IJITR

T Radhe Shyam Saini* et al.
(IJITR) INTERNATIONAL JOURNAL OF INNOVATIVE TECHNOLOGY AND RESEARCH
Volume No.4, Issue No.6, October – November 2016, 5179-5186.

Ply Wise Failure Analysis Of Mono Leaf Spring Using Hybrid C-GFRP Composites

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Abstract:- **Composite materials are a better alternative for Leaf spring material in automobiles since they have higher stiffness, high impact energy absorption, lesser stresses and also higher strength to weight ratio. The objective is to study the ply wise failure criteria in the composite leaf springs. Leaf springs are modeled and analyzed using ACP PrePost and studied for failure criteria based on four failure theories which are: maximum stress failure theory, maximum strain failure theory, Tsai-Hill failure theory and Tsai-Wu failure theory. Failure load based on these theories is calculated by conducting a parametric study. To improve the maximum failure load, hybrid composites are designed and analyzed by replacing the top, bottom and center layers of the composite laminate. The four different cross-sections which are analyzed are Eglass/epoxy, HC1, HC2 and HC3. The study shows that replacing the top, bottom and center layers does improve the maximum failure load. Although this introduces higher stresses in the component, the stresses in the Eglass/epoxy material at the same positions from the center of the laminate are reduced. HC3 shows 30.7% increment in failure load by considering only vertical loads and 20.8% increment in failure load by considering vertical, side loads and twist moment simultaneously. There is an agreeable error of 1.44 – 1.65% in the results obtained for deformation and 0.88 – 1.33% for failure load between simulation and theoretical calculations.**

Mechanical properties of the Eglass/epoxy material are evaluated by conducting tensile test and three-point bending test. Mono leaf spring similar to the dimensions of Maruthi 800 vehicle is made using hand layup method. The load vs deformation results of leaf spring show a good agreement between the experimental and the simulation values.

Keywords— **Eglass/Epoxy; Failure Criteria; Static Analysis; Carbon/Epoxy; Hybrid Composites;**

I. INTRODUCTION

Suspension systems in automobiles are engineered to provide the best comfort to the passengers and also to separate the equipment from the shocks related to the bumps. Composites are a better alternative to Steel Leaf springs since they possess higher strength to weight ratio, higher fatigue resistance, higher energy absorption and also have higher natural frequency [8]. The leaf spring is subjected to not only vertical loads but also to the transversal and longitudinal loads due to change in vehicular momentum. The composite leaf spring must sustain all these loads [3].

Several papers were devoted in studying composite leaf springs. W. J. Yu et al. actually replaced the four leaf steel springs with the double tapered leaf springs made from glass fibre and epoxy [1]. A study by E. Mahdi *et al*. demonstrated that composite elliptical leaf springs can be used with substantial weight saving and that the composites are capable of absorbing large deformations, yet show a linear behavior until the first interlaminar shear failure occurs [2]. Optimization study performed by Mahmood *et al.* showed that composite leaf springs are 80% lesser in weight than their steel counterparts and also with lower stresses [3].

Although various forces act on the leaf springs, the variable vertical load is the prominent one. Owing to this vertical load, bending stresses are induced in the spring. Many studies have been carried out on bending properties on composite laminate by considering several factors such as fiber orientation, laminate stacking, and manufacturing conditions [4, 5, 18]. Apart from the analytical results, laboratory tests and experimental results also validate the use of composite materials for leaf springs [2 - 10]. Some studies were concentrated on hybrid fiber composites other than GFRP composites. Andrea Corvi replaced carbon-epoxy layers at the mean plane of the composites to deal with transverse loads which affect the vehicular behavior around curves [7]. B. Arun et al. performed the static analysis of hybrid composite leaf spring made out of Jute/E-glass/Epoxy and found that they possess lower weight with comparable stresses and deflections [11]. Thus from these studies, it can be said that composite materials are a better alternative for steel as material for leaf spring

A successful design of a structure requires efficient and safe use of materials. An orthotropic lamina has properties different in different directions and their failure theories are based on stresses in the material or local axes. Thus in this study, a leaf spring subjected to vertical loading and specified boundary conditions is studied for failure criteria based on four failure theories which are: maximum stress failure theory, maximum strain failure theory, Tsai-Hill failure theory and Tsai-Wu failure theory [19].

Parametric study has been performed on the leaf spring to find the maximum load based on the individual failure criteria.

Leaf springs layers are modeled using shell elements in Ansys and stacking and orienting of individual layers are done in ACP prepost. And later solved under static conditions and finally layer by layer stresses and failure criteria are studied in ACP prepost.

A. Composite Leaf Spring

In the study by Mahmood *et al.*, optimization process is performed for the shape of the spring. A varying thickness and varying width is considered by keeping the total area of cross-section constant. Area of cross-section is kept constant so as to allow continuous fibers along the leaf spring. But in this study, width and thickness are assumed to be constant so as to model the whole spring as layers. Parameters for the composite leaf springs are provided in Table I.

TABLE I. PARAMETER OF COMPOSITE LEAF SPRING

Parameter	Value
Total Length	1245 mm
Arc height in axle seat	120.4 mm
Width	60 mm
Thickness	22 mm

B. Material Selection

Weight reduction in designing leaf springs results in enhanced performance and payload [7]. The amount of specific strain energy that can be stored in a leaf spring per unit volume can be calculated from the equation:

$$\gamma = \frac{\sigma_t^2}{2\rho E}$$

Here, σ_t is the static ultimate strength, ρ is the density of the material and E is the Young's modulus. Comparing the specific static ultimate strengths of various FRP materials such as SGlass/Epoxy, EGlass/Epoxy, Carbon/Epoxy and steel, it can be stated that SGlass/Epoxy has the higher specific strengths. And in terms of specific dynamic ultimate strength, Carbon/Epoxy shows itself to be superior. But the Carbon/Epoxy and the SGlass/Epoxy FRP composite are of high cost. On other hand, favorable relationships between the cost and the properties of a material can be obtained with EGlass/Epoxy [1]. In Hybrid composites making, Carbon/Epoxy layers are substituted in place of some of the Eglass/Epoxy layers.

II. EXPERIMENTATION

A rectangular specimen of dimensions 200 mm X 300 mm is prepared by Hand Layup method. And tensile test specimens are cut from it. The tensile test specimen is loaded in the flat jaws of the Universal Test Specimen as shown in fig 1. Tensile testing is performed for 3 specimens and ultimate failure load and deformation is obtained.

Fig. 1. Tensile Test Specimen loaded in UTM

The average values from the above test are shown in Table II.

TABLE II. AVERAGE VALUES OF TENSILE PROPERTIES

Parameter	Value
Ultimate Tensile Stress	267.24 MPa
Young's Modulus	11.95 GPa

C. Density Calculation

A volume of 13 mm X 4 mm X 154 mm is cut out from the prepared specimen and the mass of the specimen is measured using a weighing machine. The values are tabulated below.

$$\text{Volume} = 13 \times 4 \times 154 \text{ mm}^3$$
$$= 8008 \times 10^{-9} \text{ m}^3$$

$$\text{Mass} = 0.016 \text{ kg}$$

$$\text{Density } = 1998 \text{ kg/m}^3$$

D. Hand Layup Process

Leaf spring of Maruthi 800 model was prepared for testing for Load vs deformation. The leaf spring was obtained and a mold is prepared for the layup of glass fibers. Here, Eye part of the leaf spring is neglected. Glass fiber weave are cut into the desired dimension prior to the start of the process. The Hand Layup procedure for making Leaf spring is as described below.

- Mold is prepared and a thin plastic film is laid out on it.
- Layers of glass fiber weaves are laid out and epoxy resin is applied on them as shown in the Fig 2.

- The layers are roller on with a roller so as to remove any entrapped air.
- The leaf spring of desired thickness of 10 mm is obtained and machined for the required shape as seen in the Fig 3.

Fig. 2. LAYERS OF GLASS FIBERS

Fig. 3. EGLASS/EPOXY LEAF SPRING

E. Load Vs Deformation Test

Load versus deformation test is carried out for the leaf spring. Load increments of 1 kg is applied and deformation from the base are measured while loading and unloading. The results are as shown in the Table III.

TABLE III. LOAD VS DEFORMATION VALUES (EXPERIMENTAL)

Load	Distance from the base (cm)		Average (cm)	Deformation (cm)
	Loading	Unloading		
-	6.3	6.2	6.25	0
1 kg	5.9	5.8	5.85	0.4
2 kg	5.6	5.7	5.65	0.6
3 kg	5.3	5.3	5.3	0.95
4 kg	4.9	4.7	4.8	1.45
5 kg	4.6	4.6	4.6	1.65

The experimental load vs deformation curve for the leaf spring is shown in Fig 4.

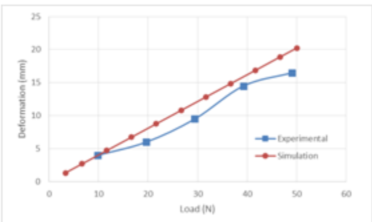

Fig. 4. Comparison of Load vs Deformation for leaf spring.

Therefore, from the above results, it can said that there is a good agreement between the experimental and the simulation results for the composite materials.

III. ANALYSIS USING ACP

Mono leaf spring is considered for the analysis in this project. For analysis, the eye part is not considered since it is difficult to manufacture the eye part using composite layers. Although various forces act on the leaf springs, the variable vertical load is the prominent one. The maximum load criteria is the one in which all the loads are acting simultaneously.

In the analysis of the different materials, two categories of loadings are applied. In the first category, only vertical loads are applied and plotted for IRF's and in the second category, vertical loads, side loads produced by the change in the angular momentum and the maximum twist angle are applied and failure criteria is calculated. Although vertical loads are the prominent kind of force on the leaf springs, but the twist angle and the side loads do have an impact on the stresses in the leaf spring. The side loads are considered to be 75 % of the vertical loads applied [3]. The twist angle of 9° is the maximum possible twist angle between the axle seat and each eye [1]. The boundary conditions and the loading conditions are as seen in the Fig 5.

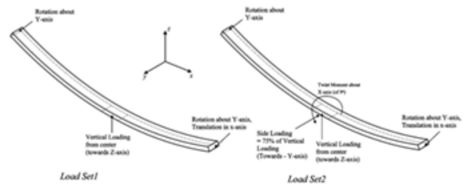

Fig. 5. Mono leaf spring boundary conditions under two different Load sets (Normal Vertical Loading and Maximum Loading)

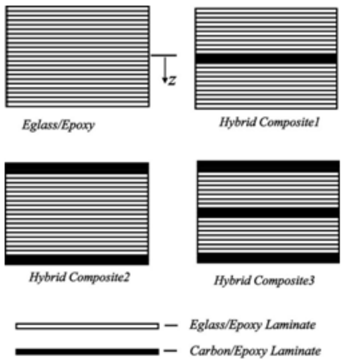

Fig. 6. Cross Section of layered composites

Leaf spring is modelled and analyzed for various materials as Steel, Eglass/Epoxy, Hybrid Composite1 (HC1), Hybrid Composite2 (HC2) and Hybrid Composite3 (HC3). For analysis using composite materials, layers of composite material are modelled with unidirectional layers along the length of the spring. Hybrid Composite1, 2 and 3 are combinations of Carbon/Epoxy and

Eglass/Epoxy layers with their cross-section are shown in the Fig 6.

The stiffness of leaf spring made of Steel and Eglass/epoxy is compared under the similar dimensions and boundary conditions. The results are as seen in the Fig 7.

For a similar dimensions of mono leaf spring, Eglass/epoxy and HC1 show similar stiffness which is much lower than that of steel while the HC2 and HC3 show similar stiffness which is slightly lower than that of steel. For the same loading, the composite materials show a higher deflection as seen from the Fig 7. While modelling Composite layered leaf spring, a lamina of thickness 1 mm is considered and 22 layers are stacked on to each other to form the leaf spring. All unidirectional leaf springs are considered in the stacking sequence with the direction of fibers along the length of the spring. Modelling of layered composite lamina is done using shell elements while the modelling of steel and

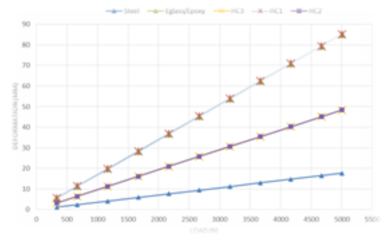

Fig. 7. Load vs deformation for different cross-sections

Eglass/Epoxy orthotropic material is done using solid elements.

The failure theories which are considered in this study are: Maximum stress failure theory, Maximum Strain failure theory, Tsai-Hill failure theory and Tsai-Wu failure theory. The reserve factor RF indicates margin to failure. The applied load multiplied by the reserve factor gives the failure load:

$$RF \times F_{applied} = F_f$$

The critical values of reserve factors lie between zero and one, whereas the non-critical values range from one to infinity. In actual practice, inverse reserve factor is preferred which is given by:

$$IRF = \frac{1}{RF}$$

The non-critical values of IRF's lie from 0 to 1 and critical values range from one to infinity.

F. Eglass/Epoxy

A parametric study has been performed on the layered Eglass/epoxy leaf spring to obtain the inverse reserve factor (IRF) based on different failure theories. This IRF from various theories are plotted for varying load as seen in the Fig 8.

The highest possible load at which the leaf spring fails is 8480 N and is based on the maximum strain failure theory. Both maximum stress failure theory and Tsai-Hill theories predict similar IRF's. Also, while plotting the IRFs under load set2, it was observed that the critical most points are near the eyes. Since the eye part is not considered and while attaching the eye part excess layers of composite layer are added near the eye part, so it is reasonable to assume that the area near these edges are less critical to failure. Thus the maximum possible load at which the leaf spring fail under the load set2 excluding the edges is 7780 N.

The IRF's on the critical layers due to maximum strain failure theory under load set 1 are plotted in the Fig 9. And the IRFs on the critical layers due to Tsai-Hill failure theory (excluding the edges) are plotted in the Fig 10.

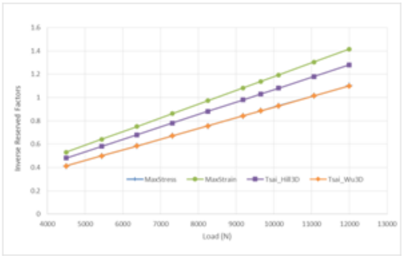

Fig. 8. Load Vs Inverse Reserved Factors

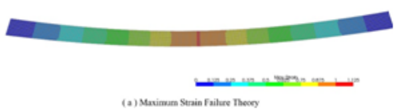

Fig. 9. IRF plot for Eglass/Epoxy under Load set1

Fig. 10. IRF plot for Eglass/Epoxy under Load set2 (excluding edges)

G. HC1

The highest possible load at which the leaf spring fails is 8482 N and is based on the maximum strain failure theory. The maximum possible load at which the leaf spring fail under the load set2 excluding the edges is 7586 N.

The IRF's on the critical layers due to maximum strain failure theory under load set 1 are plotted in the Fig 11. The IRFs on the critical layers due to Tsai-Hill failure theory under load set 2 are plotted in the Fig 12.

H. HC2

The highest possible load at which the leaf spring fails is 11080 N and is based on the Tsai-Wu failure theory. The maximum possible load at which the leaf spring fail under the load set2 excluding the edges is 8812 N.

The IRF's on the critical layers due to Tsai-Wu failure theory under load set 1 are plotted in the Fig 13. The IRFs on the critical layers due to Tsai-Hill failure theory under load set 2 are plotted in the Fig 14.

Fig. 11. IRF plot for HC1 under Load set1

Fig. 12. IRF plot for HC1 under Load set2 (excluding edges)

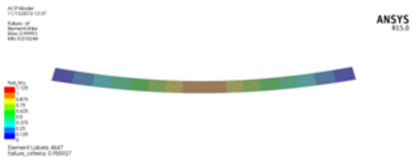

Fig. 13. IRF plot for HC2 under Load set1

Fig. 14. IRF plot for HC2 under Load set2 (excluding edges)

I. HC3

The highest possible load at which the leaf spring fails is 11084 N and is based on the Tsai-Wu failure theory. The maximum possible load at which the leaf spring fail under the load set2 excluding the edges is 9396 N.

The IRF's on the critical layers due to Tsai-Wu failure theory under load set 1 are plotted in the Fig 15. The IRFs on the critical layers due to Tsai-Wu failure theory are plotted in the Fig 16.

Fig. 15. IRF plot for HC3 under Load set1

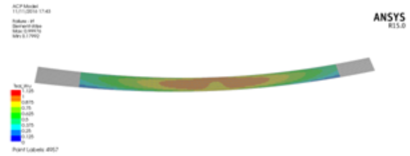

Fig. 16. IRF plot for HC3 under Load set2 (excluding edges)

TABLE IV. LOAD VS DEFORMATION VALUES (EXPERIMENTAL)

Material	Failure Load	
	Load Set1	Load Set 2 excluding the edges
Eglass/Epoxy	8480	7780
HC1	8482	7586
HC2	11080	6140
HC3	11084	9396

The failures loads for the different cross-sections of composites are tabulated in the Table IV.

To calculate the stresses acting on the cross-section, load set 2 is preferred and a similar load, say 6000 N (well below the failure loads of all cross-sections) is applied for each cross-section. Thus the side load acting on the leaf spring is 75% of vertical load which is 4500 N and a twist of $9°$ is applied at the axle seat. The stresses are plotted at the critical elements. The stresses in the local axes for different cross-sections at the critical location of failure are plotted in the Fig 17.

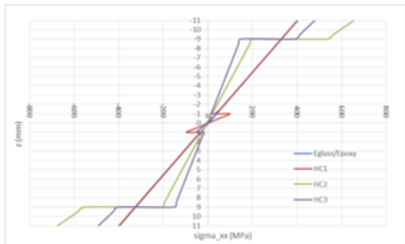

Fig. 17. Stresses in the local x–axis (along the length of leaf spring)

The stresses in the transverse direction to the fiber for the different cross-sections at critical elements of failure are plotted in the Fig 18. The stresses in the out of plane direction for various cross-sections at the critical elements of failure are plotted in the Fig 19. The in-plane shear stress for various cross-sections at critical elements of failure are plotted in the Fig 20.

IV. ANALYTICAL VALIDATION

Failure theories are based on the stresses in the material or local axes. First the reduced stiffness matrix $[Q]$ for each ply is determined. Since the fibers are along the reference direction, the reduced stiffness matrix and the transformed reduced stiffness matrix are equal.

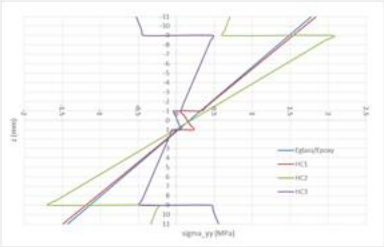

Fig. 18. Stresses in the transverse direction

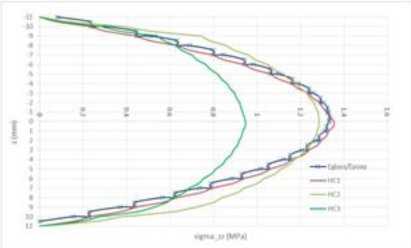

Fig. 19. Out of the Plane Stresses

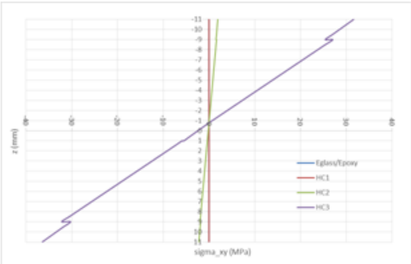

Fig. 20. In plane shear stresses

The transformed reduced stiffness matrix for the Eglass/Epoxy cross section is,

$$\left[\bar{Q}\right]=\begin{bmatrix}45.918 & 3.061 & 0\\ 3.061 & 10.20408 & 0\\ 0 & 0 & 5\end{bmatrix}\times 10^3 \text{ MPa}$$

The stiffness matrices [D] for the Eglass/epoxy is:

$$D_{ij}=\frac{1}{3}\sum_{k=1}^{22}\left[\left(\bar{Q}_{ij}\right)\right]_k\left(h_k^3-h_{k-1}^3\right),\quad i=1,2,6;\ j=1,2,6$$
$$=\begin{bmatrix}40744.572 & 2716.127 & 0\\ 2716.127 & 9054.4203 & 0\\ 0 & 0 & 4436.7\end{bmatrix}\times 10^3 \text{ N}\cdot\text{mm}$$

Therefore, the mid plane curvatures are

$$[\kappa]=[D]^{-1}[M]$$
$$\begin{bmatrix}\kappa_x\\ \kappa_y\\ \kappa_{xy}\end{bmatrix}=\begin{bmatrix}25.0439 & -7.512636 & 0\\ -7.512636 & 112.69 & 0\\ 0 & 0 & 225.393\end{bmatrix}[M]\times 10^{-9}$$

Assume the leaf spring to be s simply supported beam with a concentrated load of W at the center. Thus the end reaction is 0.5W.

Maximum moment is at the center of beam which is

$$M=-\frac{WL}{4}$$
$$M_x=-5.1875W$$

Strains developed in the laminate at a distance of z from the centroidal plane are:

$$[\varepsilon]=z[\kappa]=zM_x\begin{bmatrix}2.50439\times 10^{-8}\\ -7.512636\times 10^{-9}\\ 0\end{bmatrix}$$

Stresses developed in the laminate are:

$$[\sigma]=[Q][\varepsilon]=zM_x\begin{bmatrix}0.01126974\\ 9.23863\times 10^{-12}\\ 0\end{bmatrix}$$

At the center of the bottom most lamina stresses developed are:

$$\begin{bmatrix}\sigma_1\\ \sigma_2\\ \tau_{12}\end{bmatrix}=\begin{bmatrix}-0.0613848\\ -503.2166\times 10^{-12}\\ 0\end{bmatrix}W$$

Apply the Tsai-hill failure theory for the bottom most lamina,

$$\left[\frac{\sigma_1}{\left(\sigma_1^C\right)_{ult}}\right]^2-\left[\frac{\sigma_1\sigma_2}{\left(\sigma_1^C\right)_{ult}^2}\right]^2+\left[\frac{\sigma_2}{\left(\sigma_2^C\right)_{ult}}\right]^2+\left[\frac{\tau_{12}}{\left(\tau_{12}\right)_{ult}}\right]^2=IRF^2$$
$$W=10996.20896\,IRF$$

The maximum deformation for a simple supported beam is at the center and is given by (from beam theory),

$$\delta=\frac{WL^3}{48E_xI}\quad \text{Where, } E_x=\frac{12}{h^3D_{11}^*},\ I=\frac{bh^3}{12}$$
$$=0.0167809W$$
$$\Rightarrow W=59.59\delta$$

From the above equation, the stiffness of the leaf spring is 59.59 N/mm. The simulation and the analytical values for the Eglass/epoxy are shown in the Table V.

TABLE V. COMPARISON OF RESULTS FOR EGLASS/EPOXY

	Simulation	Analytical	Error
Stiffness of leaf sprig	58.739	59.59	-1.43%
Failure load	10898.77 N	10996.21	-0.88%

Similar calculations are performed for HC1, HC2 and HC3 and the results are compared with the simulation values. The simulation and the analytical values for the HC1 are shown in the Table VI.

TABLE VI. COMPARISON OF RESULTS FOR HC1

	Simulation	Analytical	Error
Stiffness of leaf sprig	58.81	59.67	-1.44%
Failure load	10912.09	11010.92	-0.9%

The simulation and the analytical values for the HC2 are shown in the Table VII.

TABLE VII. COMPARISON OF RESULTS FOR HC2

	Simulation	Analytical	Error
Stiffness of leaf sprig	103.40	105.11	-1.63%
Failure load	10912.09	11486.45	-0.9%

The simulation and the analytical values for the HC3 are shown in the Table VIII.

TABLE VIII. COMPARISON OF RESULTS FOR HC3

	Simulation	Analytical	Error
Stiffness of leaf sprig	103.45	105.19	-1.65%
Failure load	11499.98	11655.38	-1.33%

V. CONCLUSION

From the analysis, the following conclusions can be drawn.

- Introduction of carbon/epoxy laminas at different layers increases the failure load.
- Also, it reduces the amount of stresses in the Eglass/epoxy layers at the same level as that in normal Eglass/epoxy laminate.
- HC1 cross-section with carbon/epoxy layers at the center has no effect at all on the deformation, failure load due to vertical loads or the maximum loads.
- HC2 cross-section with carbon/epoxy layers at the extreme ends has significant effect to withstand only vertical load but shows lower failure load due to load set2.
- HC3 on the other hand which is the combination of both HC1 and HC2 shows significant improvement in the failure loads due to both the load sets 1 and 2.
- Thus HC3 finds itself to be superior in the four cross-sections with respect to vertical loading and the maximum loading case, although such a case seldom arises.
- Addition of carbon/epoxy layers in the middle of the cross-section showed no appreciable increase in the spring constant, but the addition of those layers at the extremes of the cross-section showed increase in the spring constant and is nearer to the steel leaf spring.
- Addition of 6 mm of carbon/epoxy layers to form a C-GFRP composites has increased the failure load by 30.7% in the vertical loading case and 20.8% in the maximum loading case.
- Simulation values agree closely with that of the analytical values.
- There is an agreeable error of -1.43% in the deformation results obtained by simulation and an error of around -0.89% with those of failure load.
- Tsai-Hill failure theory predicts reasonable estimates of failure loads in most of cross-sections and the load sets.
- Introduction of carbon/epoxy layers in HC3 cross-section creates higher in-plane shear stresses in the layers when compared to remaining cross-sections.

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