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Multi objective parametric optimization and composite material performance study for master leaf spring

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ABSTRACT

Design optimization of product with the objective of reducing weight is one of current focuses in a product design. In the vehicle industry, in particular, weight reduction has significant impact on vehicle efficiency improvement and the fuel economy. These improvements can have direct impact on operating costs of the vehicle. The methods used to weight reduction are by optimizing the products parameters and by replacing conventional materials with highly sustainable materials strengths. In this paper, design model of existing master leaf spring has been created and optimized using SolidWorks parametric optimization with a goal of reducing the weight of leaf spring, improving the life span of structure by reducing stress and increasing the natural frequency of the leaf spring. The constraint used was limiting stress and natural frequency with the leaf spring's thickness and width as optimization variables. Optimum values of these parameters of the leaf spring were obtained. Again, using parametrically optimized leaf spring model static and modal analysis was studied under two different composite materials, Epoxy Carbon UD Prepreg and Epoxy E-Glass UD, aiming to get minimum weight and improved life span compared to steel material (55SiMn90). The result shows that the leaf spring of composite materials performed better in terms of the stress level, stiffness and the natural frequency. At the same time, the weight of the composite leaf spring has significantly reduced. In summary, the study concluded that composite leaf spring is better efficient compared with conventional leaf spring from steel.

1. Introduction

In the current global interest to reduce dependence on fossil fuels, one of the methods employed is improving vehicle efficiency and fuel economy in the transportation sector. At the same time, reducing vehicle weight has direct impact on the vehicle efficiency, fuel economy, and can potentially reduce vehicle operating costs [1]. Among the vehicle parts, research shows that the suspension system accounts for 10% – 20% of the unsprung weight on which many modifications have been taken place over the time [2]. Ensuring optimum design of the suspension parts and the body of vehicle contributes to reduced weight, which has impact on fuel efficiency of the vehicle and improved riding qualities. Effective performance of the suspension system is directly related to the riding comfort and the vehicle safety. The leaf spring is the foremost important component of the suspension system, and its main function is both to support vertical load and to isolate vibrations caused by road roughness. The functionality of leaf spring is complicated because of its clamping effects, interleaf contact and other factors. The leaf spring contributes significant size to the vehicle weight, and it is designed to be strong enough to resist vibrations as well as jolts during while in service. An optimized design of leaf spring is required to balance the weight and stiffness of composite leaf spring. Usually leaf spring in vehicles is modelled as a simply supported beam and is loaded with both bending stress and transverse shear stress. Three design approaches are employed to design leaf springs: (i) constant thickness and varying width (ii) constant width and varying thickness and (iii) constant cross-section design [3]. The design constraints are limiting stresses and displacement. In addition to optimizing design parameters, other ways of reducing the vehicle weight without compromising safety include cost-effective design and using high-strength materials. The increasing interest of the automobile industry in replacing leaf springs of steel with composites is because composite materials have more capacity to store elastic strain energy and high specific strength com-

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pared with those of steel. By so doing, the weight can be reduced with no sacrifice of load carrying capacity and stiffness.

Composite materials have shown exceptional properties in diverse applications where high strength and high specific stiffness are required such as aircraft components, impact resistant and bullet-proof designs [4] and the automobile industry to replace the conventional materials used for the parts of vehicles. In some studies [5–7] design optimization of leaf spring is reported by replacing the conventional materials of leaf spring with composite, and the stress and deflection levels were compared with conventional materials aiming to obtain low von Misses stress and low deflection. In other studies [8–10] conducted study under identical statical loading conditions and observed large difference of deflections and stresses in leaf springs of steel and composite materials. The composite leaf spring deflected less compared to steel leaf spring and at the same time stresses are lower and stiffnesses and natural frequencies are higher. The weight of composite leaf spring was reduced in weight by 68.15% to 80% in same level of performance.

Previous studies of composites are limited to use of analytical methods such as the rule of mixtures and experimental methods. Recent works, on the other hand, use computational tools that can help to predict the mechanical behavior of composites at low cost. For instance, Bagha and Bahl [11] reported application of finite element methods (FEM) in analysis of vapor grown carbon fiber reinforced nanocomposites to predict its mechanical properties. Related works are also reported in [12] and [11] where cohesive layer concept and strain energy method, were employed to model and analyze fiber reinforced composites and nanocomposites respectively. While some of the studies are focused on predicting the strength and modulus of the composites [4], other works focused on study of the vibrational characteristics of composite materials [13] and the multi-objective optimization of the structural damping behavior.

As mentioned above, the vehicle efficiency depends on the weight of the vehicle parts and especially optimization of the suspension system contributes significantly. It is observed from the literature that replacing the existing steel materials with composite materials without any modification to the design parameters of leaf spring can have impact on the weight. This paper focuses on optimizing existing model parametrically by taking thickness and width of the leaf spring as variables to obtain optimum thickness and width under natural frequency and maximum allowable stress as constraints. The main goals considered are to obtain optimum value of the parameters and minimizing mass at the maximum von Mises stress, improving life span and maximizing the natural frequency of the leaf spring. Upon parametric optimization by using the optimized model of the leaf spring weight, deformation and natural frequency were analyzed. The design model was developed in SOLIDWORKs software and parametric optimization and material optimization were conducted using ANSYS Work Bench.

2. Materials and methods

The general methodology used in this study is described in Fig. 1, where the left side figure shows parametric optimization and the right-hand side figure is for the material optimization method.

2.1. Parametric design optimization

Design optimization is the mainstream method supporting engineering design. In design optimization, objective function is minimized (or maximized) subject to constraints by varying a set of variables, such as dimensions and material properties. In other words, optimization is the determination of the key performance parameters as a function of the independent variables, which are often unknown inputs at the early stages of the design process. In this scenario, parametric design optimization is a powerful tool. Parametric optimization method is a powerful technique used to modify multiple variables until optimum results are obtained. However, providing optimization routine that guide the optimization within a design space or allowable ranges of the variables is important. An optimization study is thus defined by goals or objective functions (the parameter to optimize), the design variables and constraints. While the design variables represent the values that are modified through the optimization process, the constraints are limits that are placed on the design variables.

2.1.1. Formulation of optimization problems

As mentioned above, an optimization problem attempts to obtain or determine the design variables that lead to the best measurable performance under the given constraints. For master leaf spring design, it is required that the spring serves its function at safe condition, be strong enough, has low weight and high natural frequency to avoid resonance and yet as inexpensive as possible. Studies show that the road irregularities usually have the maximum frequency of 12 Hz [14]. This means, the natural frequency of the suspension system should not be too close to this resonance frequency.

In this study, the weight and stress of the leaf spring are defined the merits of performance in such a way that the optimization targeted a minimum weight and a stress that does not exceed the yield strength of the material. The reason for this consideration is that a low volume leaf spring consumes less material; and hence less expensive. then, the width and thickness are selected as design variables. At this point, it is necessary to a model with equations governing the behavior of the leaf spring and define the relation between the design variables and the objective as well as the constraint functions. Defining the objective function to minimize the weight is straightforward. The natural frequency increases with the increase of thickness of leaves, and it decreases with increased span and vise-versa. Thus, as variables the thickness and width of the leaf spring were considered. For constraints: allowable stress of the material, and maximum frequency of irregularities road were considered.

The master leaf spring is modeled as shown in Fig. 2, which is originally used to carry out the design optimization in SolidWorks environment. The material used for this parametric optimization analysis is the material used commonly in automobile industry 55Si2Mn90 with the material properties listed in Table 1. In the present work, master leaf of light vehicle is designed according to standard dimensions listed in Table 1. The is given in Fig. 2. As stated, the objective is to conduct design optimization for a minimum weight, minimum stress and maximum natural frequency subjected to factor of safety, natural frequency and constraints on the stress by varying the thickness, width and camber of the cross-section. Thereafter, the design problem is mathematically formulated as shown from Eqs. (1)–(8).

$$\text{Minimize}: \ \text{Weight}; \tag{1}$$

$$\text{Minimize}: \ \text{Von Mises stress} \tag{2}$$

$$\text{Maximize}: \ \text{Natural Frequency} \tag{3}$$

$$\text{Subject to}: \ t_k^l \leq t_k \leq t_k^u \tag{4}$$

$$w_k^l \leq w_k \leq w_k^u \tag{5}$$

$$\text{Fn} > 12 \ \text{Hz} \tag{6}$$

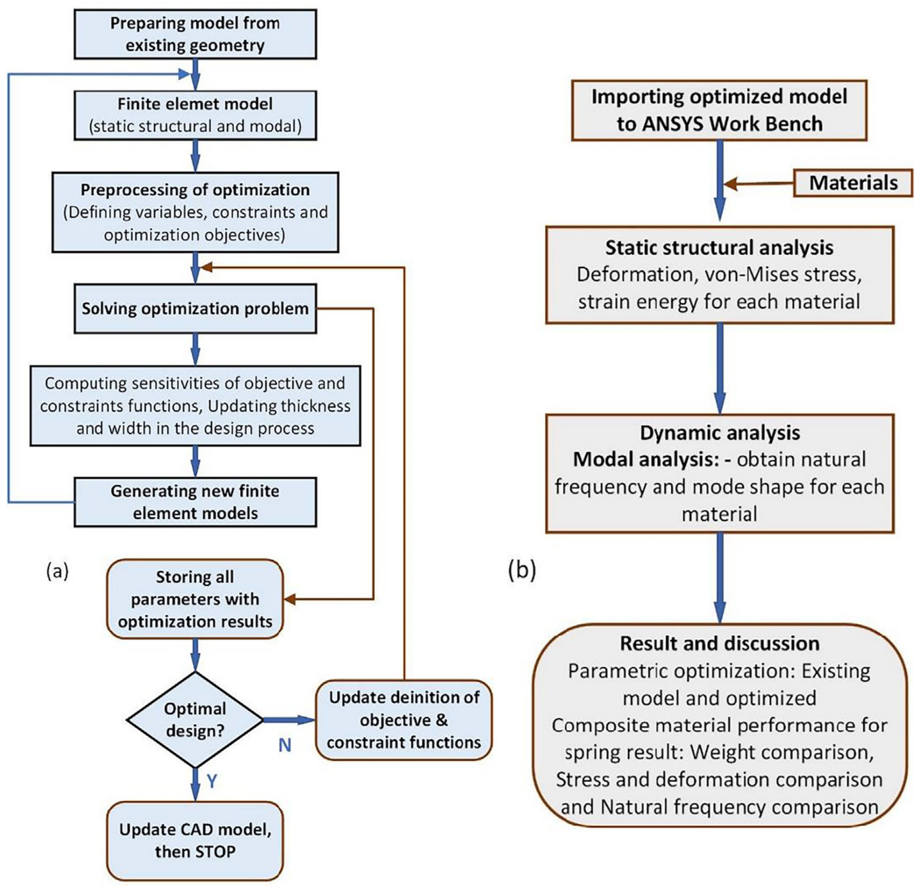


Fig. 1. Schematic flow diagram used methodology (a) SolidWorks environment (b) ANSYS Work Bench environment.

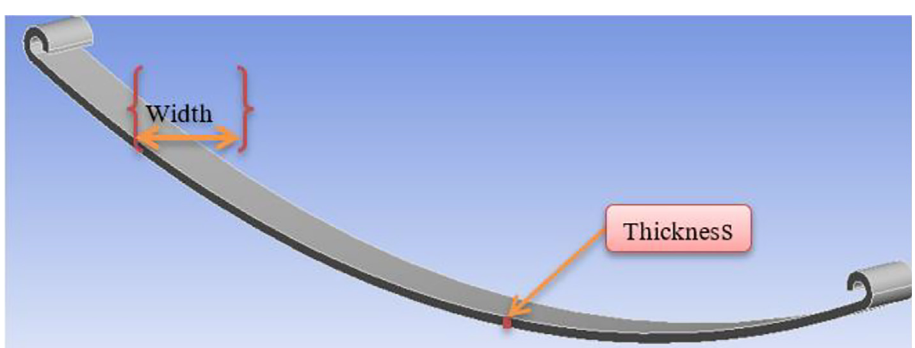


Fig. 2. Model of original leaf spring.

Table 1
Actual Parameter Specifications of Conventional Steel Leaf Spring [8,15].

Sr .No	Parameter	Value
1	Material selected	Steel–55Si2Mn90
2	Tensile strength (MPa)	1962
3	Yield strength (MPa)	1500
4	Young's modulus E (GPa)	200
5	Total Length (mm)	1540
6	Spring width (mm)	70
7	Outer Diameter of Eye(mm)	43
8	Inner Diameter of Eye(mm)	36
9	Thickness of leaf (mm)	13
11	Maximum load given on spring (N)	3850
12	Poisson's Ratio of material	0.3
13	Density of material (Kg/m3)	7850

$$\text{Maximum allowable stress } (t, w) = \sigma \ MPa \tag{7}$$

where 'Fn' is the natural frequency, 'w' the width, and 't' thickness of leaf spring.

2.1.2. Solution of optimization problems in solid works

Solid work uses the gradient-based solution technique for optimization for structural problems. The gradient-based approach solves optimization problems by searching in the design space based on the gradients of objective and constraint functions that are active using numerical algorithms.

Baseline simulation: For optimization baseline simulation is necessary. Original designed leaf spring was a master leaf spring modeled in SolidWorks and the geometry model was solved by using fine mesh of 16,916 nodes and 2212 elements. The first base line simulation was obtained by applying the boundary conditions on the both end direction of the spring. For base the first natural frequency of first mode of original leaf spring was analyzed in solid work simulation as shown from Fig. 3(a).

Creation of optimization design study: Creation of variables (items allowed to change within the software), constraints (condition that the final design must satisfy) and goals (objective of the study) are first step in optimization of the model. Design variables, constraint and goal are selected and specified as shown in Fig. 4. The design variables, i.e. the thickness and the width were varied with 0.25 mm and 3 mm intervals within their 5 mm to 13 mm and 10 mm to 70 mm respectively. Accordingly, the thickness varied 33 times and the width varied 21 times. These variations in design variables constitute 693 (i.e. 21x 33) scenarios to search for an optimal solution. For the road irregularities a maximum frequency of 12 Hz [14] was considered. Therefore, the leaf spring can be designed to have a natural frequency that is not so close to 12 Hz so that resonance is avoided. In addition to the natural frequency of 12 Hz, the maximum von Mises stress is used as a constraint. As shown from Fig. 3(b), the stress in the existing master leaf spring is 13.67 N/mm^2. It is expected that the optimized stress does not exceed this value to improve the life span of leaf spring. Thus, this value (14 N/mm^2) was used as constraint. Minimizing stress, mass of the leaf spring and maximizing natural frequency is the main objective (goal) of the study. So, considering the above, the design objective, constraint and goals with its sensor was defined as shown in Fig. 4. High quality was selected for more refined iterative solution.

2.2. Composite material performance study for leaf spring

As stated earlier, there exist other methods of reducing the weight of the suspension system without reducing the load carrying capacity and the stiffness. Since composite materials have high specific strength compared to steel, using composite material for leaf spring reduces the weight of the leaf spring. With this regards, Epoxy Carbon UD (230 GPa) Prepreg and Epoxy E-Glass UD were selected as spring material. A static structural and modal analysis was performed in ANSYS workbench for the constant maximum load given on spring applied was 3850 N. An element size of 3 mm was used by the model size, body curvature and the complexity of the mocdel. Upon meshing of the model, 42,120 elements and 217,306 nodes were obtained.

3. Result and discussion

3.1. Parametric optimization efficiency

In this study, 695 iterations of the "Baseline Study" were conducted to find the optimal solution of the two design variables (width and thickness). The optimal solution was found for Scenario

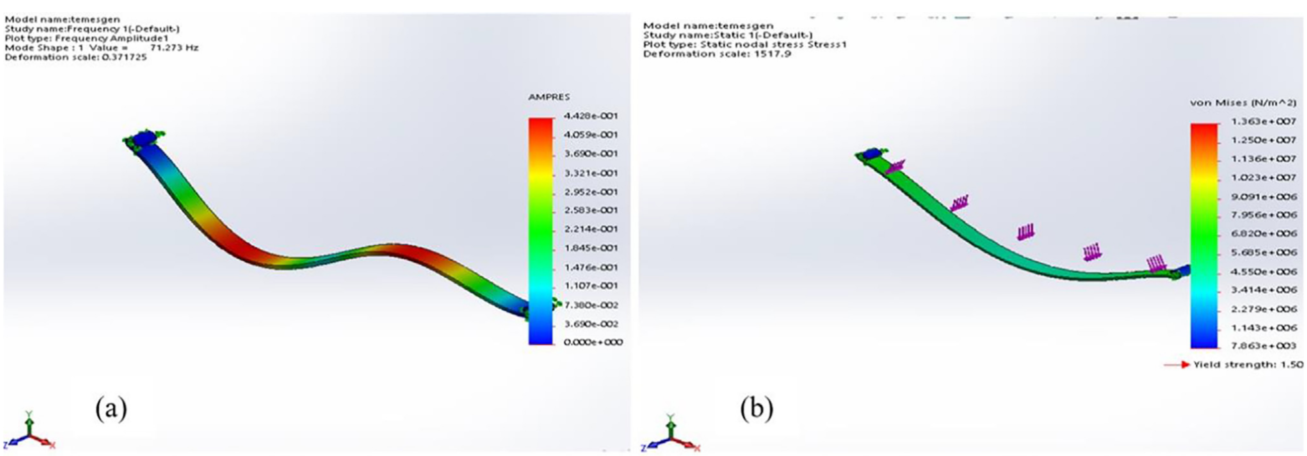


Fig. 3. Base line simulation: - (a). First Natural Frequency (b). Von Mises stress (MPa).

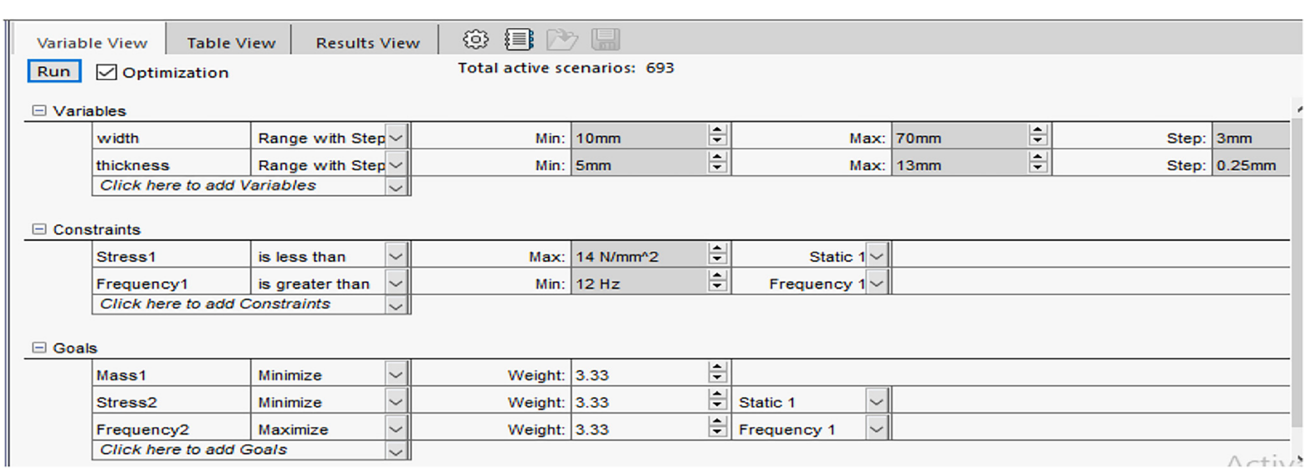
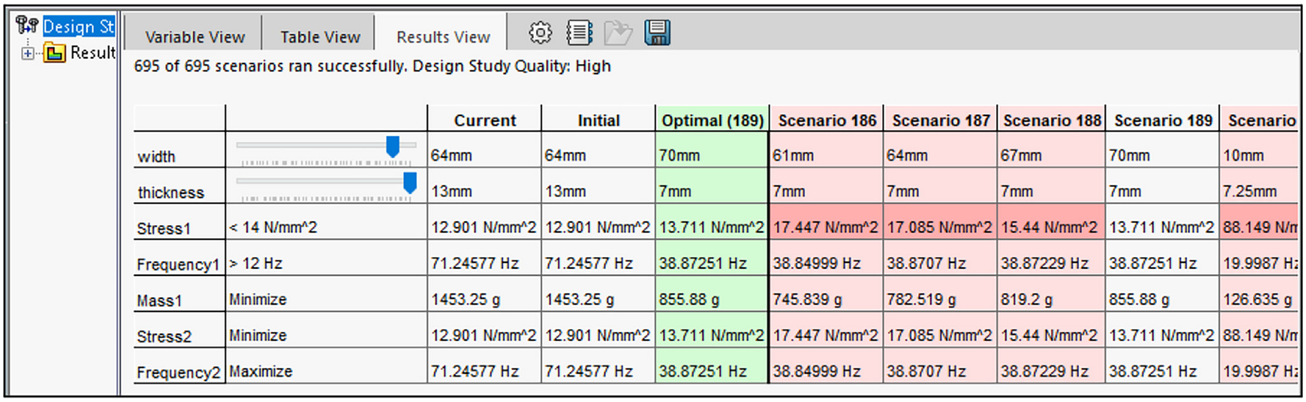


Fig. 4. Definition of the design objective, constraint and goals with its sensor.



Design St | Result

Variable View | Table View | Results View

695 of 695 scenarios ran successfully. Design Study Quality: High

		Current	Initial	Optimal (189)	Scenario 186	Scenario 187	Scenario 188	Scenario 189	Scenario
width		64mm	64mm	70mm	61mm	64mm	67mm	70mm	10mm
thickness		13mm	13mm	7mm	7mm	7mm	7mm	7mm	7.25mm
Stress1	< 14 N/mm^2	12.901 N/mm^2	12.901 N/mm^2	13.711 N/mm^2	17.447 N/mm^2	17.085 N/mm^2	15.44 N/mm^2	13.711 N/mm^2	88.149 N/m
Frequency1	> 12 Hz	71.24577 Hz	71.24577 Hz	38.87251 Hz	38.84999 Hz	38.8707 Hz	38.87229 Hz	38.87251 Hz	19.9987 H:
Mass1	Minimize	1453.25 g	1453.25 g	855.88 g	745.839 g	782.519 g	819.2 g	855.88 g	126.635 g
Stress2	Minimize	12.901 N/mm^2	12.901 N/mm^2	13.711 N/mm^2	17.447 N/mm^2	17.085 N/mm^2	15.44 N/mm^2	13.711 N/mm^2	88.149 N/m
Frequency2	Maximize	71.24577 Hz	71.24577 Hz	38.87251 Hz	38.84999 Hz	38.8707 Hz	38.87229 Hz	38.87251 Hz	19.9987 H:

Fig. 5. Optimal solution reported by Simulation.

189 (see Fig. 5), where the width is 70 mm and the thickness is 7 mm. By this optimization, the stress reduces from 13.764 MPa to 13.711 MPa. Natural frequency is 38.87251 Hz (greater than12 Hz), and the total mass is 855.88 g (reduced from 1589.49 g of the existing master leaf spring).

Table 2 shows comparison of the von Misses stress and weight of the leaf spring for the original and optimized models. The results indicate that using the optimization has reduced the weight almost to half and this reduces the cost of the material while maintaining the stress at an equivalent level. This reduction of weight helps to improve vehicle efficiency and fuel economy and can potentially reduce vehicle operating costs [1].

3.2. Composite material performance for spring result

Static analysis result:-Static structural analysis was done on the optimized model using three different materials: (1) structural steel (55Si2Mn90), (2) Glass/Epoxy composite and (3) Carbon/ Epoxy composite. The results of the static structural analysis for the total deformation and equivalent stress of leaf spring of Carbon/Epoxy are shown in Fig. 6. The results for the other materials are omitted due to page limitation. Table 3 shows the summary of the static analysis of the results for the three selected materials.

It can be seen from the tabulated results that the leaf spring of steel material gets maximum deflection (0.52704 mm) while the Epoxy Carbon UD (230 GPa) Prepreg gets minimum deflection (3.2359 mm) for identical geometry and loading condition. The intent of the optimization is reduction of the weight, which is a function of the material selected. The reduction in weight of the

Table 2
Comparison of weight and stress.

Parameter	Original	Optimized	Improvement (%)
Von Misses Stress (MPa)	13.764	13.711	0.385
Weight of the spring (g)	1589.49	855.88	46.1538

Table 3
Comparison of von misses and deflection result for different material leaf spring.

	Optimized leaf spring	
	Maximum von Misses (MPa)	Maximum Deflection (mm)
Steel–55Si2Mn90	117.59	0.52704
Carbon UD	88.876	3.2359
E-Glass UD	100.47	4.558

Table 4
Comparison of Weight of different material leaf spring.

	Optimized leaf spring	
	Weight (kg)	Weight reduction (%)
Steel–55Si2Mn90	6.7186	–
Carbon UD	1.2753	81
E-Glass UD	1.7117	74.5

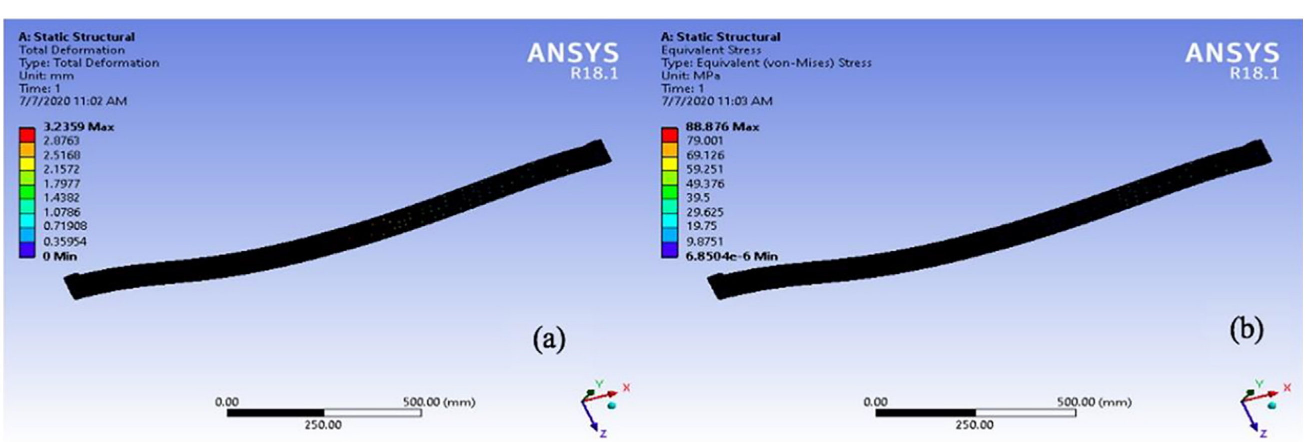


Fig. 6. Static analysis results of leaf spring of Carbon/Epoxy (a) Total deformation) (b) Equivalent stress.

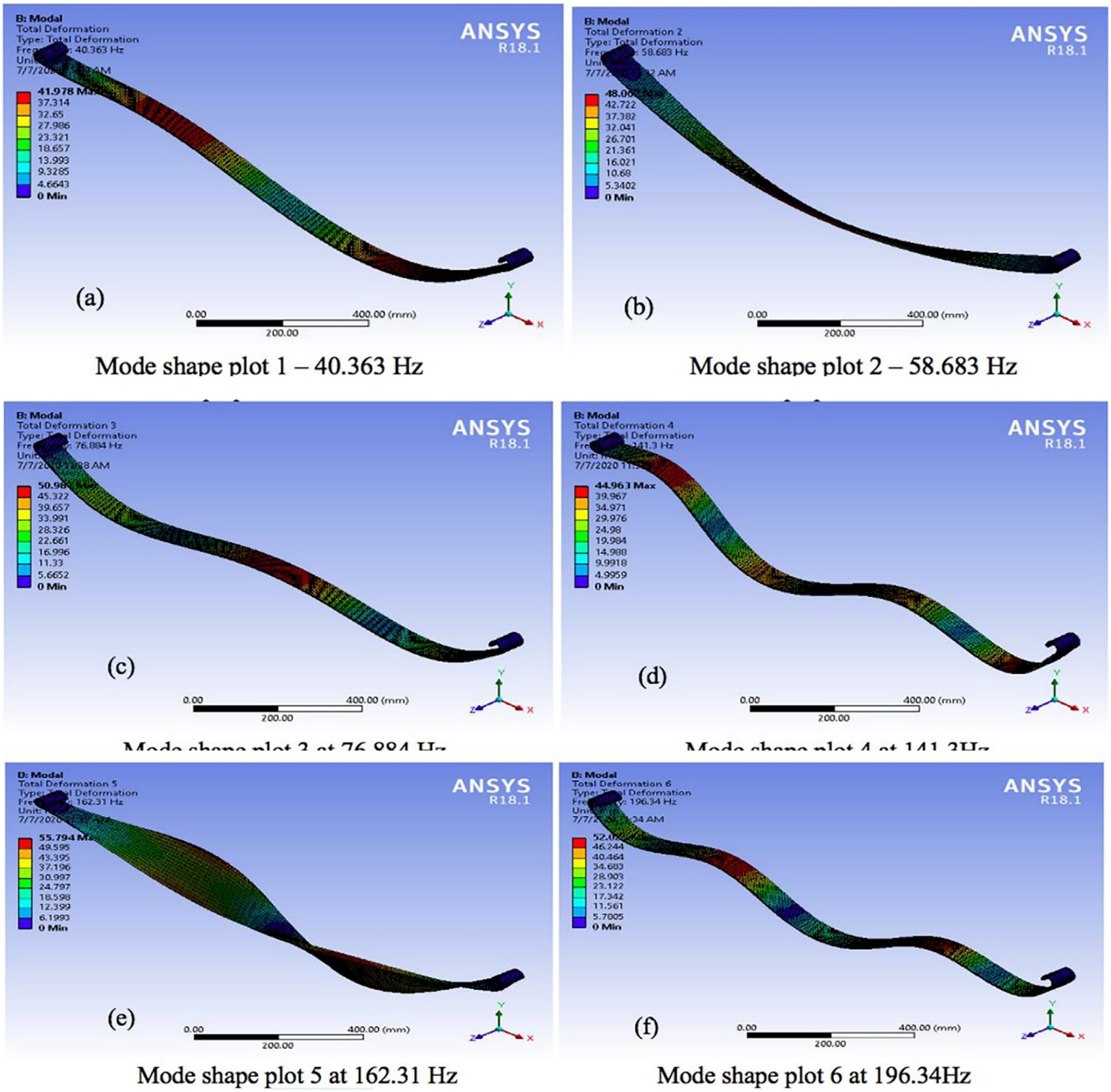


Fig. 7. Mode shape of Epoxy Carbon UD (230 GPa) Prepreg leaf spring.

leaf spring implies improved fuel efficiency because the leaf spring represents the unsprung mass of the vehicle. Reduction of weight of the unsprung leads to less vertical acceleration forces while the vehicle is in motion. This in turn increases ride quality and handling. Table 4 shows the comparison of weight of leaf spring for the selected materials. It can be seen that the replacement of steel based leaf spring by Epoxy Carbon UD (230 GPa) Prepreg, E-Glass/Epoxy leads to a significant weight reduction per leaf spring by 81% and 74.5% respectively.

Modal analysis result: Modal analysis was performed on the optimized model to find out the first 6 natural frequencies of the leaf spring system for the three materials. Results plots of mode shapes of Epoxy Carbon UD (230 GPa) Prepreg materials are shown in Fig. 7. Total deformation values in mode shape plots are not accounted for here because these plots only represent the shape of the modal frequency deformation pattern.

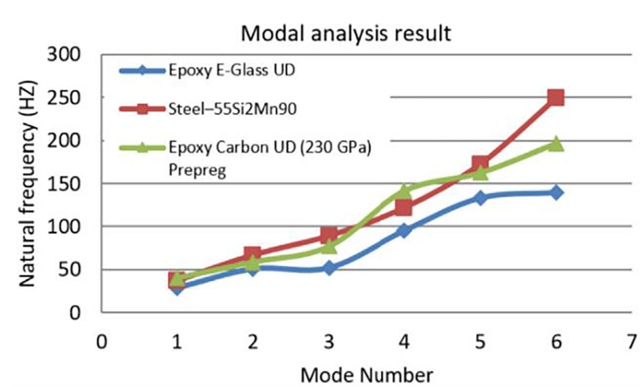


Fig. 8. Natural frequency (Hz) for each material up to 6 modes.

As shown in Fig. 8, all the first natural frequencies are greater than 12 Hz, which is the maximum frequency the road irregularities [14]. Therefore, the natural frequency of the designed leaf spring should not be close to this value in order to avoid resonance. The obtained first natural frequencies of Steel–55Si2Mn90, Epoxy Carbon UD (230 GPa) Prepreg and Epoxy E-Glass UD leaf spring are nearly 3.0, 3.35 and 2.35 times larger than the constraint natural frequency due to road irregularities and therefore resonance will not occur. This means that the designed suspension provides improved ride comfort.

4. Conclusion

In the present work, master leaf spring was optimized by varying width and its thickness taking constraint natural frequency and maximum allowable stress with objective of reducing the weight of leaf spring under optimum minimum stress and maximum natural frequency. For parameters optimization the design constraints were limiting stresses, natural frequency. After obtaining optimum model weight, Von Mises stress and natural frequency of the leaf spring was studied under different composite material aiming minimum weight and minimum stress to improve the life of the structure. Based on the conducted analysis, the following conclusions can be mentioned:

- By optimizing the existing model parametrically (thickness and width) stress improved by 0.4% and weight of the leaf spring reduced by 46.1538%.
- The replacement of steel-based leaf spring by Epoxy Carbon UD (230 GPa) Prepreg, E-Glass/Epoxy leads to a weight reduction per leaf spring by 81%, 74.5% is achieved respectively for optimized leaf spring.
- The optimized composite leaf spring has lower stress, higher stiffness and higher natural frequency compared with original leaf spring from steel.
- The higher damping capacity of composite leaf spring will reduce vibration and noise, and as a result, the ride comfort is improved.

The continuing work of this study further optimization of the design variables beyond the current scenario (more than 693 times), simulating other alternative materials such as hybrid of natural and synthetic fibers for similar purposes and validation of results with experimental research.

CRediT authorship contribution statement

Temesgen Batu: Conceptualization, Methodology, Writing - original draft, Investigation. **Hirpa G. Lemu:** Supervision, Validation, Writing - review & editing, Data curation. **Elias G. Michael:** Methodology, Visualization, Software, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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