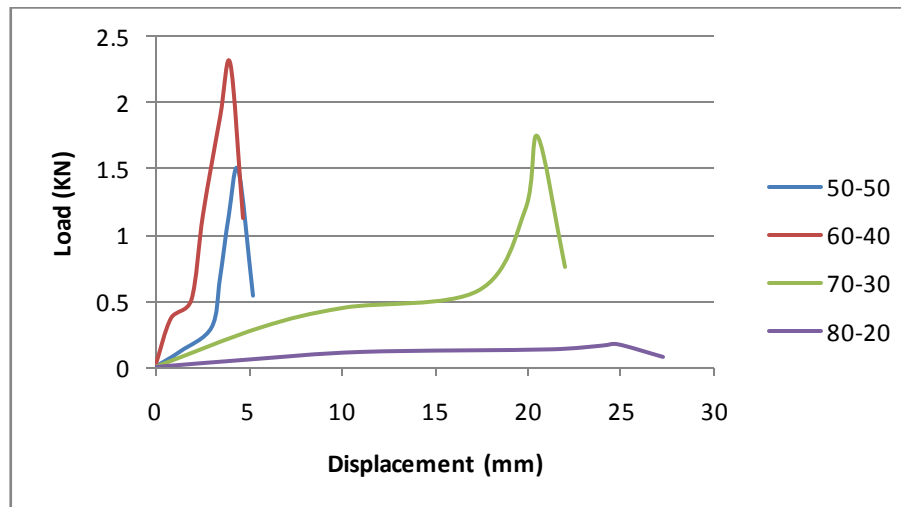


Figure 13. Load v/s displacement graph for transverse specimen

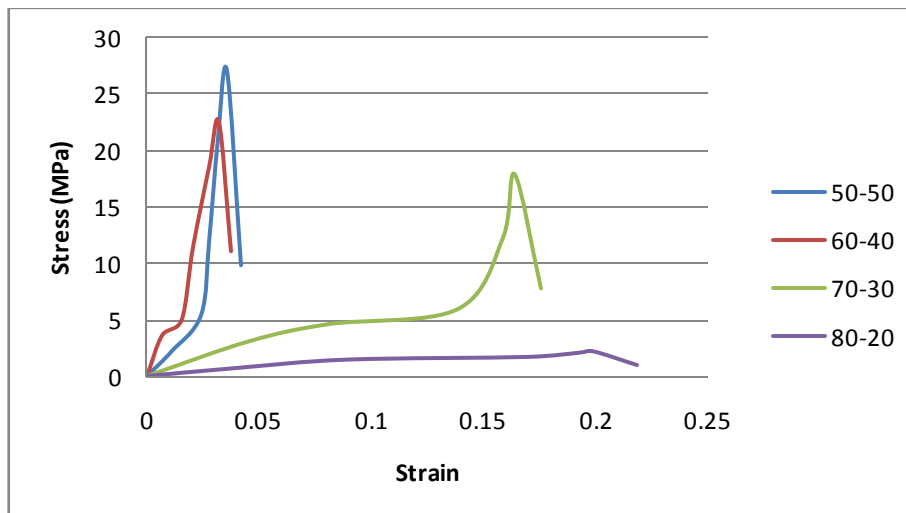


Figure 14. Stress v/s strain graph for transverse specimen

Table 3. Strength obtained in longitudinal and transverse direction from tensile testing

Fiber-Matrix Volume fraction	Longitudinal strength (Mpa)	Transverse strength (Mpa)
40-60	658.182	28.130
50-50	764.180	27.192
60-40	974.611	22.510
70-30	1178.73	19.680
80-20	364.265	2.191

Compression strength for all the specimen was nearly same and its value for 70-30 fiber-matrix volume fraction was 489.289 Mpa in longitudinal direction and 103.579 Mpa in transverse direction.

5. Predictive models

Predictive models are the mathematical models that give the properties of the composite theoretically. From the literature it is observed that these models are reliable [13]. Generally these are used to obtain the young's modulus (E), shear modulus (G) and Poisson's ratio (ν) because large numbers of

experiments are required to find all these material constants. Thus the above material properties were calculated using formulae given below and tabulated in Table 4.

5.1 Properties in longitudinal direction

- i. $E_c = V_f E_f + V_m E_m$
- ii. $v_c = v_f V_f + v_m V_m$
- iii. $G_c/G_m = (1 + nV_f)/(1 - nV_f)$
Where,
 $n = [(G_f/G_m) - 1]/[(G_f/G_m) + 1]$

5.2 Properties in transverse direction

- i. $E_c = (E_f E_m)/[(1 - V_f)E_f + V_f E_m]$
- ii. $v_c = v_f V_f + v_m V_m$
- iii. $G_c/G_m = (1 + nV_f)/(1 - nV_f)$
Where,
 $n = [(G_f/G_m) - 1]/[(G_f/G_m) + 1]$

Table 4. Material constants obtained from predictive model

Fiber-matrix volume fraction	E_x (Mpa)	E_y (Mpa)	E_z (Mpa)	μ_x	μ_y	μ_z	G_{xy} (Mpa)	G_{yz} (Mpa)	G_{zx} (Mpa)
40-60	70668	5560	5560	0.284	0.376	0.284	2650	2169	2650
50-50	87390	6303	6303	0.295	0.385	0.295	3093	2328	3093
60-40	104112	7274	7274	0.306	0.392	0.306	3815	2514	3815
70-30	120000	8600	8600	0.317	0.4	0.317	4690	2731	4690
80-20	137000	10514	10514	0.328	0.406	0.406	5918	2989	5918

6. Failure criteria

In isotropic materials the failure prediction is based on maximum principle stress, maximum principle strain, columb-mohr etc. But these criteria are not used for unidirectional lamina because the planes which are possibly weak may or may not be aligned with the direction of principal stress. Thus several alternate failure criteria like Puck, Tsai-Wu, Tsai-Hill criteria are developed for predicting the failure of composite lamina.

Inverse Reverse Factor (IRF) is the parameter used in composite failure. The failure load can be defined as the load value divided by IRF. Thus when $IRF > 1$ the composite fails and if $IRF < 1$ it is safe. But to avoid unnecessary bulky structure IRF must be maintained between 0.9 and 1.

7. Calculation of member's thickness

The thickness of control arm was selected by using the flow chart as shown in figure. In process-1 initial thickness of composite control arm was chosen based on the steel control arm with some increase in arm thickness. Then, IRF of the model was obtained based on failure envelope of PUCK and Tsai-Hill criterion. If the obtained $IRF > 1$, then the thickness is needed to be increased. On the other hand if $IRF < 0.9$, the thickness of the arm is above required thickness. Thus in this case reduce the thickness.

In process-2, the structure shall be tested against the vertical deflection criteria. If the resultant deflection greater than allowable deflection then the thickness have to be increased. After completing process-2, in order to make sure that IRF is still between 0.9 and 1 process-1 shall be repeated.

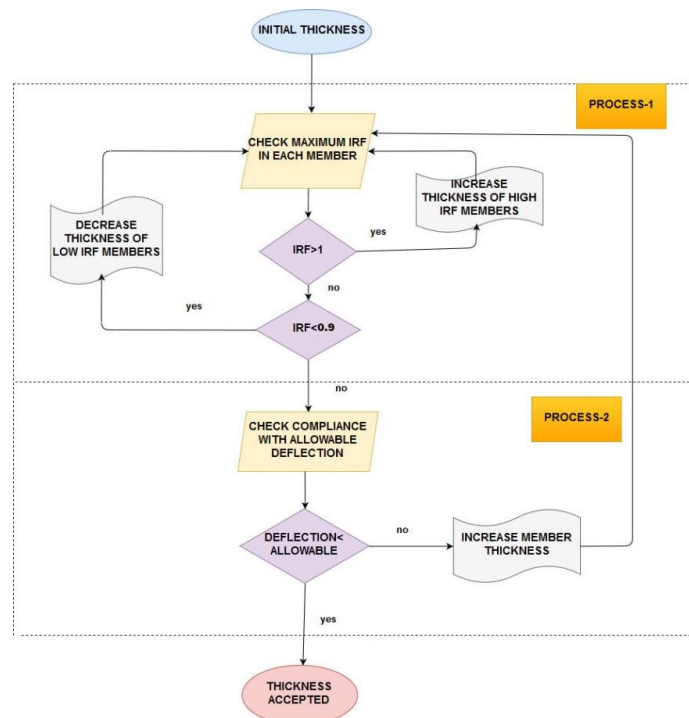


Figure 15. Algorithm used for selection of thickness for composite control arm

8. Design of Suspension system

The suspension is one of the most crucial part of the vehicle. The main purpose of suspension is to absorb the energy transmitted by the bump to the vehicle. It also helps to maintain the surface contact of wheels with the road for better stability, ride and comfort.

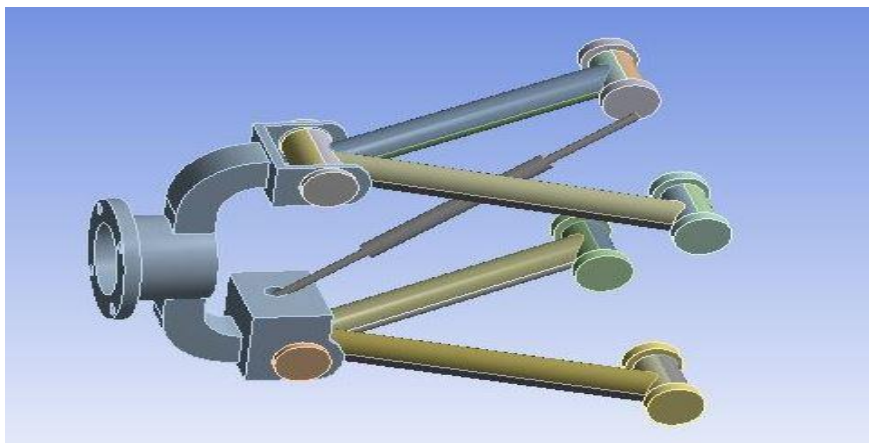


Figure 16. Double wish bone suspension

In this paper we have selected a double-wish suspension. The control arms which are generally made up of low carbon steels are replaced by unidirectional carbon fiber and the effect of Fiber-matrix volume fraction and Fiber orientation is observed.

The suspension model is designed in UG NX 11.0. Since the control arms are to be made from composite, the arms must be designed using the surface entity and remaining parts such as knuckle and bolts can be designed using the solid entity. The model is then exported to Ansys 18.1.



Figure 17. Carbon fiber control arm



Figure 18. 3d printed prototype of suspension assembly

The control arm was fabricated using the unidirectional carbon fiber according to the dimensions. 1:2 scale-down prototype model of the complete suspension assembly was 3d printed using fusion deposition modelling.

9. Analysis

The analysis of the composite suspension was carried out in ANSYS 18.1 using ANSYS (ACP) module. The properties obtained from the testing of the composite specimen are taken as input to the ANSYS software. The suspension arms which are modelled using the surface entity are layered up in ANSYS ACP Pre module and various fiber orientations are provided in it.

The load of 1750 N was applied on each arm. Since the suspension system mainly failed due to loads generated during bumps. Generally 4 G load is taken on the vehicle during the bump.

Total load on vehicle = $4G = 4 \times 350 \times 10 = 14000 \text{ N}$

Load on each arm = $14000/8 = 1750 \text{ N}$

Analysis was carried on by considering various fiber orientations for the unidirectional carbon fiber. Deformation, IRF and Von-misses stresses were obtained and tabulated below.

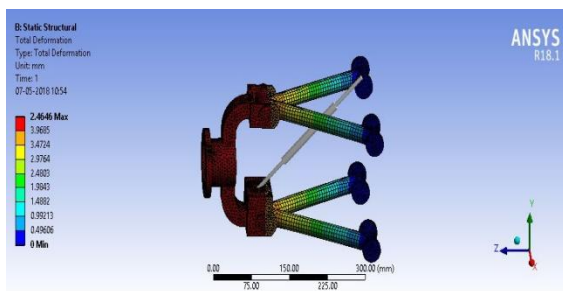


Figure 19. Deformation in suspension system

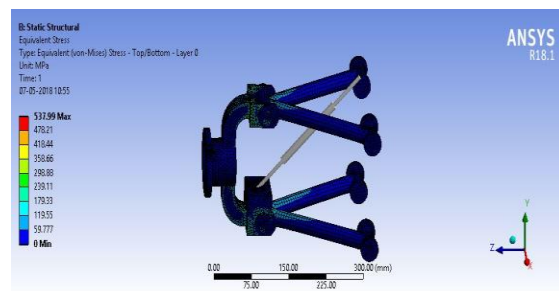


Figure 20. Von-misses stress in suspension system

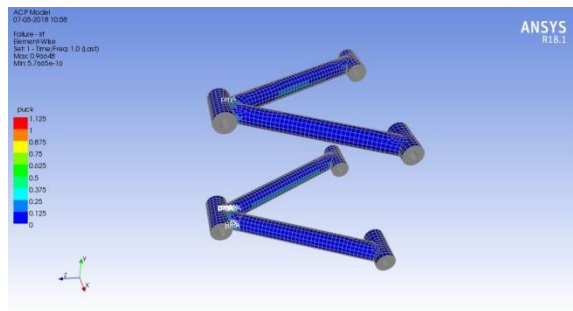


Figure 21. Failure by using PUCK failure criteria

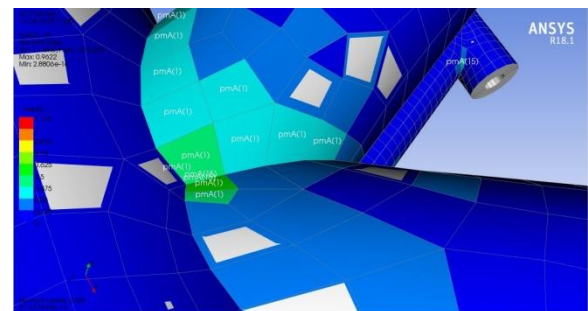


Figure 22. Type of failure occurred

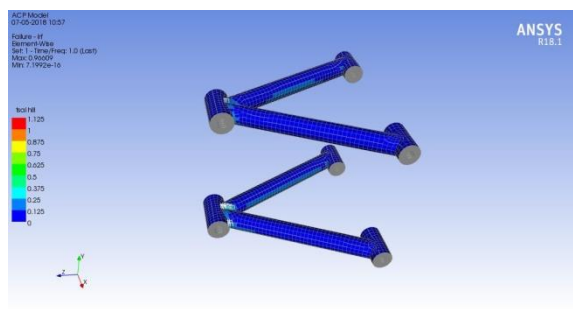


Figure 23. Failure by Tsai-Hill failure criteria

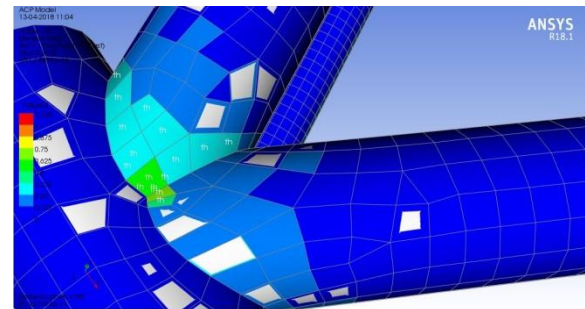


Figure 24. Type of failure occurred

The analysis was also carried out by using the low carbon steel (LCS) material.

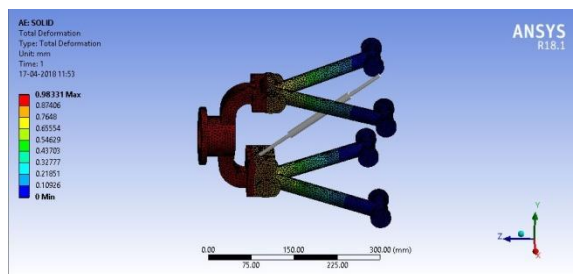


Figure 25. Deformation in LCS suspension

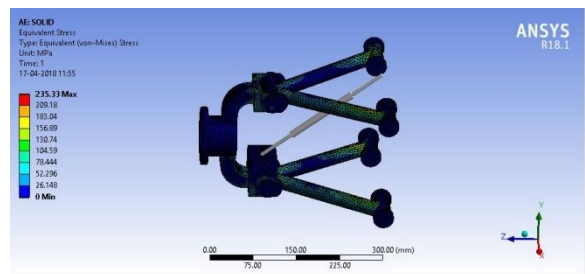


Figure 26. Von-mises stress in LCS suspension

Table 5. Deflection, IRF and Von-mises stress obtained from analysis

Angle (degrees)	Deflection (mm)	IRF (Puck failure criteria)	IRF (Tsai hill failure criteria)	Von-mises stress (N/mm ²)
0,0,0,0	2.4646	0.96648	0.96609	537.99
10,10,10,10	4.8917	1.02796	1.0104	542.47
20,20,20,20	6.2843	1.2964	1.2892	550.28
30,30,30,30	7.0968	1.897	1.8904	469.71
40,40,40,40	10.405	2.9463	2.9404	555.98
50,50,50,50	12.185	3.4082	3.4047	554.46
60,60,60,60	13.724	3.6374	3.635	552.12
70,70,70,70	15.066	3.7225	3.7226	549.92
80,80,80,80	16.191	3.6942	3.6911	548.16
90,90,90,90	16.725	3.6659	3.6608	547.28

10. Results and Conclusion

In the testing of composite specimen on UTM with different volume fractions, as the fiber content increased from 40% to 70%, the strength of the composite also increased, since the fiber strength is higher than the matrix material. But on further increase in fiber content i.e. from 70% to 80% there was decrease in the strength. This is due to insufficient amount of matrix needed to wet the fibers, thus leading to debonding and premature failure of the composite material due to shear stress developed between the lamina. Thus 70-30 fiber-matrix volume fraction has optimum strength equal to 1178.730 MPa. Thus material properties of 70-30 fiber-matrix volume fraction are considered for the design of suspension control arm.

Among all the fiber orientation considered, (0,0,0,0) showed minimum deformation of 2.4646 mm and minimum IRF of 0.96648 with both of them being in the allowable limits. From Puck and Tsai-Hill failure criterion critical area in the composite control arms are at joint and the mode of failure is “pmA” which indicates that the failure is due to matrix tension failure. The term “th” indicates failure of composite at critical points where the distortion energy exceeded the allowable value. Thus by combining both the failure criterion all the critical points and there modes of failure is obtained.

About 53.28% weight reduction was observed for the control arms when unidirectional carbon fiber was used instead of low carbon steel.

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