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Design, Simulation, and Prototyping of Single Composite Leaf Spring for Light Weight Vehicle

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Abstract - Reducing weight while increasing or maintaining strength of products is getting to be highly important research issue in this modern world. Composite materials are one of the material families which are attracting researchers and being solutions of such issue. In this project reducing weight of vehicles and increasing or maintaining the strength of their spare parts is considered. As leaf spring contributes considerable amount of weight to the vehicle and needs to be strong enough, a single E-glass/Epoxy leaf spring is designed and simulated following the design rules of the composite materials considering static loading only. The constant cross section design of leaf springs is employed to take advantages of ease of design analysis and its manufacturing process. And it is shown that the resulting design and simulation stresses are much below the strength properties of the material, satisfying the maximum stress failure criterion. The designed composite leaf spring has also achieved its acceptable fatigue life. This particular design is made specifically for light weight three wheeler vehicles. Its prototype is also produced using hand lay-up method.

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I. Introduction

a) Motivation on composite leaf spring

It is known that the failure nature of steel leaf springs is usually catastrophic. It is very important to reduce accidents and to replace steel leaf springs by gradually failing FRP (fibre reinforced polymer) composite material. Another point is to reduce weight of the vehicle while required strength is maintained, which is possible by FRP composite materials.

b) Objective

i. General Objective

This project has a general objective of designing, simulating, and prototyping of a single leaf spring for light weight, three wheeler vehicles, from composite material.

ii. Specific Objectives

- Selecting proper composite material,
- Design analysis and model simulation,
- Prototype manufacturing.

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c) Scope and limitation of the project

This project covers the design, simulation and prototyping of the single E-glass/Epoxy composite leaf spring for a light weight three wheeler vehicle. But the design is limited to the static loading only.

II. Literature Review

A composite material is the combination of two or more materials that produce a synergistic effect so that the combination produces aggregate properties that are different from any of those of its constituents attain independently. This is intentionally being done today to get different design, manufacturing as well as service advantages of products. Up on those products leaf spring is the focus of this project for which researches are running to get the best composite material, which meets the current requirement of strength and weight reduction in one, to replace the existing steel leaf spring. Here researches on this area are well reviewed showing the back ground of this project, as follows.

a) Basics of composite materials and their application on leaf springs

To meet the need of natural resources conservation, automobile manufacturers are attempting to reduce the weight of vehicles in recent years. The interest in reducing the weight of automobile parts has necessitated the use of better material, design, and manufacturing processes. The suspension leaf spring is one of the potential elements for weight reduction in automobiles as it leads to the reduction of un-sprung weight of automobile. The elements whose weight is not transmitted to the suspension spring are called the un-sprung elements of the automobile. This includes wheel assembly, axles, and part of the weight of suspension spring and shock absorbers. The leaf spring accounts for 10-20% 0f the un-sprung weight. The reduction of un-sprung weight helps in achieving improved ride characteristics and increased fuel efficiency. The cost of materials constitutes nearly 60-70% 0f the vehicle's cost and contributes to the better quality and performance of the vehicle.

The introduction of fibre reinforced plastics (FRP) made it possible to reduce the weight of machine element without any reduction of the load carrying capacity. Because of FRP material's high elastic strain energy storage capacity and high strength-to-weight ratio compared with those of steel, multi-leaf 33steel springs are being replaced by mono-leaf FRP springs. FRP springs also have excellent fatigue resistance and durability. But the weight reduction of the leaf spring is achieved not only by material replacement but also by design optimization [6].

Weight reduction has been the main focus of automobile manufacturers in the present scenario. The leaf spring suspension accounts for about 10-20% of vehicle un-sprung weight. Thus it becomes a potential unit for weight reduction. The weight reduction can be achieved by choosing better materials and optimized design etc. The replacement of steel with optimally designed composite leaf spring can provide 93% weight reduction. Moreover the composite leaf spring has lower stresses compared to steel spring. All these will result in fuel saving which will make countries energy independent because fuel saved is fuel produced [12]. Composite leaf springs in particular in light trucks deal with the cargo load, comfort, and safety aspects. Fibre reinforced epoxy coil springs have been known for years. Now a process for mass production has been developed. The era of electrically driven cars requires a change of thinking. It will be essential to reduce the weight of the vehicle. The question, "Battery **or** Passenger?" would be answered in a consumer-friendly manner, "Battery **and** Passenger". A significant amount of today's automotive composite applications are still parts which support the structure or are parts of the car body such as fenders, trunk lids, hoods. However the new generation of electrically driven cars require chassis and other load bearing structures made from CFRP (Carbon Fibre Reinforced Polymers). Epoxy carbon and glass composites have proven their outstanding mechanical, thermo-mechanical and fatigue resistance properties [18].

b) Approaches for design, analysis, modelling and simulation of a composite leaf spring

Based on the specific strain energy of steel spring and some composite materials, the E-glass/epoxy is selected as the spring material. Many attempts have been made to substitute more economic resins for the epoxy but all attempts to use polyester or vinyl ester resins have been unsuccessful to date. The stored elastic strain energy in a leaf spring varies directly with the square of maximum allowable stress and inversely with the modulus of elasticity both in the longitudinal and transverse directions according to:

$$S = \frac{1}{2}\frac{\sigma_t^2}{\rho E} \text{---------------}2.1$$

Where S is the strain energy, σ_t *is* the allowable stress, E is the modulus of elasticity and ρ is the density.

A life data analysis method is used. Two constants in their relation on the basis of experimental results are proposed. It is proved that the analytical formula predicts the fatigue life of component with E-glass/epoxy composite material, using Hwang and Han relation:

$$N = \{B(1-r)\}^{1/C} \text{-------------}2.2$$

Where, N is the number of cycles to failure; B = 10.33; C = 0.14012; $r = \frac{\sigma_{max}}{\sigma_u}$; σ_{max} is the maximum stress; σ_u is the ultimate tensile strength and r is the applied stress level.

Design and experimental fatigue analysis of composite multi leaf spring using glass fibre reinforced polymer are carried out using life data analysis, in this particular literature. Compared to steel spring, the composite leaf spring is found to have 67.35 % lesser stress, 64.95 % higher stiffness and 126.98 % higher natural frequency than that of existing steel leaf spring. The conventional multi leaf spring weighs about 13.5 kg whereas the E-glass/Epoxy multi leaf spring weighs only 4.3 kg. Thus the weight reduction of 68.15 % is achieved. Besides the reduction of weight, the fatigue life of composite leaf spring is predicted to be higher than that of steel leaf spring. Life data analysis is found to be a tool to predict the fatigue life of composite multi leaf spring. It is found that the life of composite leaf spring is much higher than that of steel leaf spring. The 3D FEM model of leaf spring is simulated using ANSYS [2].

Venkatesan and Devaraj [7] also used three-dimensional finite element method of analysis. They pointed that the leaf spring behaves like a simply supported beam and the flexural analysis is done considering it as a simply supported beam. The simply supported beam is subjected to both bending stress and transverse shear stress. Flexural rigidity is an important parameter in the leaf spring design and test out to increase from two ends to the centre. They tried to access three design approaches; i) constant thickness, varying width design, ii) constant width, varying thickness design and iii) constant cross-section design. Out of the above mentioned design concepts. The constant cross-section design method is selected due to the following reasons: due to its capability for mass production and accommodation of continuous reinforcement of fibres. Since the cross-section area is constant throughout the leaf spring, same quantity of reinforcement fibre and resin can be fed continuously during manufacturing. It is also quite suitable for filament winding process.

Shivashankar, Vijayarangan, and Pradeep [12] stated that taking the advantages of mass production and continuous fibre accommodation, composite leaf spring with constant cross sectional area is designed using Genetic Algorithm (GA) method. The weight of the composite leaf spring can be reduced by 53.5% by applying the GA optimization technique. Composite mono leaf spring reduces the weight by 85% for E-

Glass/Epoxy over conventional leaf spring. The reduction of 93%weight is achieved by replacing conventional steel spring with an optimally designed composite mono-leaf spring.

Here experimental and numerical methods of analysis are employed. The element SHELL 99, SOLID 46 is the best suited for modelling of composite material. SHELL 99 is an 8 – node, 3D shell element with six degree of freedom at each node. The advantage of SOLID 46 is that we can stack several elements to model more than 250 layers. Here selected element was SOLID 46.Static Analysis is performed and the procedure consists of, Build the Model and Defining Parameters. The parameters for building the composite leaf spring are; Young's modulus, (EXX) value, Poison ratio, Y(PRXY) value, Length of cantilever beam, Width of cantilever beam, and Height of cantilever beam. Experimental results from testing the leaf springs under static loading containing the stresses and deflection are calculated. These results are also compared with FEA. The weight of the leaf spring is reduced considerably about 85 % by replacing steel leaf spring with composite leaf spring. Thus, the objective of reducing the un-sprung mass is achieved to some extent. Also, the stresses in the composite leaf spring are much lower than that of the steel spring [13].

Krishan and Aggarwal [4] followed a finite element approach for design and stress-deflection analysis of a multi leaf spring using CAE tools (i.e CATIA, ANSYS). The found that when the leaf spring is fully loaded, a variation of 0.632 % in deflection is observed between the experimental and FEA result, and same in case of half load, which validates the model and analysis. On the other hand, bending stress in both the cases is also close to the experimental results. The maximum value of equivalent stresses is below the Yield Stress of the material that leads to safe design from failure.

c) Manufacturing process of composite leaf spring

In the present scenario the main focus of automobile manufacturers is weight reduction of the automobile. Weight reduction can be achieved mainly by introducing the better material, design optimization and better manufacturing processes. In automobiles, leaf spring is one of the potential parts for weight reduction as it accounts for 10% - 20% of the un-sprung weight. Composite materials have made it possible to reduce the weight of leaf spring without any reduction in load carrying capacity and stiffness. Composite materials are now used extensively in place of metal parts [1].

Jadhao.et.al discussed about the manufacturing system of leaf spring. Using plywood as a mould material, prototype was fabricated as per desired dimension. The constant cross section design, which ensures the fibre pass continuously without interruption along length direction, which is advantageous to fibre reinforced structure, was employed. The glass fibres were cut to desired length, so that they can be deposited on mould layer- by-layer during fabrication of composite leaf spring. Apply the wax/gel. Prepare the solution of resin & Place the first layer of glass fibre chopped mat on mould followed by epoxy resin solution over mat. Wait for 5-10 min. Repeat the procedure till the desired thickness was obtained. The duration of the process may take up to 25- 30 min. And finally remove the leaf spring from mould [13].

Fig. 2.1 : Leaf springs with constant cross section design.

The constant cross section design is selected due to its capability for mass production, and to accommodate continuous reinforcement of fibres and also it is quite suitable for hand lay-up technique. Many techniques can be suggested for the fabrication of composite leaf spring. Composite leaf spring was fabricated using wet filament winding technique. In the present work, the hand lay-up process was employed. The templates (mould die) were made from wood and plywood according to the desired profile obtained from the computer algorithm. The glass fibres were cut to the desired lengths, so that they can be deposited on the template layer by layer during fabrication. In the conventional hand lay-up technique, a releasing agent (gel/wax) was applied uniformly to the mould which had good surface finish. This is followed by the uniform application of epoxy resin over glass fibre. Another layer is layered and epoxy resin is applied and a roller was used to remove all the trapped air. This process continued till the required dimensions were obtained. Care must be taken during the individual lay-up of the layers to eliminate the fibre distortion, which could result in lowering the strength and rigidity of the spring as a whole. The duration of the process may take up to 30 min. The mould is allowed to cure about 4 – 5 days at room temperature. Mono composite leaf springs with and without eye ends was fabricated by using above said technique [5].

The amount of elastic energy that can be stored by a leaf spring varies directly with the square of maximum allowable stress and inversely with the modulus of elasticity both in the longitudinal direction. Composite materials like the E-Glass/Epoxy in the direction of fibres have good characteristics for storing strain energy. So, the lay-up is selected to be unidirectional along the longitudinal direction of the spring. The unidirectional lay-up may weaken the spring at the mechanical joint area and require strengthening the spring in this region [5].

III. Design Analysis Of Composite Leaf Spring

a) Specific Design Data

Here Weight and initial measurements of three wheeler "Model: BA200ZK" light vehicle are taken.

Weight of vehicle= 380 kg

Maximum load carrying capacity= 390 kg

Total weight= 380 + 390 = 770 kg;

Taking factor of safety (FS) = 2, acceleration due to gravity (g)= 10 m/s^2

There for; Total Weight (W') = 770*10*2 = 15400 N

Since the vehicle is 3-wheeler, a single leaf spring corresponding to one of the wheels takes up one third of the total weight.

$F = \frac{15400}{3}$ = 5140 N

From the material point of view a *unidirectional Glass/Epoxy* composite material is selected. It is selected due to its relative advantages stated in the literature review above, mainly high strength to weight ratio and high capacity of storing strain energy in the longitudinal direction of the fibres.

The properties of Glass/Epoxy composite material are given as follows [20].

E_1(modulus of elasticity along the longitudinal direction) = 54 GPa,

E_2(modulus of elasticity along the longitudinal direction)= 18 GPa,

G_{12}(shear modulus)= 9 GPa,

ν_{12}(major poison's ratio) = 0.25,

X_t= 1035 MPa, Y_t= 28 MPa, X_c= 1035 MPa, Y_c= 138 MPa,S= 41 MPa

Where,

$X_t$and $X_c$are longitudinal tensile and compressive strengths respectively,

Y_t and $Y_c$are transverse tensile and compressive strengths respectively, and

S is shear strength.

From Shiva and Vijayaranga [5] for E-glass/ Epoxy;

Maximum stress (σ_{max}) = 473 MPa

Maximum deflection(δ_{max}) = 105 mm

Measured data of the above statedlight weight three-wheelervehicle:

Straight length of the leaf spring (L) = 900 mm

Leaf span of load free curved leaf spring (L') = 880 mm

From ManasPatnaik, L.P. Koushik, and Manoj Mathew [19];

$\frac{C}{L'} = 0.089$; where C is the camber length and L' is the leaf span.

Thus C = 0.089*L' = 0.089*880 = 78 mm

b) Analysis

Since the leaf spring is fixed with the axle at its centre, only half of itis considered for analysis purpose;

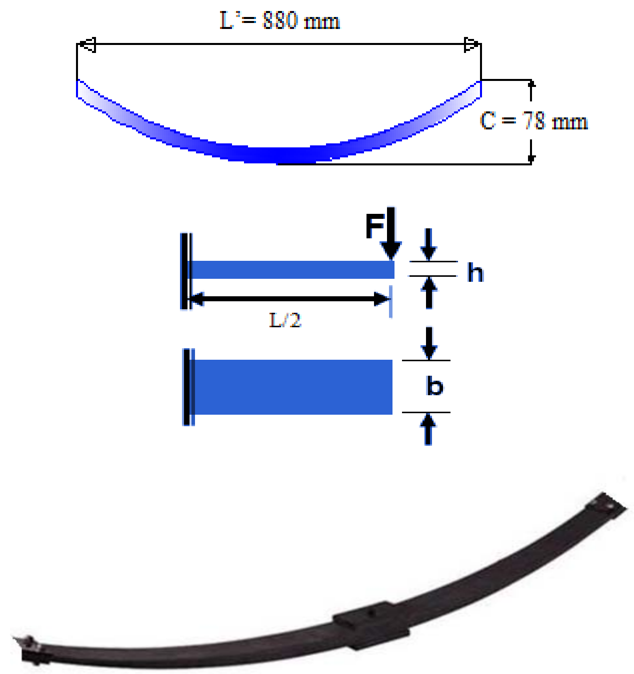


Fig. 3.1 : Important dimensions and free body diagram to analyse half of the leaf spring

Since analysing half of the leaf spring is enough, half of the applied force would have been taken. But here we took as it is to account over loadings of the vehicle and flexures of the leaf spring.

Hence, L/2 = 450 mm, F = 5140 N, h=? and b=?

Calculating for 'h' and 'b' dimensions which are capable of withstanding the loading behaviour of the composite (E-glass/ Epoxy) leaf spring is the result of this design.

From equations of strength of materials we have;

$$\sigma_{max} = \frac{6FL}{bh^2} \text{------------} 3.1$$

$$\delta_{max} = \frac{4FL^3}{Ebh^3} \text{-----------} 3.2$$

Solving equations 3.1 and 3.2 simultaneously for 'h' (thickness of the leaf spring);

$$h = \frac{\sigma_{max} L^2}{E\delta_{max}} \text{------------} 3.3$$

Since we consider half of the leaf spring we substitute 'L/2' instead of 'L' to calculate 'h' and 'b'. As the ends of the leaf spring are hinged, the entire leaf spring will only be loaded under tension. Therefore, we consider only the longitudinal properties. Equation 3.3 will be written as:

$$h = \frac{\sigma_{max}\ (L/2)^2}{E_1 \delta_{max}} = \frac{473*10^6*(450)^2*10^{-6}}{54*10^9*105*10^{-3}}$$

h = 17 mm

Rearranging equation 3.1 and solving for the width 'b';

$$b = \frac{6F(L/2)}{\sigma_{max}\ h^2} = \frac{6*5140*450*10^{-3}}{473*10^6*(17)^2*10^{-6}} = 102 \text{ mm}$$

Calculating the bending stress(σ_b);

$\sigma_b = \frac{M*y}{I}$-------------3.4;

Where 'M' is the bending moment, 'y' is the distance from the neutral axis= h/2 and 'I' is the moment of inertia.

M= F*L/2= 5140*0.450= 2313 Nm

$$I = \frac{bh^3}{12} = \frac{0.102*(0.017)^3}{12} = 4.18*10^{-8} m^4$$

y = 17/2= 8.5 mm

Therefore, $\sigma_b = \frac{2313*0.0085}{4.18*10^{-8}} = 470.35$ MPa

Since we use unidirectional orientation of fibres and pure tensile loading nature of the leaf spring is considered, we took plane stress condition as the leaf is thin plate. Thus the bending stress, completely, is responsible to the longitudinal stress; $\sigma_1 = \sigma_b$.

$$\sigma_1 = 470.35\ MPa$$

Stress along the transverse direction will be;

$$\sigma_2 = \frac{F}{b*\left(\frac{L}{2}\right)} = \frac{5140}{102*450*10^{-6}} = 0.112 \text{ MPa}$$

The shear stress will also be calculated as follows;

$$\tau_{12} = \frac{F}{A_S} = \frac{5140}{17*102*10^{-6}} = 3 \text{ MPa}$$

Now we need to calculate the strains to cross check with the simulation results of the product model of the leaf spring.

$$\begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \gamma_{12} \end{Bmatrix} = \begin{bmatrix} S_{11} & S_{12} & 0 \\ S_{12} & S_{22} & 0 \\ 0 & 0 & S_{66} \end{bmatrix} \begin{Bmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{Bmatrix} \text{----------------3.5}$$

Where ε_{ij} = strain matrix, S_{ij} = compliance matrix and σ^{ij} = stress matrix

$S_{11} = \frac{1}{E_1} = \frac{1}{54\ GPa} = 18.5*10^{-12}\ Pa^{-1}$; $S_{22} = \frac{1}{E_2} = \frac{1}{18 GPa} = 55.6*10^{-12}\ Pa^{-1}$

$S_{12} = \frac{-\gamma_{12}}{E_1} = \frac{-0.25}{54 GPa} = -4.63*10^{-12}\ Pa^{-1}$; $S_{66} = \frac{1}{G_{12}} = \frac{1}{9GPa} = 111.1*10^{-12}\ Pa^{-1}$

Substituting the values of compliance and stress matrices' elements in to equation 3.5;

$$\begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \gamma_{12} \end{Bmatrix} = \begin{bmatrix} 18.50*10^{-12} & -4.63*10^{-12} & 0 \\ -4.63*10^{-12} & 55.6*10^{-12} & 0 \\ 0 & 0 & 111.1*10^{-12} \end{bmatrix} \begin{Bmatrix} 470.35*10^6 \\ 0.112*10^6 \\ 3*10^6 \end{Bmatrix}$$

$\varepsilon_1 = 8.7*10^{-3}$; $\varepsilon_2 = 2.17*10^{-3}$; $\gamma_{12} = 3.333*10^{-4}$

We can calculate the fatigue life, number of cycles to fail, of the composite leaf spring using equation 2.2 [2].

$$N = \{B(1-r)\}^{1/c};$$

$r = \frac{473\ MPa}{1035\ MPa} = 0.457$; then

$$N = \{10.33(1-0.457)\}^{1/0.14012} = 221.16*10^3 \text{ cycles.}$$

c) Modelling and simulation of composite leaf spring

A single E-glass/ Epoxy leaf spring is modelled and simulated using Abaqus/ CAE 6.10 and the stresses, strains and displacements are obtained as follows.

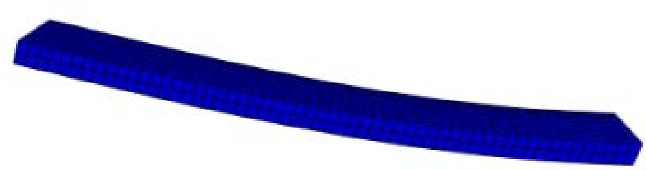


Fig. 4.1 : CAE solid model of single E-glass/Epoxy leaf spring

As the simulation with 8565 nodes and an element type of C3D20R is well done, the following results are observed.

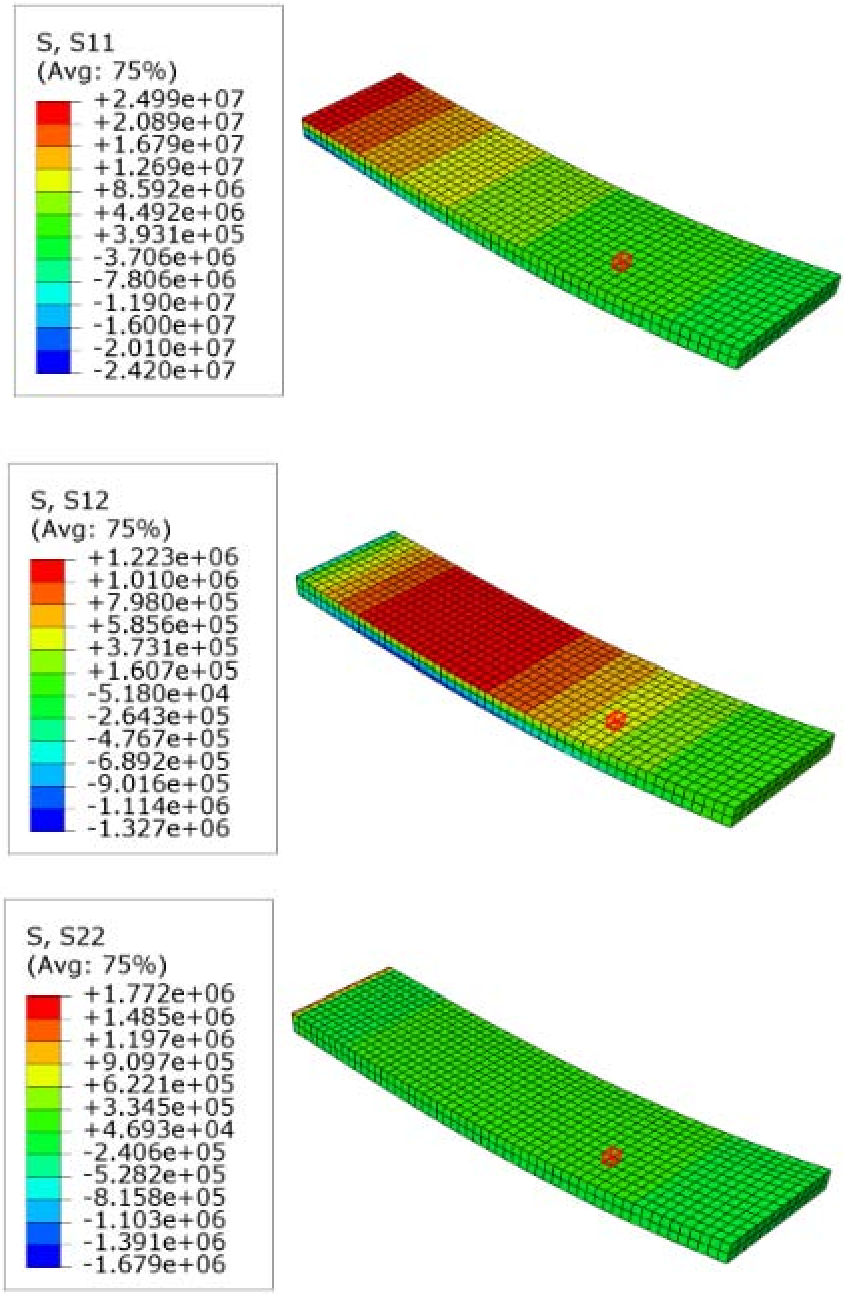
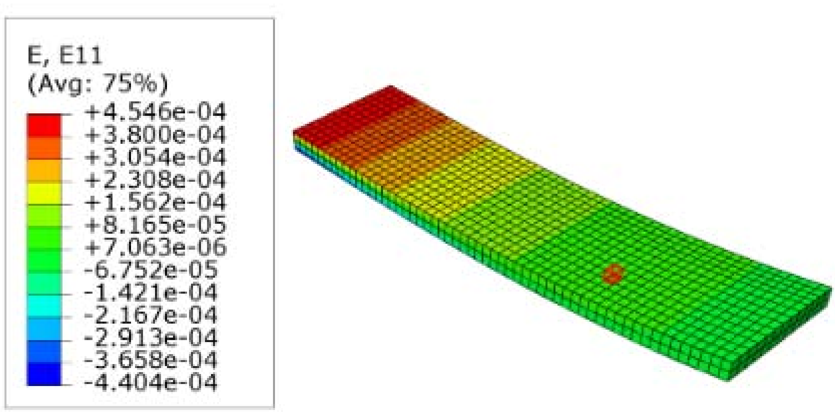


Fig. 4.2 : Simulation results of longitudinal, shear and transverse stresses



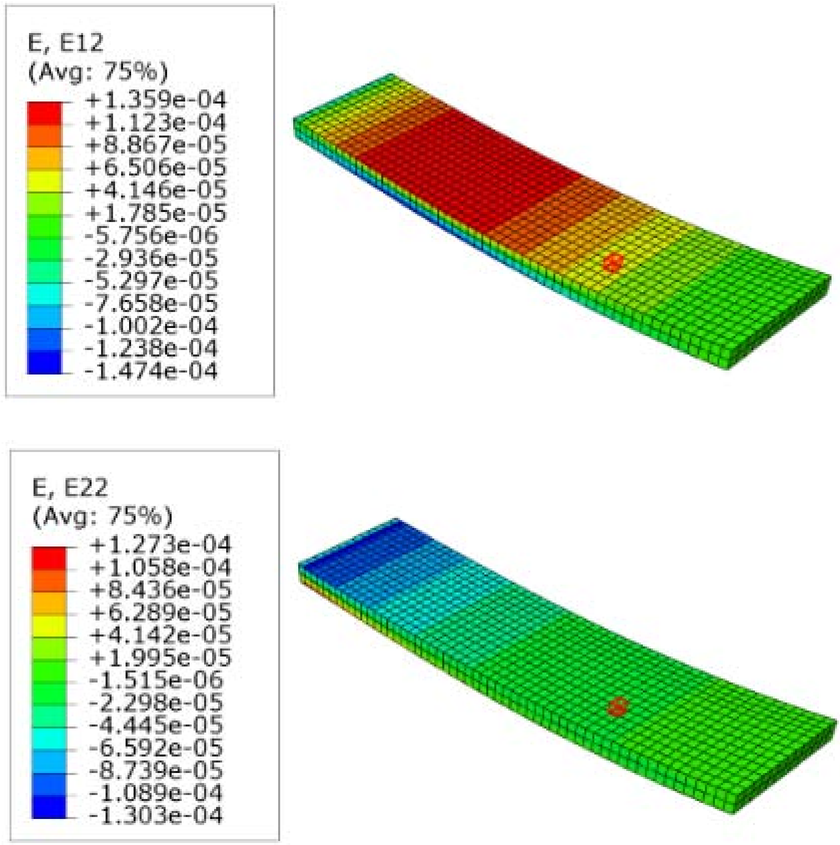


Fig. 4.3 : Simulation results of longitudinal, shear and transverse strains

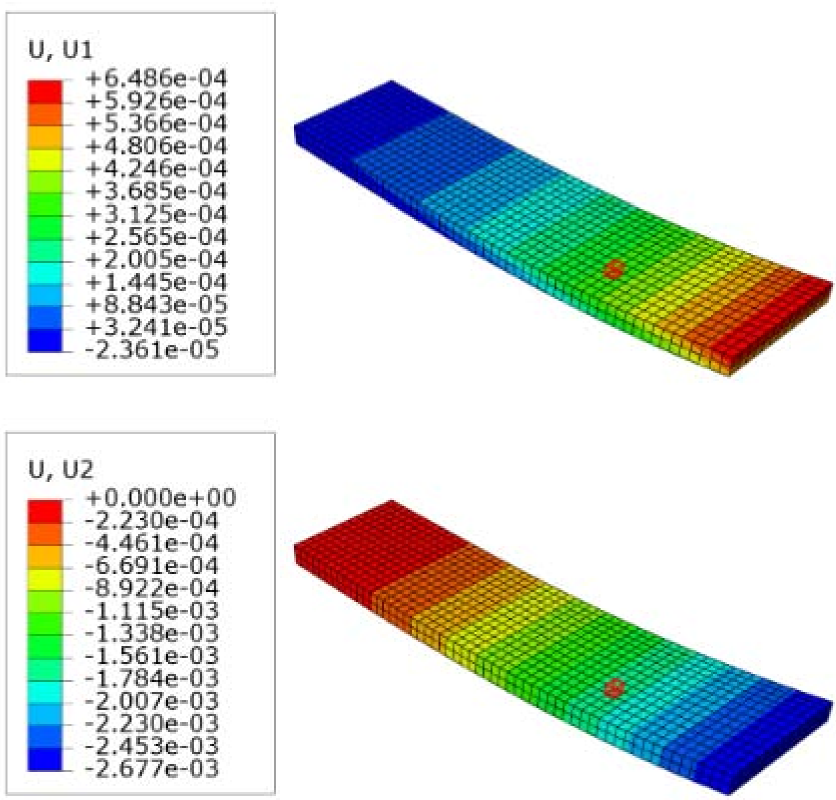


Fig. 4.4 : Simulation results of longitudinal and transverse displacements

IV. Prototype Manufacturing

We used a hand-lay-up method to produce the prototype of a single composite leaf spring. The constant cross section design is used which accommodate continuous reinforcement of fibres and quite suitable for hand lay-up technique. 40 layers of E-glass fibre of 0.4 mm thick each are used to achieve 17 mm thickness of the designed leaf spring.

The steps below are followed during prototyping:

- Preparing moulds as per the shape of the leaf spring and the setup.
- Preparing stiffener and clamping plates.
- Cutting fibres to desired dimensions.
- Applying wax/gel on the fibre side of the lower mould for ease of removal.
- Preparing mixture of epoxy resin and polyamine hardener.
- Apply the mixture just above the wax.
- Start laying up the first ply and apply the matrix on it again, repeat the same procedure up to the desired thickness.
- Apply the matrix well on the topmost layer and Cover the upper mould after the wax film is done on its fibre side.
- Put the stiffener on the covered mould and clamp tightly using the plates and c-clamps.
- Allow the composite leaf spring to cure enough at room temperature.
- Remove it from the set up and trim the excess material.

Fig. 5.1 : E-glass/ Epoxy composite leaf spring curing on the mould set up.

Fig. 5.2 : Untrimmed E-glass/ Epoxy composite leaf spring prototype

Fig. 5.3 : Trimmed final prototype of E-glass/Epoxy composite leaf spring

V. Results And Discussions

Since the shear stress (τ_{12}= 3 MPa) multiplied by a factor of ‘9’ (9*3 = 27 MPa) is much less than the shear strength (S=41 MPa) of the specified composite material, E-glass/Epoxy. Specifying the criteria (9*τ_{12}< S), design is safe even for the flexural failure.

Using maximum stress failure criterion [20], the design and simulation results are evaluated as follows.

Table 6.1 : Comparison of the strength properties with the design and simulation results

Strength properties and design and simulation results of E-glass/Epoxy single composite leaf spring					
Strength properties	Design stresses	Design strains	Simulation stresses	Simulation strains	Simulation displacements(mm)
X_t=1035MPa	$\sigma_1 = 470.35\ MPa$	ε_1 = 8.7*10^{-3}	S_{11}= 25MPa	E_{11}= 4.5*10^{-4}	U_1= 0.65
Y_t= 28 MPa	σ_2=0.112 MPa	ε_2 = 2.17*10^{-3}	S_{22}= 1.8MPa	E_{22}= 1.3*10^{-4}	U_2= -2.68
S= 41 MPa	τ_{12} = 3 MPa	γ_{12}=3.333*10^{-4}	S_{12}= 1.3MPa	E_{12}= 1.5*10^{-4}	

When we compare the values, tabulated in Table 6.1 above, both the design and simulation stress values are much less than that of strength properties of the material. Therefore the maximum stress failure criterion is satisfied, hence safe design of the product. It can also be observed that the simulation strains are less in order of one tenth than that of design strains. The nodal displacementU_2(-2.68 mm) corresponds to the deflection of the leaf spring along its transverse direction, which is very small compared to the considered maximum deflection δ_{max} (105 mm) and the camber C (78 mm).

The fatigue life of the designed single E-glass/ Epoxy composite leaf spring is predicted and obtained as N= 221.16*10^3 cycles. This shows the acceptable life or good resistance of the material to failure under fatigue loading.

VI. Conclusion And Recommendation

As reducing weight and increasing strength of products are high research demands in the world, composite materials are getting to be up to the mark of satisfying these demands. In this project reducing weight of vehicles and increasing the strength of their spare parts is considered. As leaf spring contributes considerable amount of weight to the vehicle and needs to be strong enough, a single E-glass/Epoxy leaf spring is designed and simulated following the design rules of the composite materials. And it is shown that the resulting design and simulation stresses are much below the strength properties of the material satisfying the maximum stress failure criterion. It has achieved an acceptable fatigue life of 221.16*10^3 cycles. This particular design is made specifically for light weight three wheeler vehicles. Its prototype is also produced using hand lay-up method. It is recommended that any interested researcher has to go through this project and do the dynamic analysis of the design, since only the static loading case is considered here.

Acknowledgement

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