Optimization Design of Composite Material Using Genetic Algorithm for Automobile Leaf Spring

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Abstract: In all automobile components, leaf spring is one of the important and heavy component which ensures the comfortable suspension system in the vehicle. Therefore better leaf spring leads to more comfort. This paper is based on replacing conventional leaf spring with parabolic leaf spring of composite material. This paper describes design of composite material. The main objective of this work is to obtain composite material properties to have high strain energy and low weight. The composite material used are kevlar fiber, glass fiber and epoxy matrix. These three composite material is based on application, cost, availability, environmental cause and many other factors which can lead to increase in overall cost of the material. In order to obtain composite material properties, volume fraction of each fiber and matrix is required which is obtained using single objective optimization technique, multi-objective optimization technique and multi-criteria decision making. Genetic Algorithm is used as an optimization technique and TOPSIS method is used for multi-criteria decision making.

Keyword: Optimization, Genetic Algorithm, Multi-criteria decision making.

1. Introduction

Conventionally the material used for leaf spring is EN45 which is a medium carbon steel. This steel has high density value around 7870 kg/m^3 which lead to have high weight in leaf spring. Also it's Young's modulus value is high which cause low strain energy absorption. In order to overcome these problem composite material is used which have low density, low Young's modulus value and high strength. There are many fibers and matrices (i.e. glass fiber, kevlar fiber, ceramic fibers, polymer matrix and metal matrix, etc.) which can be used to obtain the composite material.

In order to find the suitable fiber and matrix for composite material strain energy per unit volume relation is used.

$$S = \frac{1}{2}\frac{\sigma^2}{E} \tag{1}$$

From above strain energy relation it can be observe that the strain energy is inversely proportional to Young's modulus, E. That means fibers and matrices which has less Young's modulus value can give rise to increase in strain energy. Also strain energy is directly proportional to stress, i.e. fibers and matrices with more yield stress value will give rise to increase in strain energy.

2. Fiber and Matrix for Composite Material

There are many fiber and matrix exists. Based on cost, availability, environmental cause, microscopic structure behaviour and the Young's modulus value, it have been identified that kevlar fiber, glass fiber and epoxy matrix is suitable for composite material. The following table gives the details of mechanical properties of EN45 steel, fibers and matrix.

Table 1. Mechanical properties of fibers and matrix

	Density (kg/m^3)	**Tensile Modulus, E (GPa)**	**Poisson's ratio**	**Shear Modulus, G (GPa)**	**Tensile Strength, σ (MPa)**	**Cost Rs./kg**
Epoxy	1540	3.5	0.33	1.25	60	576
Glass Fiber	2450	71	0.22	30	3500	51
Kevlar Fiber	1450	154	0.35	2.9	3620	324
EN45 Steel	7870	210	0.29	80	310	38

3. Design of Composite Material

According to assumptions in theory of laminated beam in pure flexure, each ply is linearly elastic with no shear coupling (i.e., ply orientation are either 0^o or 90^o). In our case ply angle is considered as 0^o, since it has good stress distribution along the longitudinal direction.

Also by stacking same ply one over another the composite material is made. In this way the final composite material obtained will be an orthotropic composite material.

Also while bending of beam the individual ply made of fibers and matrix will have same strain which satisfy the iso-strain condition (i.e. voigt model).

The maximum strain offered by kevlar fiber, glass fiber and epoxy matrix is 0.024, 0.028 and 0.018 respectively. The minimum strain among fibers and matrix is 0.018 for epoxy matrix. Therefore the maximum strain allowed in the composite material should not exceed 0.018.

Also to have high strain energy in the composite material the material should have more strain. Therefore in our case maximum strain will be equal to the breaking elongation of the epoxy matrix (i.e. 0.018).

Also, according to fiber packing fraction theory the maximum volume fraction achievable for fiber in simple cubic packing is 0.786. But in real practice the maximum volume fraction that can be achieved is around 0.60.

3.1 Weight density optimization problem

An objective function is derived for minimizing weight density using newton's first law, hook's law, voigt model and maximum strain energy theory as shown below.

$$\text{Min. weight density, } \mathrm{w} = \frac{40}{9}\,\frac{(\sigma_{YG}V_G+\sigma_{YK}V_K+\sigma_{YM}V_M)^2\times(\rho_G V_G+\rho_K V_K+\rho_M V_M)}{(E_G V_G+E_K V_K+E_M V_M)^2\times\varepsilon^2} \quad (2)$$

$$\mathrm{w} = \frac{40}{9}\,\frac{(3500V_G+3620V_K+60V_M)^2\times(2.45V_G+1.45V_K+1.54V_M)}{1000000\times(71000V_G+154000V_K+3500V_M)^2\times\varepsilon^2}$$

Subjected to constraints:

$$\varepsilon_{max} = 0.018$$

$$V_G + V_K + V_M = 1$$

$$V_G + V_K \leq 0.6$$

The above optimization problem is solved using Genetic Algorithm by using MATLAB optimization toolbox. It has been observed that the optimum value of V_G, V_K and V_M is 0, 0 and 0.999 respectively for minimum weight density objective function by satisfying all constraint. This is because minimum weight density is obtained when volume fraction of fibers and matrix will be zero. But in constraints only fibers volume fraction is allowed to have less than 0.60 and total volume fraction should be 1. Therefore we are getting V_G and V_K as 0 and V_M as 0.999. Hence, the objective function in above optimization problem is validated.

3.2 Strain energy density optimization problem

An objective function is derived for maximizing strain energy density using voigt model and strain energy relation.

$$\text{Max. Strain energy density, } \mathrm{s} = \frac{1}{2}\,\frac{(\sigma_{YG}V_G+\sigma_{YK}V_K+\sigma_{YM}V_M)^2}{(E_G V_G+E_K V_K+E_M V_M)} \quad (3)$$

Converting maximization problem into minimization by putting negative sign in objective function so that it can be solved using MATLAB.

$$\text{Min. Strain energy density, } \mathrm{s} = -\frac{1}{2}\,\frac{(3500V_G+3620V_K+60V_M)^2}{(71000V_G+154000V_K+3500V_M)}$$

Subjected to constraints:

$$V_G + V_K + V_M = 1$$

$$V_G + V_K \leq 0.6$$

The above optimization problem is solved using Genetic Algorithm by using MATLAB optimization toolbox. It has been observed that the optimum value of V_G, V_K and V_M is 0.6, 0.001 and 0.398 respectively for minimum strain energy density objective function by satisfying all constraint. This is because strain energy is inversely proportional to the Young's modulus as shown in Eq. (1). In both fibers glass fiber have less Young's modulus value. Having high volume fraction of glass fiber compare to kevlar fiber give rise to minimum strain energy density value. Hence, the objective function in above optimization problem is validated.

3.3 Multi-objective Optimization

In this present work our objective is to decrease weight and to increase strain energy in the composite material. In such case we need a solution at which both objectives will partially satisfied. Therefore, multi-objective optimization problem is defined by combining both Eq. (2) and Eq. (3).

$$\text{Min. weight density, } \mathrm{W} = \frac{40}{9}\,\frac{(\sigma_{YG}V_G+\sigma_{YK}V_K+\sigma_{YM}V_M)^2\times(\rho_G V_G+\rho_K V_K+\rho_M V_M)}{(E_G V_G+E_K V_K+E_M V_M)^2\times\varepsilon^2}$$

and

$$\text{Max. Strain energy density, } \mathrm{S} = \frac{1}{2} * \frac{(\sigma_{YG}V_G+\sigma_{YK}V_K+\sigma_{YM}V_M)^2}{(E_G V_G+E_K V_K+E_M V_M)}$$

Subjected to constraints:

$$\varepsilon_{max} = 0.018$$

$$V_G + V_K + V_M = 1$$

$$V_G + V_K \leq 0.6$$

The Multi-objective optimization problem is solved using Genetic Algorithm by using MATLAB Optimization Toolbox. The solver used for solving multi-objective optimization is "*gamultiobj*". To have converged solutions for the optimization problem input parameters are given to the optimization tool and Pareto front is obtained.

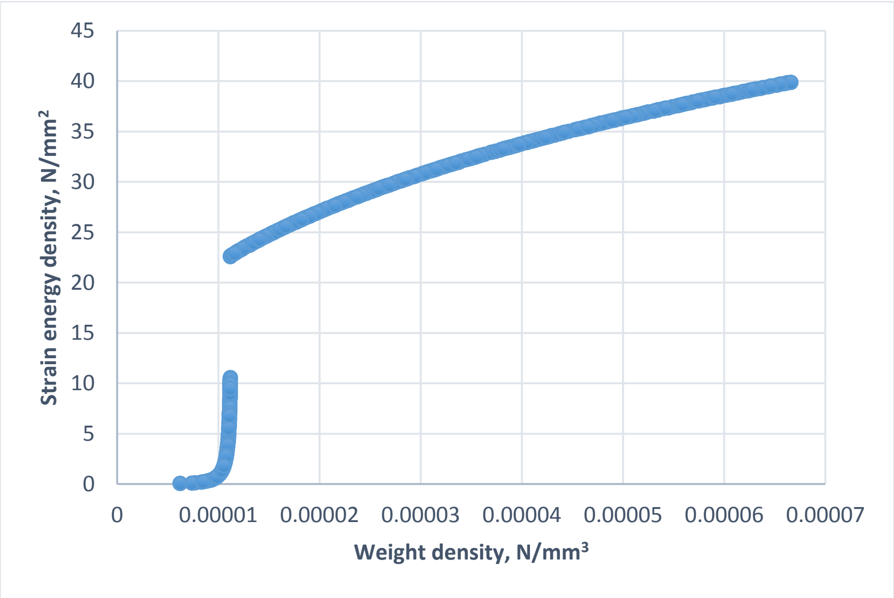

Fig 3. Pareto front for multi-objective optimization problem

3.4 Multi-Criteria Decision Making

There are 540 non-dominated Pareto solution which is obtained by using multi-objective Genetic Algorithm and all are equally acceptable. To find the best among them we are using a multi-criteria decision making technique called TOPSIS method. The principle concept is that the best alternative should have shortest distance (i.e. Euclidean distance) from the ideal solution.

Therefore, volume fraction of fibers and matrix is obtained using TOPSIS method is shown in below table.

Table 4. Fibers and matrix volume fraction

Name	Value	Units
Glass fibre volume fraction, V_G	11	%
Kevlar fibre volume fraction, V_K	49	%
Epoxy matrix volume fraction, V_M	40	%
Weight Density function, w	1.44×10^{-5}	N/mm^3
Strain Energy Density, s	24.4803	N/mm^2
Performance Score	0.74654	

4. Mechanical properties of KGFRP

The obtained volume fraction of fibers and matrix using TOPSIS method is now used to determine the mechanical properties of composite material which is named as Kevlar-glass fiber reinforced polymer matrix (KGFRP).

The mechanical properties are obtained by using halpin-tsai equations and voigt model. These properties are shown in below table.

Table 5. Mechanical properties of KGFRP

Property	Value	Units
Longitudinal Tensile Modulus, E_1	84.67	GPa
Transverse Tensile Modulus, E_2	16.06	GPa
Poisson's ratio, ν_{12}	0.3277	
Poisson's ratio, ν_{23}	0.2847	
Poisson's ratio, ν_{13}	0.3277	
Shear Modulus, G_{12}	2.6426	GPa
Shear Modulus, G_{23}	6.2484	GPa
Shear Modulus, G_{13}	2.6426	GPa
Yield Strength, σ_y	2182.8	MPa
Mass Density, ρ	1596	kg/m^3

5. Conclusion

The mechanical properties of KGFRP and EN45 steel are shown in Table 5 and Table 1. It can be observed that the density of the KGFRP is 1596 kg/mm^3 and density of EN45 steel is 7870 kg/mm^3, because of this huge difference the weight of any component made of KGFRP will be very less as compare to the component made with EN45 steel. Also, it can be observed that the Young's modulus value for KGFRP along X-direction is 84.67 GPa and Young's modulus of EN45 steel is 210 GPa which can leads to have high strain energy in the component made of KGFRP as compare to EN45 steel. Therefore, the objective of the present work is successfully achieved.

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