Finite Element Analysis and Performance Evaluation of Composite Leaf Spring for Lightweight Three Wheeler Vehicle

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Abstract

The modern world has growing demand on light weight vehicle for which fuel efficiency is most important. This has drawn into research on the alternative materials for vehicle suspension system which is crucial in enhancing the efficiency of vehicle. This research presents a finite element analysis of composite leaf spring to evaluate their feasibility as replacement for steel leaf spring. The composite materials considered to carry out this research includes Epoxy/E-Glass, Epoxy/Carbon, and Epoxy/Bamboo. The static structural analysis for these materials is carried out using ANSYS Static Structural domain under various loading condition. The results indicate that composite leaf springs has a 23-26% weight reduction as compared to steel material, improved stress distribution and enhanced vibration damping characteristics. Among the analyzed materials, Epoxy/Carbon shows the highest stiffness and durability that makes this material suitable for light weight vehicle application.
Keywords: *Composite, Stress Analysis, Harmonic Response Analysis, Finite Element Analysis, Safa Tempo.*

1. INTRODUCTION

The modern automotive industry has been progressively shifting towards light-weight materials to enhance vehicle efficiency which is possible by using composite material or by using Nano materials. Suspension system is a crucial component for a vehicle where leaf spring stands as an important part for the passenger vehicle where the applying load are uneven. But the leaf spring has higher weight that increase the overall weight of the vehicle which decrease the efficiency of vehicle. Traditional steel material leaf springs are durable but heavy. So, use of composite material offers enhanced mechanical properties while reducing the weight of spring. In this research paper, the mechanical properties of high-strength steel leaf springs have been examined to improve their resilience under heavy loads. It shows that high-strength steels can extend fatigue life while supporting higher loads, although they remain heavier than composite material which limits the fuel efficiency improvements (Fragoudakis & Zindeluk, 2022). This research has shown that composite materials particularly in laminated structures form provides enhanced stress resistance and reduced weight for leaf springs. Through finite element analysis, composite leaf springs demonstrate better performance in terms of stress distribution and weight-to-strength ratios which makes them an alternative option for optimizing ride quality (Shokrieh & Rezaei, 2003). He has conducted the research on composite materials for leaf springs to highlights the advantages of using alternatives like Epoxy/E-Glass, Epoxy/S-Glass, and carbon fiber. This studies show that these materials can enhance strength-to-weight ratios and reduce overall vehicle weight, which is critical for fuel efficiency and ride comfort. By utilizing materials with high fatigue resistance, the lifespan of the leaf springs can be improved while reducing the risk of catastrophic failure seen in traditional steel springs (Bhandari, 2021). Various studies have explored a range of lightweight and fatigue-resistant materials for leaf springs, including composite materials, advanced alloys, and hybrids. These materials have shown better results in enhancing durability, reducing weight, and minimizing fatigue. These properties make them suitable alternatives to traditional steel for automobile applications (Pal & Ghosh, 2017). This paper reveals that the geometry, thickness, and configuration of leaf springs significantly affect a vehicle's handling, ride comfort. These design factors play an essential role in optimizing the balance between comfort and control, suggesting that careful adjustments in these areas can improve vehicle performance (Abhijeet, 2019).

2. MATERIAL SELECTION

The composite materials which are considered to carry out this research includes Epoxy/E-Glass, Epoxy/Carbon, and Epoxy/Bamboo. These three materials are unidirectional composite material which have distinct mechanical properties. We have selected these materials based on the availability, cost and mechanical properties. Epoxy/E-Glass has balanced between the mechanical strength and the manufacturing cost. The Epoxy/Carbon can provide the higher stiffness and fatigue resistance while the Epoxy/Bamboo is a natural fiber composite that offers sustainability benefits but the mechanical strength is lower. Since, these properties of the composite materials application in load bearing structures that makes them suitable for the suspension component materials.

3. METHODOLOGY

Safa Tempo a three-wheeler passenger vehicle commonly operating in the Kathmandu valley is taken into consideration for this research. A 3D model of steel leaf spring was created using the SolidWorks and Finite Element Analysis is carried out using the ANSYS 2025R1 STUDENT. The static structural and modal analysis were performed to evaluate stress distribution, deformation and vibrational response. Dynamic response was carried out by converting static load to dynamic load which is verified by ISO 8608 standard value of vertical acceleration that replicates the bumps from roads at moderate speed of 30m/s to 50m/s in harmonic response analysis domain of ANSYS. The leaf spring was modeled as a cantilever beam. Material properties wear applied as per the literature value (Alemu & Fatoba, 2022) and the validation was achieved by comparing simulation results for steel with the theoretical calculations using standard machine design equations and for the composite material result verified using comparative analysis with steel.

Table 1 Material Properties of Composite Material

S.N.	Properties	E-Glass/Epoxy	Carbon/Epoxy	Bamboo/Epoxy
1	EX (MPa)	43000	177000	13360
2	EY (MPa)	6500	10600	6840
3	EZ (MPa)	6500	10600	6800
4	PRXY	0.27	0.27	0.346
5	PRYZ	0.06	0.02	0.435
6	PRZX	0.06	0.02	0.346
7	GXY (MPa)	4500	7600	2490
8	GYZ (MPa)	2500	2500	2380
9	GZX (MPa)	2500	2500	2490
10	$\rho\ (Kg/m^3)$	2000	1600	1390

The theoretical design is carried out on the basis of the concept used in Mechanics of Material and Machine Design. The direct measured thickness and width of the leaf spring is compared with the standards given in machine design data book to ensure the accuracy of measurement. We can consider leaf spring as simply supported beam or as cantilever beam for various parameter analysis. In this project, we have considered leaf spring cantilever beam. The below equations are used from the Machine Design-II (Gopinath & Maturam).

$$(\sigma) = \frac{6WL}{nbh^2} \tag{1}$$

$$(\delta) = \frac{12WL^3}{E\left(2n_g + 3n_f\right)bh^3} \tag{2}$$

$$R = \left(\frac{H^2 + l^2}{2H}\right) = \left(\frac{100^2 + 388^2}{200}\right) = 800.78mm$$

Table 2 Leaf Spring Parameters

S.N.	Leaf Spring Parameter	Notation	Value	Unit
.1	Total overall Length of leaf	2L	776	mm
2	No. of full-length leaves	$\mathrm{N_f}$	3	unit
3	No. of graduated-length leaves	$\mathrm{N_g}$	10	unit
4	Total no. of leaves	$\mathrm{N_g + N_f = N}$	13	unit
5	Thickness of leaf	T	6	mm
6	Width of leaf	B	37	mm
7	Inside diameter of eye design	D	23.5	mm
8	Radius of Curvature	R	800.78	mm

For the calculation of weight of the vehicle, assuming that the three-wheeler electric vehicle weight is maximum around 1500Kg. It is verified that the load distribution will be 70% on the rear wheel and 30% on the front wheel which is based on practical vehicle geometry. We have taken maximum allowable passenger of 10 of each weight around 60Kg which is verified by various research.

The total weight of the vehicle $= 1500 + 10 \times 60 = 2100Kg = 20601N$

The weight on the rear axle$= 0.7 \times 20601 = 14420N$

The net force on the single leaf$= 0.5 \times 14420 = 7210N$

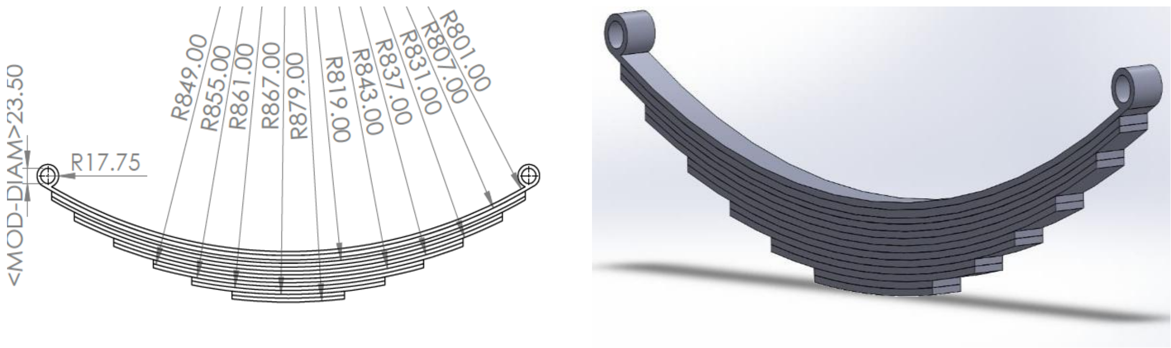

Fig. 1 Leaf Spring Model and Front View.

4. MESHING AND BOUNDARY CONDITION

The leaf spring was applied with 6mm of element size with no of element and no of nodes 96788 and 15295 respectively. The 6mm mesh element size is selected by conducting the mesh independent test. In order to find the correct result from the FEA, this boundary condition is applied which replicate the real world leaf spring attached to the vehicle (Rao, S.S).

- At point 'A', remote displacement was applied where fixed displacement in (X,Y,Z)-axis whereas fixed rotation about (X,Y)-axis and rotation about Z-axis as free.
- At point'B', remote displacemet is applied where displacement about X-axis as free and (Y,Z)-axis as fixed where as rotation about (X,Y)-axis fixed and rotation about Z-axis as free.
- Force is applied in upward direction from the bottom most leaf (i.e., Positive Y-axis)
- All the 13 layers of leafs are assumed to be bonded.

The boundary conditions applied on the point A represent the fixed eye of the leaf spring which doesnot moves. The B point represent the sachakle of the leaf that allows some displacement in leaf spring which prevents from sudden leaf spring failure. The force applied from the bottom of the leaf spring replicates the reaction force (2W) which is equal to the load from the vehicle on the both eye of the leaf spring (W) each.

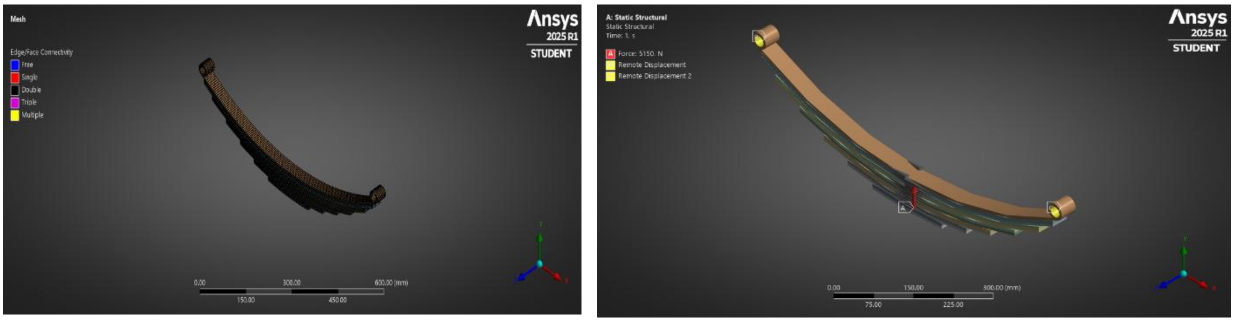

Fig. 2 Leaf spring model with boundary conditions and 6mm mesh

5. RESULT AND DISCUSSION

5.1 Static Structural Analysis

The various static loading conditions are taken into the consideration for this analysis. At varying loading conditions, the simulated value for the deformation and equivalent stress data are collected and tabulated. All the load taken are realstic and the varying load are taken 1.3 times the previous load. Since the analytical result and simulated result for the structural steel are nearly equal, we can carryout comparative analysis for the other material. The result from the static structurue shows the linear behaviour.

Table 3: Calculated result for Structural Steel material using formula.

S.N.	Load (N)	Deformation (mm)	Stress (MPa)
1	5150	35.708	129.39
2	6695	40.798	168.21
3	7203	51.014	180.97
4	8703	61.216	218.60
5	9363	68.363	235.34
6	12172	91.836	305.82

Table 4: Simulated Result of deformation and stress.

Load (N)	**Structural Steel**		**Epoxy/E-Glass**		**Epoxy/Carbon**		**Epoxy/Bamboo**	
	δ (mm)	σ(MPa)	δ (mm)	σ(MPa)	δ (mm)	σ(MPa)	δ (mm)	σ(MPa)
5150	35.708	129.39	7.32	96.18	3.45	108.06	15.305	110.04
6695	40.798	168.21	9.52	125.04	4.49	140.48	20.78	148.96
7203	51.014	180.97	10.24	134.53	4.83	151.14	21.40	153.9
8703	61.216	218.60	12.38	162.55	5.83	182.01	25,90	185.95
9363	68.363	235.34	13.32	174.87	6.27	190.46	27.82	200.06
12172	91.836	305.82	17.31	227.34	8.16	255.4	36.17	260.08

The value of deformation and stress increases with the increase in the load. For structural steel the maximum stress is 305.82MPa at 12172N load which is close to the material yield strength. This means steel can withstand this load without failure but the high deformation of 91.83mm reduces the comfort. The deformation in Epoxy/E-Glass is very low around 17.31mm at 12172N that indicates the higher stiffness. The stress generated is also low that indicates Epoxy/E-Glass performs better in handling with minimum bending. For this analysis, this material has shown better balance between strength and flexibility. Among selected all the materials Epoxy/Carbon has the lower deformation of 8.16mm at 12172N which indicates that it has highest stiffness. Stress value for Epoxy/Carbon is slightly higher than that of Epoxy/E-Glass but within the safest limit. Carbon/Epoxy is the best material in terms of strength-to-weight-ratio, making the most lightweight option. The Epoxy/Bamboo shows much higher deformation that other two composite materials that indicating the lower stiffness. But the stress value at 36.17mm deformation is similar to the carbon whereas this deformation is around 4-5 times greater. This shows that the bamboo composite material is not ideal for high load application.

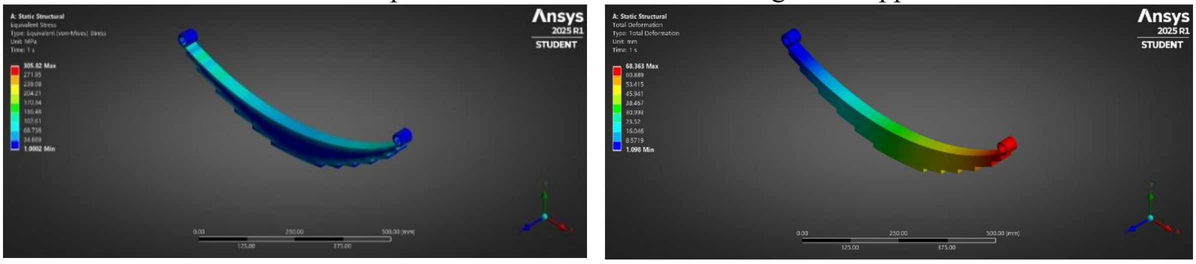

Fig. 3 Contour plot of von-mises stress and deformation at 12172N static load for Structural Steel.

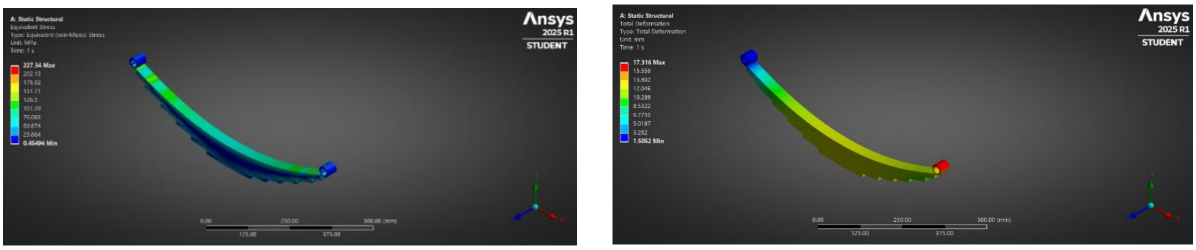

Fig. 4 Contour plot of von-mises\stress and deformation at 12172N static load for Epoxy/E-Glass.

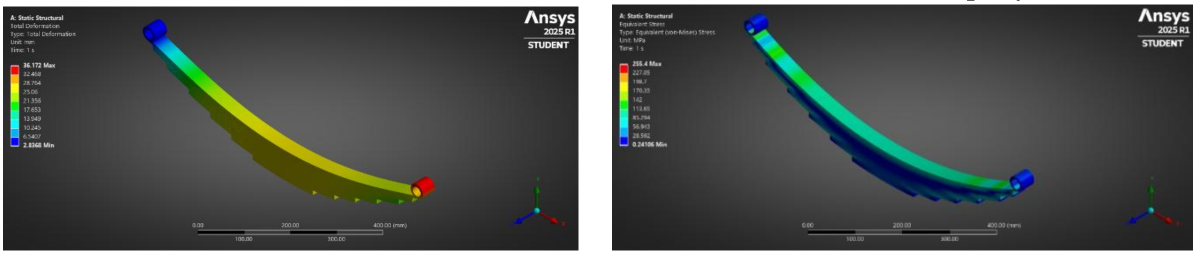

Fig. 5 Contour plot of von-mises stress and deformation at 12172N static load for Epoxy/Carbon.

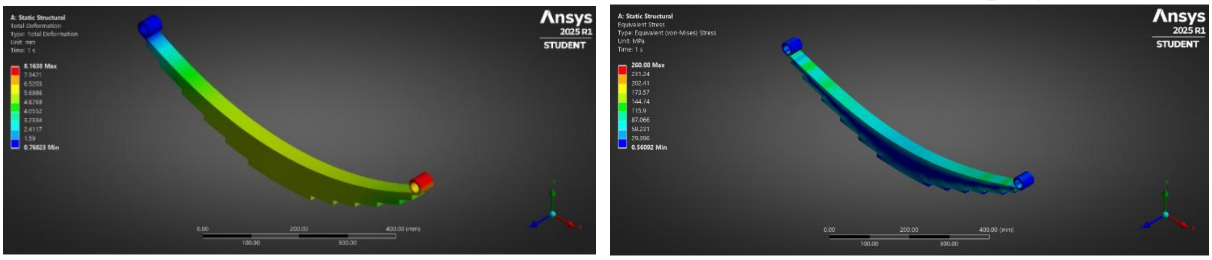

Fig. 6 Contour plot of von-mises stress and deformation at 12172N static load for Epoxy/Bamboo

5.2 Modal Analysis and Harmonic Response Analysis

We have carried out modal analysis for 15 modes but the data sets are only taken for bending condition since there doesn't occurs others effect in leaf spring like torsion. The data sets are first taken for the structural steel and the for the tree different types of the composite material. The solution for the mode shape and natural frequencies from the modal analysis is dragged to the harmonic response analysis domain in ANSYS. By the help of frequency vs amplitude plot, we have analyzed how the displacement varies with increasing the frequency taken at minimum frequency of 10HZ and maximum frequency of 1500HZ at difference of 10HZ.

Table 5: Modal analysis result for the different materials.

Mode	Materials							
	Structural Steel		Epoxy/E-Glass		Epoxy/Carbon		Epoxy/Bamboo	
	Hz	mm	Hz	mm	Hz	mm	Hz	mm
1	120.62	11.83	392.67	40.59	77.78	12.25	55.07	11.68
2	626.88	19.72	869.98	127.24	182.05	13.89	147.87	18.707
3	1218.40	34.15	1167.70	167.25	448.21	33.63	361.67	14.63

Based on the mode shapes that we have obtained from the modal analysis, we can see that Epoxy/E-Glass has highest natural frequency across all the nodes that indicates the highest stiffness. According to ISO 2631, higher stiffer leads to harsh ride experience. We can see from the above table 6.1.2.1 that the structural steel exhibits moderate natural frequencies whereas the other two material have lower frequencies. Bamboo composite have lower frequencies than other materials which means that it can absorb more shocks than other material with the better riding comfort. Based on the deformation pattern, Epoxy/E glass composite have highest deformation across all the modes that indicates for the flexibility. According to the ISO 2631, E glass also can absorb the better vibrations as we have seen from above table that it has highest deformation which means it is more flexible like as structural steel has lower deformation which indicates the less comfortable ride. Carbon composite have moderate natural frequencies than other that balances between the handling properties and comfort. The carbon composite materials have balance between stiffness and vibration absorption capacity whereas the structural steel provides less vibration absorption which is defined by the higher deformation.

Epoxy/E-Glass has the highest natural frequency ensuring the excellent handling but a stiffer ride whereas the Epoxy/Bamboo has lowest natural frequency that offers better shock absorption and comfort. The composite material Epoxy/Carbon has well balance between the stiffness and vibration absorption. The factor of safety is highest for Epoxy/E-Glass around 3.52 which is followed by Epoxy/Carbon around 2.35. 1.47 and 1.15 are the factor of safety for structural steel and Epoxy/Bamboo respectively.

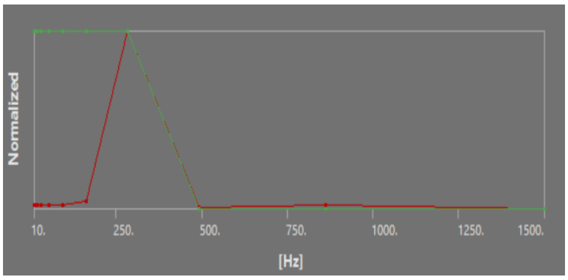

Fig. 7 Frequency plot of dynamic load for Structural Steel

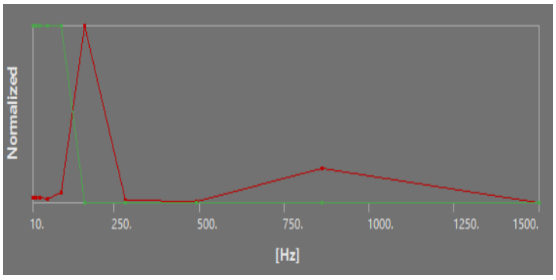

Fig. 8 Frequency plot of dynamic load for Epoxy/E-Glass

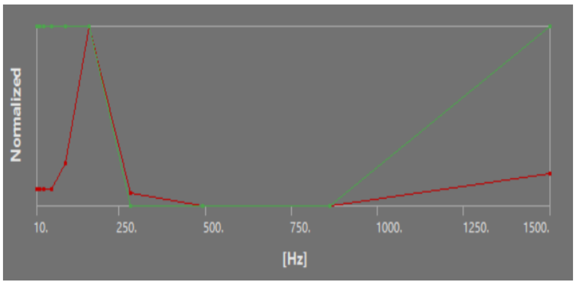

Fig. 9 Frequency plot of dynamic load for Epoxy/Carbon

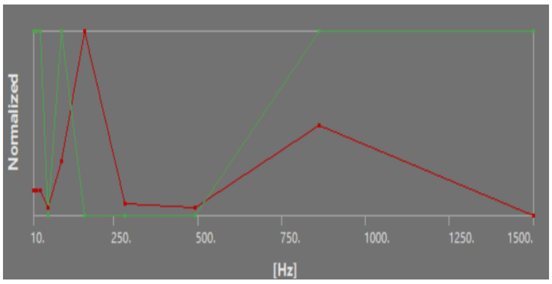

Fig. 10 Frequency plot of dynamic load for Epoxy/Bamboo

To carry out the initial costing of leaf spring material we have first calculated the total weight of the 13-span leaf spring using the relation given below. The weight of leaf spring for structural steel and the composite material in only master leaf is tabulated below.

$$Mass = Volume \times Density = Length \times Width \times Thickness \times Density \tag{3}$$

Table 6: Summary of weight calculation

Material	Weight (kg) 13 span	Percentage Reduced (%)
Structural Steel	14.3	←--→
Epoxy/E-Glass	10.96	23.35
Epoxy/Carbon	10.87	23.98
Epoxy/Bamboo	10.81	24.40

From the above table we can see that by using the composite material in the master leaf, the overall weight of the leaf is decreased by around 25% in every material. By using glass composite in master leaf we have seen that 23.35% of weight reduction is seen while using the carbon we have seen around 23.98% of weight reduction and the bamboo composite reduces overall weight of leaf spring to 10.81kg which is 24.40% below as compared with structural steel whose weight is 14.3kg.

6. LIMITATION

The limitation for this study is given in the following points:

- The perfect bonding between leaf layers is not possible.
- Manufacturing defects, environmental effects were not considered.
- The model does not include nonlinear material behavior and UDL load is not considered.

7. CONCLUSION

The result from various finite element analysis suggest that the composite material leaf spring that is made-up of from Epoxy/Carbon provides a best alternative to the structural steel. This material leaf spring offers improved performance and reliability. Thus the future researches should explore the hybrid composite material for leaf spring to optimize the overall outcome and cost. The weight of Epoxy/E-Glass UD, Epoxy/Carbon UD Epoxy/Bamboo UD composite material are found to be approximately 23%, 23% and 26% lower than the structural steel material respectively.

i. The use of Epoxy/Carbon UD can provide the best handling due to high stiffness as its overall natural frequency higher than other materials.
ii. Among the comparison of the result from the finite element analysis, the Epoxy/Carbon have high fatigue resistance that can improve the durability of leaf spring.
iii. The factor of safety values from the result of harmonic analysis is greater for composite materials as compared with the structural steel that reduces the risk of the mechanical failure.
iv. Comparing all the material for vibration absorption, we have seen that the Epoxy/E Glass and Epoxy/Bamboo can absorb more vibrations than other material. So, using this material can enhance the ride comfort.
v. The harmonic response analysis that we have carried out shows that Epoxy/Carbon has least vibration amplitude that makes it ideal for stability.
vi. The higher natural frequencies and lower value of stress for composite material improves durability and reduce the risk of mechanical failure.

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