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Developing polymer composite-based leaf spring systems for automotive industry

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Abstract: Composite-based mono-leaf spring systems were designed and manufactured to replace existing mono-leaf metal leaf spring in a light commercial vehicle. In this study, experimentally obtained mechanical properties of different fiber-reinforced polymer materials are presented first, followed by the description of the finite element analytical model created in Abaqus 6.12-1 (Dassault Systemes Simulia Corp., RI, US) using the obtained properties. The results from the finite element analysis are presented next and compared with actual size experimental tests conducted on manufactured prototypes. The results demonstrated that the reinforcement type and orientation dramatically influenced the spring rate. The prototypes showed significant weight reduction of about 80% with improved mechanical properties. The hybrid composite systems can be utilized for composite-based leaf springs with considerable mechanical performance.

Keywords: composite leaf spring; finite element analysis (FEA); glass fibers; hybrid composites; mechanical properties; resin transfer molding.

1 Introduction

Fiber reinforced-polymer composites have been utilized as a substitute for metallic materials in many weight-critical components in aerospace, automotive, and other engineering fields owing to their low density and better strength to weight ratio and modulus to weight ratio. In addition to the aforementioned properties, many fiber-reinforced composites present excellent fatigue strength and higher corrosion resistance [1].

Mandatory carbon dioxide (CO_2) emission reduction targets set by the European Commission [2–5] and other countries have led the automobile industry to look for ways to reduce the CO_2 emission rates in the past 15–20 years. Besides developing new-generation engines that consume less fuel, another effective way to achieve low CO_2 emissions is to reduce the weight of the vehicles without compromising safety and other features. There are many components in a vehicle that can be considered in weight reduction applications. One of these components is the leaf spring, which constitutes an important part of the suspension system of a vehicle. Conventional leaf spring suspension systems used in commercial vehicles are generally produced from high carbon steel. Despite its susceptibility to corrosion, long-term fatigue problems, and relatively high strength to weight ratio, carbon steel is a relatively cheap material that possesses high stiffness and strength and is used in several parts of commercial vehicles. Recently, manufacturers of the automotive industry have started to replace these steel leaf springs with lighter, yet sufficiently stiff and strong fiber-reinforced composite leaf springs [6].

Over the last two decades, several studies were carried out regarding the application of composite-based materials for automotive suspension systems. For example, Sancaktar and Gratton [7] investigated the capabilities of composite leaf springs for lightweight vehicle applications. Glass fiber-reinforced polyester double-leaf spring was designed, manufactured, and tested for rail freight vehicles to replace existing multi-leaf steel springs on a wagon by Hou et al. [8]. Gebremeskel [9] carried out the design analysis of a single E-glass/epoxy leaf spring analytically and fabricated a prototype using the hand lay-up technique. He also modeled and simulated the spring using Abaqus/CAE 6.10. Rajendran and Vijayarangan [10] studied the design optimization of a mono-leaf composite leaf spring using genetic algorithm. Different types of joints to fix the spring to the axle and

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the vehicle body were presented by Shokrieh and Rezaei [1]. Shokrieh and Rezaei [1] also designed and optimized a composite mono-leaf spring. Al-Qureshi [11] utilized a hybridization method to improve the performance of the composite-based leaf springs. Meatto and Pilpel [12] described a hybrid mono-leaf spring for light truck applications that arise from an existing steel main leaf in company with an E-glass/epoxy composite cladding. Furthermore, composite-based leaf springs are continously generating large interest in the academic field in recent years [13–18].

Although several studies exist in this field, the relationship between material selection, composite structure design, material physical test results, and leaf spring mechanical behavior is still inadequately investigated. The purpose of this study is to obtain convenient composite leaf spring structures providing the desired spring rate and also to fabricate composite leaf spring prototypes. The investigation consisted of experimental and computational studies. This paper presents results mainly from the computational study. As part of the study, composite structures having different material configurations were manufactured using the resin transfer molding (RTM) process, and the mechanical and thermo-mechanical behavior of these structures were determined. Glass fiber-epoxy composites were selected as the optimum material when their cost and strength properties were taken into consideration.

Experimentally obtained mechanical properties of different fiber-reinforced polymer materials are presented first, followed by the description of the finite element analytical model created in Abaqus 6.12-1 using the obtained properties and an overview of the study. Results from the finite element analysis are presented next and compared with actual size tests conducted on manufactured prototypes. Comparison of the predicted results with the experimental results for the prototypes showed good agreement in terms of the load-displacement response, and so the finite element model (FEM) of the composite leaf spring systems was improved successfully.

2 Composite-based mono-leaf spring

Leaf springs are expected to absorb vertical vibrations due to road irregularities and store the potential energy as strain energy. Therefore, high specific strain energy capability is the main material property required for leaf springs [1]. Besides, as mentioned earlier, high specific strength, low specific modulus, corrosion resistance, and superior fatigue strength make fiber reinforced-polymer composites ideal materials for replacing conventional steel leaf springs. A comparison of material properties required for leaf springs between high carbon steel and fiber-reinforced composites is shown in Table 1. In addition, the changing arrangements of continuous fibers in a structure provide design flexibility [20]. Moreover, fatigue strength, which is crucial for many structural components, is rather important for the classical leaf springs and many tests should be performed on the different design alternatives that may contain different leaf layers. This design procedure for the multi-leaf steel spring takes a long time and the cost causes problems from the manufacturing point of view [21, 22]. For this reason, these design and test procedures have necessitated that the design of mono-leaf springs arise from a composite-based material.

2.1 Design of composite-based mono-leaf spring

The composite-based mono-leaf spring was designed to replace the existing mono-leaf metal leaf spring in a light commercial vehicle. The constant width, constant thickness design was preferred for the sake of practical concerns in manufacturing [10]. The design parameters were determined by using geometric constraints and specified loading and boundary conditions. The requirements and parameters of the composite-based leaf spring used in this study were as follows:
- gross axle load, $W = 2.5$ ton,
- maximum desired vertical deflection, $s_{max} = 135$ mm,
- total length, $L = 1300$ mm,
- spring rate, $k = 18–20$ kgf/mm, and
- existing space for spring width, $w = 70–80$ mm.

The composite-based leaf spring designed considering the aforementioned parameters is shown in Figure 1.

Table 1: Comparison of the material properties required for leaf springs between high carbon steel and fiber-reinforced polymer composites [1, 19].

Material	Specific strength (10^6 cm)	Specific modulus (10^8 cm)	Specific strain energy (10^3 mm)
High carbon steel	1.3	2.7	0.06
Glass fiber-reinforced epoxy	5.3	2	0.16
Carbon fiber-reinforced epoxy	10.3	9.7	0.46

2.2 Material selection

Five different configurations as shown in Table 2 for composite plates were considered and manufactured using the RTM process. These configurations were selected so as to determine the effect of the fabric type and orientation on the mechanical behavior of the composite structures. These plates consisted mainly of unidirectional (UD) fabrics so that the leaf spring resists the stresses caused by the vertical load, which is the most dominating mechanical load applied on a leaf spring [23], as UD fibers have good strength properties along the fiber direction.

From each composite plate configuration, at least five samples were tested to obtain fiber volume fraction, thermo-mechanical properties, tensile properties, and flexural properties. Matrix burnout test, dynamic mechanical analysis, tensile test, and three-point bending test were applied, respectively, to determine the given characteristics. These properties were utilized to create the material model in Abaqus. For each configuration, average values were used as representative values for corresponding properties shown in Table 3. Table 4 shows the target values that were compared with the test results.

SEM images of tensile fracture surfaces of whole composite plates are shown in Figure 2. SEM micrographs have shown that there is strong adhesion between fiber and matrix for whole composite configuration. It was observed that fibers are pulled-out from interface between plies so that delamination was approved as primary failure mode for whole composite plates. Besides, fiber breakage was seen in Plate 3–5.

Based upon the material characterization results, it can be concluded that the volume fraction of all plates agreed with the target range. However, the fiber volume fraction of carbon fiber-reinforced plates is slightly lower. This behavior can be attributed to the density of the carbon fibers used in this study. The glass transition temperature (Tg) of the plates also varies from 93°C to 115°C. These values are rather higher than the working temperature of the leaf springs. UD plates have superior tensile strength along the fiber direction, as expected. On the other hand, UD plates have low mechanical properties in transverse direction. In addition, UD plates have maximum bending strength as tensile properties of the reinforcements play an effective role when an external bending load is applied. It is worthwhile to mention that the bending modulus of Plate 3 is also much higher than that of the other plates. This affects the rigidity of the material, and this kind of materials having high modulus are not desired for spring applications lest the high modulus should restrict the deflection of the spring. Moreover, materials with high

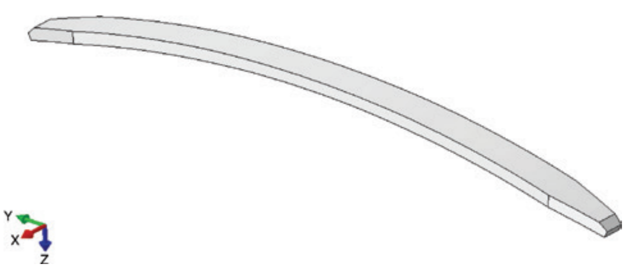

Figure 1: Solid model of the composite leaf spring.

Table 2: Manufactured composite plate configurations.

Composite plate	Fabric	Orientation
Plate 1	UD E-glass	UD
Plate 2	UD E-glass	[0°/90°]
Plate 3	UD carbon	UD
Plate 4	UD carbon	[0°/90°]
Plate 5	[+45/−45] hybrid	[+45°/−45°]

Table 3: Material characterization results.

Composite plate	Fiber volume fraction (%)	Glass transition temperature (°C)	Ultimate axial tensile strength (MPa)	Axial tensile modulus (GPa)	Transversal tensile modulus (GPa)	Flexural strength (MPa)
Plate 1	49.00	93.38	689.65	35.99	9.77	757.63
Plate 2	46.10	98.70	434.64	30.57	30.57	528.28
Plate 3	42.63	114.41	984.40	105.70	8.80	1023.22
Plate 4	40.07	96.92	450.67	46.44	46.44	646.40
Plate 5	45.09	110.74	464.37	40.28	40.28	585.30

Table 4: Target values for material selection.

	Fiber volume fraction (υ_f)	Glass transition temperature (Tg) (°C)	Ultimate axial tensile strength (σ_{11}) (MPa)	Axial tensile modulus (E_{11}) (GPa)	Transversal tensile modulus (E_{22}) (GPa)	Flexural strength (MPa)
Target values	45–50	>90	>500	~40	~30	>750

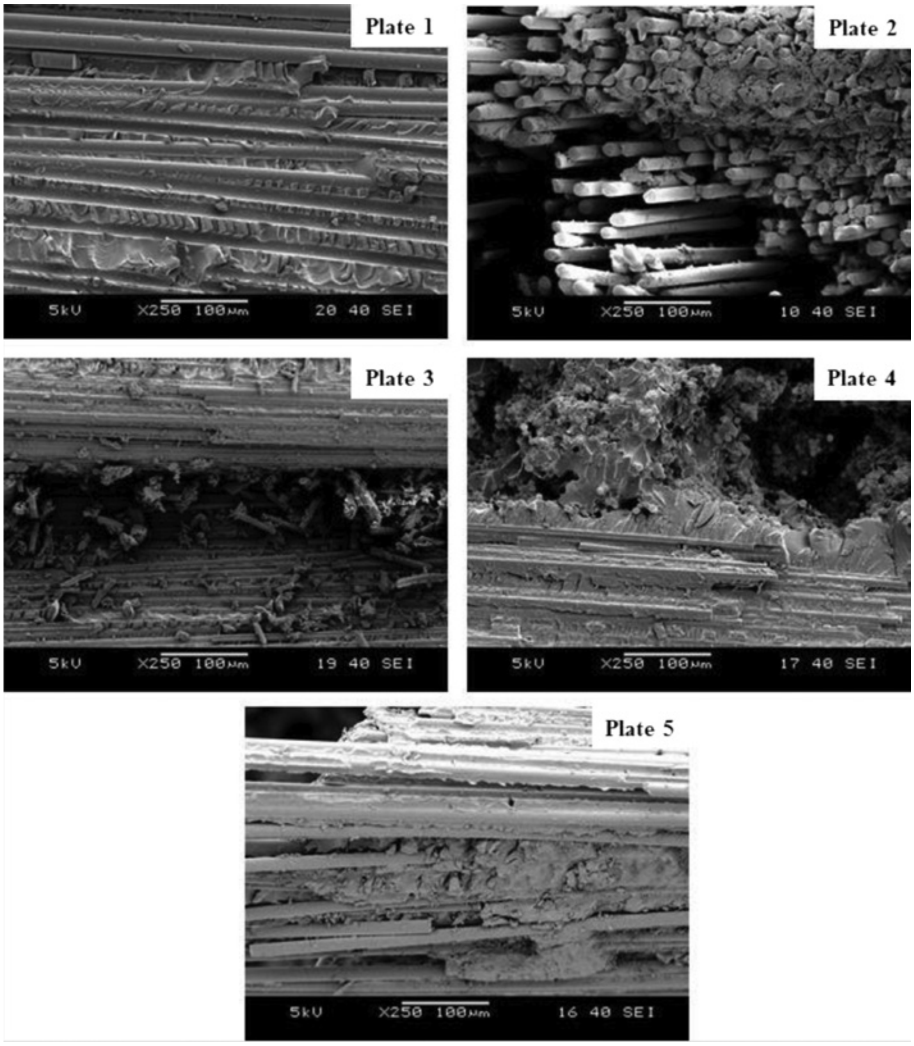

Figure 2: Scanning electron microscopic images of the tensile fracture surfaces of all manufactured composite plates.

modulus decrease the specific strain energy storage capacity of the material [10, 11]. Therefore, UD glass fiber-reinforced epoxy material was selected as an optimum material for the leaf spring applications owing to its high tensile strength and low tensile modulus.

3 Finite element modeling and analysis

In order to investigate the behavior of the proposed mono-leaf spring configurations, the FEM of the spring was created using Abaqus 6.12-1 software. This model was used to simulate the response of the spring and to check whether or not the proposed configuration complies with the requirements. A solid mono-leaf spring model created in CATIA CAD (Dassault Systemes, US) software was imported into Abaqus 6.12-1, and then repaired using partition methods to provide great convenience in mesh generation and prepared for composite modeling. Figure 3 depicts the final shape of the part after the repair and partition process. Within the study, the Abaqus/Standard implicit finite element procedure was selected as the FEM solver. This procedure solves the algebraic equations at the next time step by use of the solution of the previous time step. In addition, the equilibrium is inspected at each time increment. The quasi-static finite element formulations and convergence criteria are given in Abaqus 6.12-1 Theory Manual [24].

The composite lay-up interface of Abaqus was used as a composite modeler, and solid composite lay-up was selected as the element type. The lay-up orientation, basis orientation of plies, and stacking direction were carefully selected in the model. The rotation angle was selected as 0° as the fiber-reinforced composites have superior characteristics in the direction of fibers in terms of the strain energy [25]. The material orientation of the model is presented in Figure 4.

As mentioned before, glass fiber-epoxy composites were selected as the optimum materials that are used in the spring fabrication when their cost and strength properties are taken into consideration. Table 5 represents the material properties of UD E-glass/epoxy plies. These properties were obtained from the experimental characterization results and other studies [26, 27].

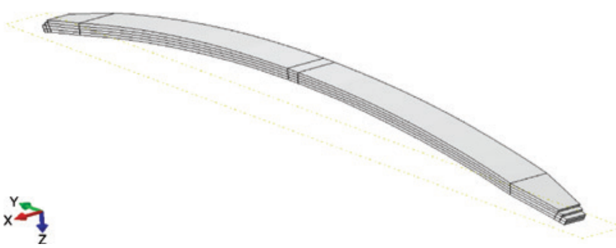

Figure 3: Final shape of the solid part.

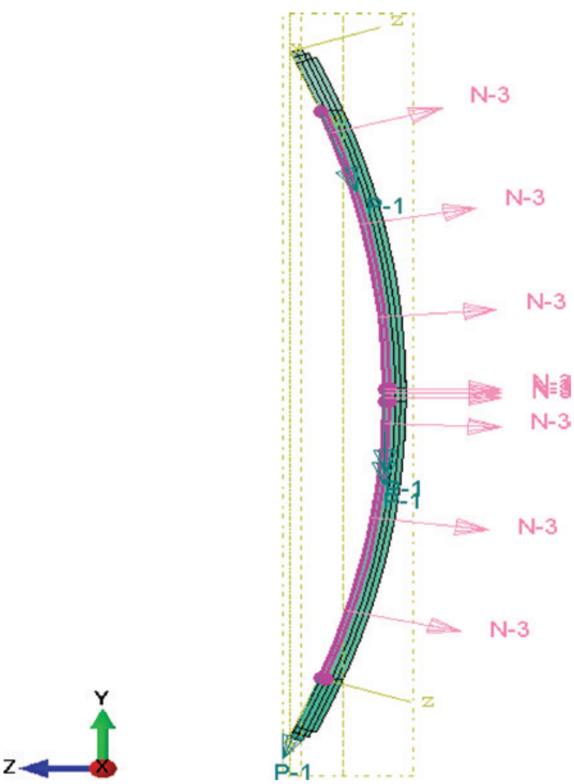

Figure 4: Composite mono-leaf spring material orientation with discrete coordinate system.

Many elements can be used for different problems in Abaqus. Continuum, shell, beam, rigid, and membrane elements are the commonly used ones. C3D8R elements were selected firstly as the element type in reference to the proposals of Abaqus documentation and literature studies [24, 28, 29]. In addition, they gave accurate results after a validation study was performed. These elements provide an advantage especially in the hybrid composite modeling including various plies of different materials, as they can comprise different material properties. Figure 5 shows the completed mesh in the model.

The boundary conditions and the load applied were determined by taking into consideration the upper limit value of the mechanical loads that take place due to the vehicle weight and road conditions. Vertical load was decided as the most dominating and critical mechanical load applied on a leaf spring [1]. The theoretical load-deflection diagram of the spring system is shown in Figure 6. The loading was executed by the upper rigid support through the displacement of 135 mm in *z*-direction (Figure 5), and alternative displacement and rotation degrees of freedom were restrained in this support. In addition, all displacements and rotations of the other supports on the bottom surface of the model were restrained. Moreover, the rigid body constraint was applied for each support so that the reference point governs the rigid body.

In this study, the penalty-based algorithm was selected so as to define the interaction properties and surface-to-surface contact was defined between the composite model and the rigid supports. In the tangential

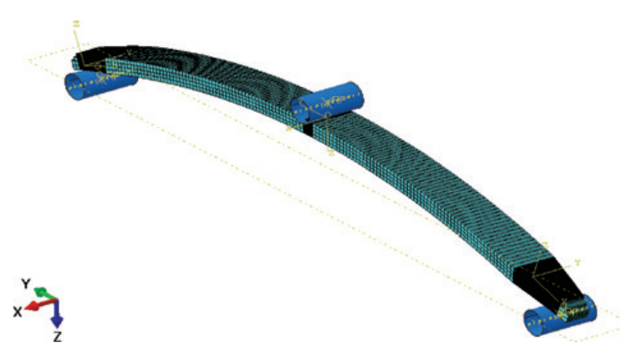

Figure 5: Meshed composite leaf spring model.

Table 5: Mechanical properties of UD E-glass/epoxy plies.

E_1 (GPa)	$E_2=E_3$ (GPa)	G_{12}[a] (GPa)	G_{13}[a] (GPa)	G_{23}[a] (GPa)	$\nu_{12}=\nu_{13}$	ν_{23}[a]	d (kg/m^3)
36–40	9–10	3.5	3.78	3.47	0.25–0.30	0.36	2500–2750

[a]Ref. [26].

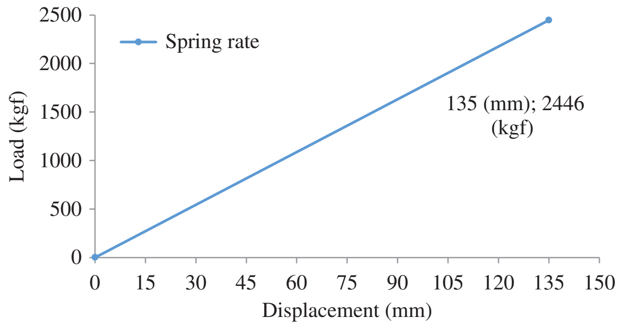

Figure 6: Desired load-deflection diagram for the leaf spring.

behavior of the contact, the friction coefficient is assumed as 0.2 [30] and the stiffness scale factor is also determined as 20 in an attempt to prevent the abnormal penetration of the composite model into the rigid rollers.

4 Results and discussion

4.1 Results of stress analysis

Three different composite-based leaf spring models including alternative material configurations were created. Table 6 shows the created model list.

The behavior and mechanical properties of the designed springs were investigated via simulation runs in Abaqus [31]. The response of the springs to the prescribed loading conditions with the intended boundary conditions is estimated, and the maximum deflection and stresses observed in these simulations are recorded for comparison. Figure 7 shows the comparison between the desired theoretical spring rate and the predicted results of the created composite-based leaf spring models. As seen from the figure, the predicted results of Design 3 are in agreement with the required spring rate correctly with 0.514% deviation with C3D8R elements.

Within the scope of the analyses, the stress results in the critical regions were also investigated. The stress distribution results of Design 3, which is the most appropriate configuration in terms of the load-displacement response among the created designs, are presented in Figures 8–11. Plotted in the figures are the stress distribution curves in the fiber and transverse direction in the direction of the longitudinal distance along the leaf spring (both upper and bottom surfaces). According to these results, it is clearly understood that Design 3 is allowable in terms of stress when the strength property of each ply are taken into account.

Table 6: Configurations of composite-based leaf spring systems created.

Design	Plies	Material	Orientation
1	60	Glass	$[0°]_{60}$
2	60	Carbon	$[0°]_{60}$
3	60	Glass and carbon	$[0°G/0°C/0°G]_s$

G, glass; C, carbon.

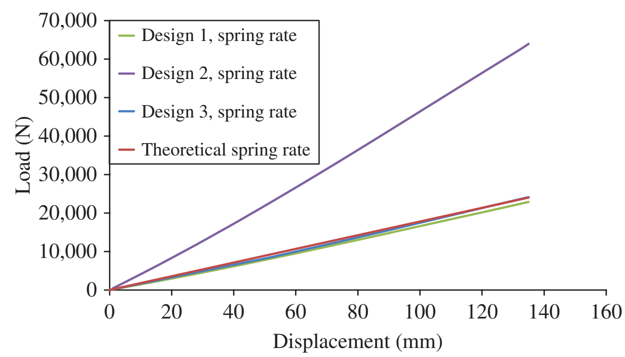

Figure 7: Load vs. displacement response comparison of the designed springs.

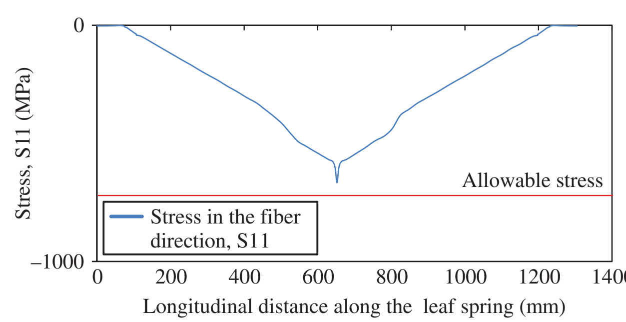

Figure 8: S11 stress distribution on the glass and carbon fiber/epoxy leaf spring upper surface along the longitudinal length.

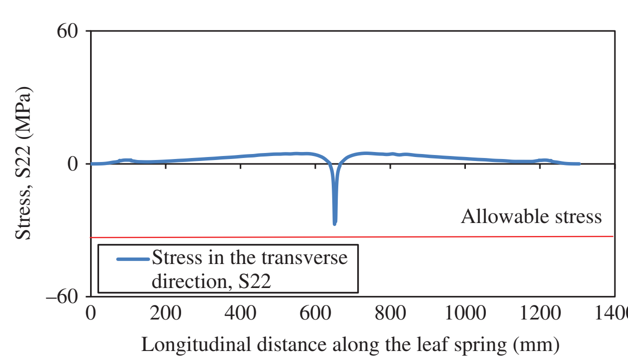

Figure 9: S22 stress distribution on the glass and carbon fiber/epoxy leaf spring upper surface along the longitudinal length.

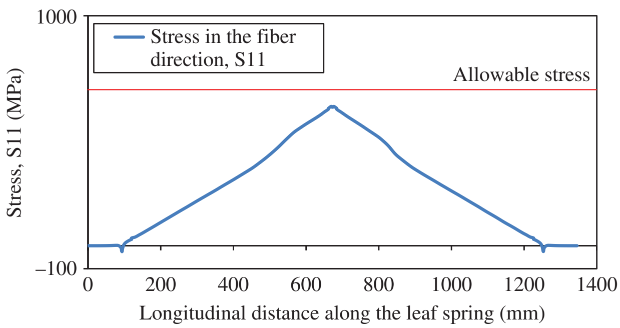

Figure 10: S11 stress distribution on the glass and carbon fiber/epoxy leaf spring bottom surface along the longitudinal length.

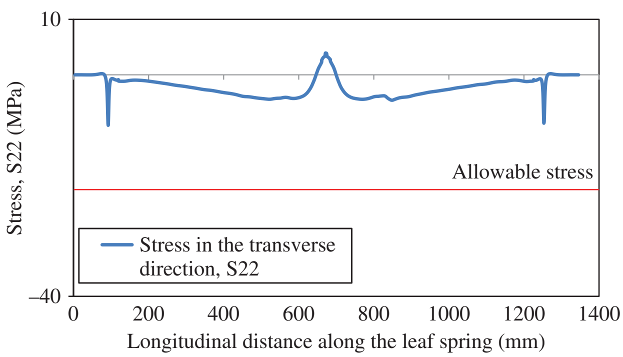

Figure 11: S22 stress distribution on the glass and carbon fiber/epoxy leaf spring bottom surface along the longitudinal length.

4.2 Fabrication procedure

There are many manufacturing techniques used in the fabrication of composite leaf springs. Composite leaf spring prototypes with three different material configurations were manufactured by using the vacuum-assisted RTM process in this study.

In the process, fabrics were cut according to the templates obtained from the CAD model of the composite leaf spring. The prepared fabrics were laid up into the mold, respectively, until the stacking process of the fabrics was completed. Then, the mold was closed and appropriate vacuum was applied from the vacuum ports of the mold. Resin injection was started with proper pressure by the RTM machine after ensuring that the mold was under vacuum entirely. Wetting of all fabrics in the mold was ensured through the observation of the resin flow in all vacuum ports. The injection process was completed in this way. Then, the composite-based mono-leaf springs were removed from the mold after the completion of the curing time of 24 h at room temperature. Figure 12 shows the setup of the manufactured composite-based mono-leaf springs.

4.3 Behavior of the manufactured composite-based leaf spring prototypes

Three different composite-based mono-leaf springs including different material configurations were manufactured so as to compare whether or not the created leaf spring designs comply with the prototypes within the study. The composite-based mono-leaf springs manufactured are listed in Table 7. Figure 13 also shows the photographs of the spring prototypes.

Prototype 1 contains 60 plies of E-glass/epoxy with 0° orientation similar with Design 1.

Figure 12: Manufacturing setup for the composite-based mono-leaf spring.

Table 7: Specifications of the composite-based leaf spring systems manufactured.

Prototype	Plies	Fiber material	Orientation
1	60	Glass	$[0°]_{60}$
2	60	Glass and carbon	$[0°G/0°C/0°G]_{S}$
3	60	Glass and hybrid	$[0°G/0°H/0°G]_{S}$

G, glass; C, carbon; H, [+45/−45] biaxial glass-carbon hybrid.

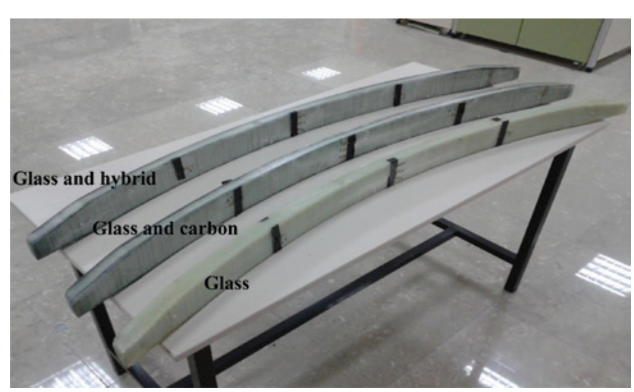

Figure 13: Photographs of the manufactured prototypes.

Prototype 2 includes glass and carbon/epoxy plies, and represents the optimum configuration in the structure similar with Design 3.

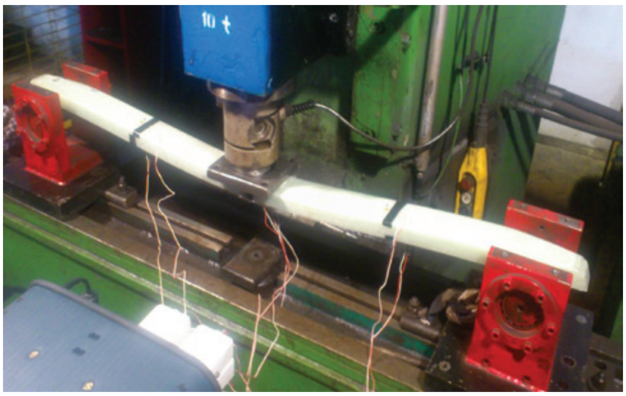

Figure 14: Test rig setup of the composite-based leaf springs.

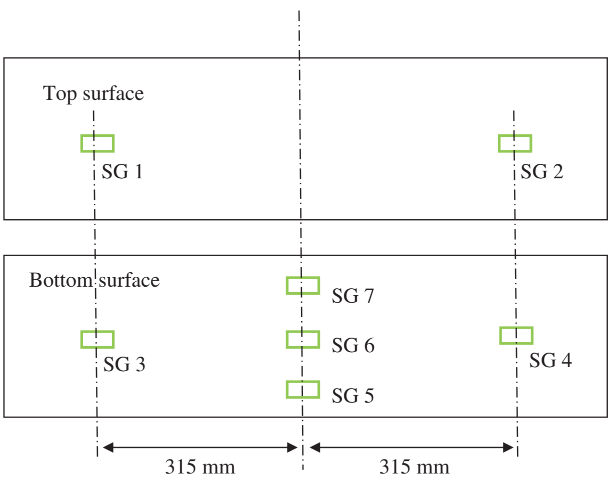

Figure 15: Positions of the strain gauges (SG).

Prototype 3 is created by using glass and hybrid/epoxy plies similar with the stacking sequence of Design 3.

The prototypes were also tested by using a leaf spring test rig for determining the behavior of the prototypes experimentally. The test rig is shown in Figure 14. There is a distance of 1160 mm between two supports. The prototypes were placed simply supported and critical vertical load was gradually applied to the center of the leaf springs. In this study, not only the spring rate but also the strain measurements on the spring surfaces were investigated. There were seven strain gauges on the part, and two of them were positioned on the compression side and the other five were on the tension side. Record data obtained from strain gauges were collected by a data acquisition device with a computer connection. Figure 15 schematically shows the strain gauge positions on the composite-based leaf springs.

4.4 Comparison of predicted results with experimental test results

Figures 16–18 show the comparison between the predicted and experimental test results in terms of the load-displacement response. It was observed for the three samples of Prototype 1 that the predicted results were in good agreement with the experimental results, with about 4.79%, 1.64%, and 2.43% deviation.

Figure 17 depicts that the predicted results for Prototype 2 are again in good agreement with the experimental test results with about 2.93% deviation.

It was observed for Prototype 3 that the comparison results were in compliance with about 2.70% deviation.

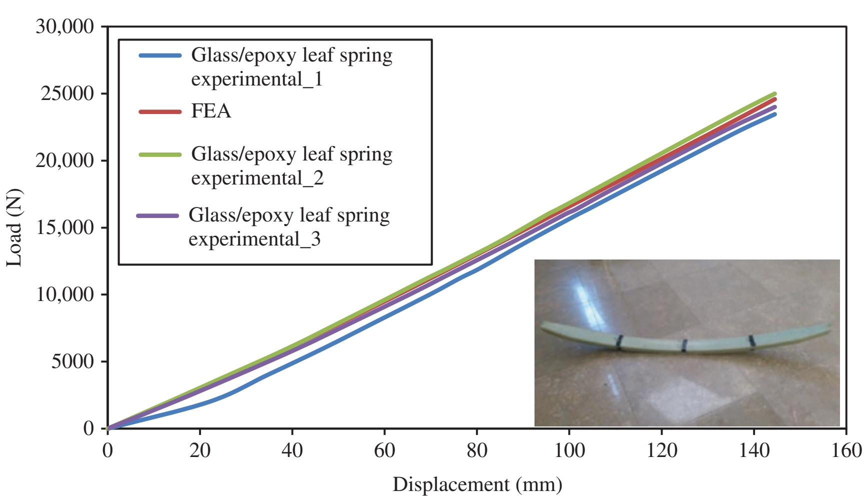

Figure 16: Predicted and experimental load-displacement response of Prototype 1.

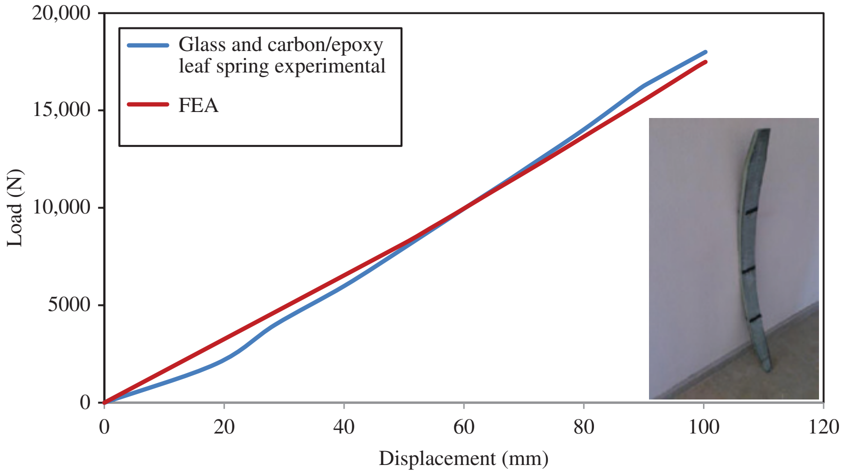

Figure 17: Predicted and experimental load-displacement response of Prototype 2.

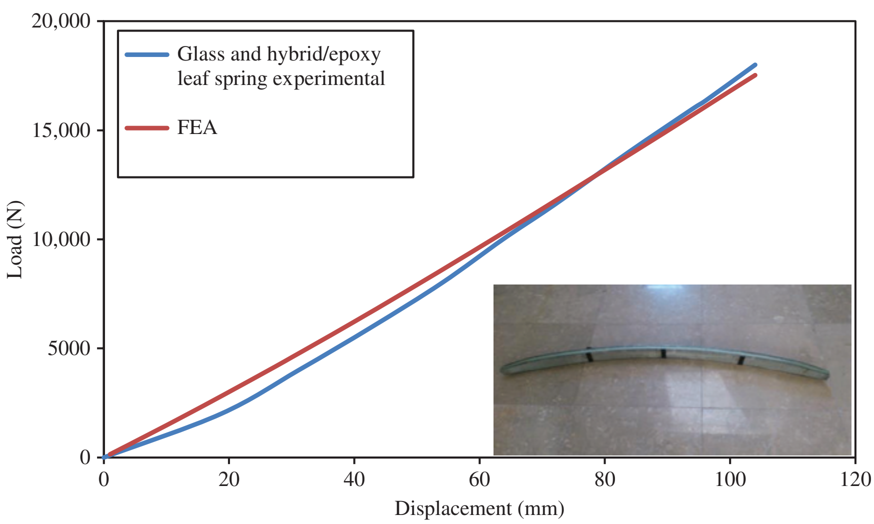

Figure 18: Predicted and experimental load-displacement response of Prototype 3.

Consequently, the general treatment of the finite element simulation results was in good agreement with the experimental test results of the manufactured composite-based leaf spring prototypes.

5 Conclusions

In this study, composite-based leaf spring systems with different material configurations were designed and the composite mono-leaf spring behavior was investigated successfully by using three-dimensional FEM. The analysis results demonstrated that all the proposed designs experience stress levels below the yielding. However, the carbon fiber/epoxy system (Design 2) was rather stiff considering the desired spring rate. Therefore, other two designs were considered from the manufacturing point of view. Manufacturing of the designed leaf spring systems was also achieved, and those prototypes were tested experimentally. The prototypes showed significant weight reduction of about 80% with improved mechanical properties.

Comparison of the predicted results with the experimental test results for the manufactured prototypes showed good agreement in terms of the load-displacement response, although the manufacturing processes of the composite-based leaf springs may affect the structural properties in a negative way. Thus, the FEM of the composite-based leaf spring systems was enhanced securely.

This study also showed that the hybrid composite systems can be utilized for composite-based leaf springs with considerable mechanical performance. Through this way, design flexibility can be provided with different reinforcements and the strength properties of the structure can be improved.

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