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Design and Fabrication of Layered Fiber-Reinforced Polymer Spring for Lightweight Vehicles

Dhia A. Alazawi, Mohammed Ismael Hameed*

Department of Mechanical Engineering, University of Diyala, Iraq

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Corresponding Author:
Mohammed Ismael Hameed
mohammedismael_eng@uodiyala.edu.iq

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Abstract

Reducing the weight of a vehicle is a key aspect that affects its performance, driving economy and overall safety. The suspension system is one of the major components for weight saving in vehicles as it contributes to a considerable rate of the unsprung weight. The developing of hybrid materials technology can be employed for avoiding bulky leaf spring with identical load carrying ability and stiffness. This paper describes the design and experimental analysis of composite leaf spring made of woven glass fiber reinforced polymer (FRP). The main goal of this study is to investigate the load carrying capability, stiffness, and possibility for weight minimization in composite materials as a lightweight alternative to conventional metallic leaf springs. The effective geometric parameters have been designed for 1000 kg automobile mass. The finite element analysis has been used as a computer-based simulation technique for prediction spring thickness (h) related to safe displacement and induced stress due to the applied load. The numerical and experimental outcomes demonstrate the strength, durability, and fatigue performance of composite materials. Additionally, the proposed fabricated prototype demonstrates an 80% weight reduction compared to a steel multi leaf spring, confirming its suitability for lightweight and high efficiency applications.

1. Introduction

Leaf springs are used for damping vertical vibrations caused by road terrains and saving the potential energy as strain energy. Thus, high specific strain energy ability is the important material feature required for leaf springs [1]. Recent technologies have begun to find alternatives of energy sources to minimize the environmental pollution. Thus, it becomes obvious the target is to replace fossil fuel sources [2]. Composite materials are so important in numerous engineering industries, such as automobile parts, aero components and medical tools [3]. In recent technologies, the glass fiber reinforcement is frequently used in hybrid beams because of their higher tensile properties for many loadings [4]. Laminated fibrous materials are made by combination two or more materials work together to give properties more desirable than those of the certain parts used individually. The introduction of composites is useful for cost saving and weight minimization also high strength to weight ratio [5, 6]. Consequently, replacing the heavy steel material by suitable light composites is the main plan for the relevant researchers.

Many proposed analytical and experimental studies were related to the carbon fiber utilization in engineering applications, where the papers of [7, 8] investigated the performance of composite members under the action of compressive load. The authors in [9] performed FEM analysis for steel and composite leaf springs. The comparison results showed that the layered carbon and epoxy leaf spring is less weight, stiffer and more economic than the typical steel spring for the same design requirements. Design and fabrication of master leaf with tapered thickness made of carbon fiber was proposed in the work of [10], whereas glass fiber was used for uniform thickness in [11]. The characteristics of composite materials was also resulted in a benefit for strain energy level enhancement as recorded when using carbon fiber with viscoelastic core in the study of [12]. Moreover, performing static analysis on mono composite leaf spring for the purpose of stiffness and strength improvement was observed to be of interest as explained in [13, 14]. Numerous analyses were carried out on a mono hybrid leaf spring to achieve the safe design through displacement and stress estimation. Besides, the study of reference [15] analyzed both the metallic and hybrid leaf spring. A comparison between the steel and composite devices about the cost and weight was performed in [16, 17]. Many prior studies has focused on examine the dynamic performance of layered spring made of fibers reinforced plastic resin. The outcomes of the experimental test showed that the failure of the device happened as a result of layers delamination through the neutral line [18]. Prediction of service life of laminated damping structure was estimated numerically and practically as described in the work of [19] and [20]. The studi~~e~~s of [21, 22] presented a methodologies to determine the number of cycles and endurance limit to reach a damage under dynamic load. Other studies examined the identical structure to specify the failure type due to the action of impact load [23, 24]. Many researchers were involved in utilizing different kinds of fibrous materials to improve the efficiency of the reinforcement, the specifications of unidirectional E- glass fiber are appropriate to capture the strain energy as claimed in [25], whereas in [26] the paper reviewed the benefits of replacing metallic spring by a spring made of composite materials. Based on this aspect, S-glass and graphite materials were employed for design and fabrication of suspension device in [27, 28], Kevlar was used in [29] and aramid fiber in the study of [30].

The originality of this research lies in its approach to designing and fabricating woven glass fiber reinforced plastic (FRP) leaf springs as a lightweight and efficient alternative to conventional steel leaf springs for vehicles. Tailoring the design to lightweight vehicles such as solar vehicles, which are emerging technologies. The research shows a low degree of originality within its niche application area, particularly in the detailed design, fabrication, and testing of the FRP leaf spring. It contributes to ongoing efforts in the automotive field to reduce weight and improve performance using advanced composite materials.

2. Theoretical Part

2.1. Parametric Design of the Leaf Spring

The introduction of composite materials made it possible to reduce the weight of the leaf spring without reduction of load carrying capacity and stiffness due to more elastic strain energy storage capacity and high strength to weight ratio, the strain energy density of material is [30]:

$$\boldsymbol{s = \frac{1}{2}\frac{\sigma^2}{\rho E}} \qquad (\mathbf{1})$$

Where E is the modulus of elasticity and ρ is the density of the material. High strain energy level can be obtained when utilizing high stiffness, strength and low weight materials. These specifications are the key for selection composites in design of leaf spring.

The prototype shown in Figure (1) has been proposed to bear one ton duty vehicle. The length (L) and width (b) of the spring was chosen to be the dimensions of a master leaf steel spring that is present in such vehicles, whereas the required thickness (h) should be designed based on the car mass. The mechanical properties of the fabrication materials and the constrained boundary conditions have been selected to be as follows:

The load on each spring can be calculated by dividing the total load on the number of wheels:

$$\boldsymbol{P = \frac{1}{4}W} \qquad (\mathbf{2})$$

The thickness of the spring and the spring radius of curvature were calculated from the following equations [31]:

$$R = \frac{\delta}{2} + \frac{L^2}{8\delta} \qquad (3)$$

$$\sigma = \frac{M.y}{I} \qquad (4)$$

$$\delta = \frac{PL^3}{48EI} \qquad (5)$$

For a beam made of fibrous composite materials, the bending stiffness is function of the number of layers, beam width and fiber direction**.**

The geometric design parameters of the entire design is illustrated in Figure (1). Table (1) explains the specifications of the suggested prototype. Based on literatures, almost design studies suggested a factor of safety range (1.2 -2) for various types of design duties. However, for light weight application in [27], a factor of safety 1.25 was assumed and therefore it was considered in this work. The mechanical properties of woven glass fiber and epoxy composites were experimentally evaluated through tensile test and utilized in the current analysis, as listed in Table (2). The mechanical properties were determined experimentally as discussed later.

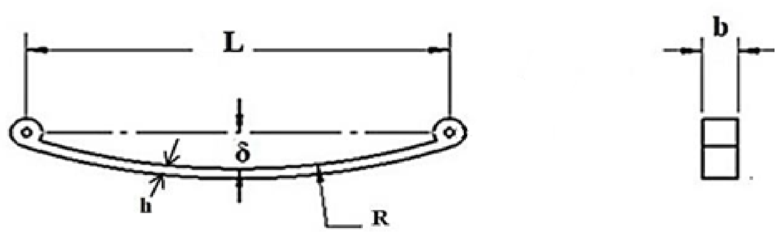

Figure (1): Proposed composite leaf spring and design parameters.

Table (1): Specifications of the developed model.

length (L)	740 mm
Radius of curvature R	1170.83 mm
Camber δ	60 mm
Width b	56 mm
Thickness h	Design parameter
Car mass	1000 kg
Factor of safety	1.25[27]
Load on spring	3065.625 N

Table (2): Material properties**.**

material	Woven glass fiber and epoxy
Young modulus	4000 MPa
Tensile strength	176 MPa

2.2. Bending Stiffness of Composite Beam

The bending stiffness of a beam made of laminated fibrous materials as shown in Figure (2) can be formulated as [32, 33]:

$$EI = b\left(D_{22} - \frac{{D_{12}}^2}{D_{11}}\right) \quad (6)$$

Where:

$$D_{ij} = \sum_{k=1}^{N} [\bar{Q}_{ij}]_k \left(\frac{t_k^3}{12} + t_k \bar{z}_k^2\right) \quad (7)$$

And

$$\left.\begin{aligned}
\bar{Q}_{11} &= Q_{11}m^4 + 2(Q_{12} + 2Q_{66})m^2n^2 + Q_{22}n^4 \\
\bar{Q}_{12} &= (Q_{11} + Q_{22} - 4Q_{66})m^2n^2 + Q_{12}(m^4 + n^4) \\
\bar{Q}_{22} &= Q_{11}n^4 + 2(Q_{12} + 2Q_{66})m^2n^2 + Q_{22}m^4 \\
\bar{Q}_{16} &= (Q_{11} - Q_{12} - 2Q_{66})m^3n + (Q_{12} - Q_{22} + 2Q_{66})mn^3 \\
\bar{Q}_{26} &= (Q_{11} - Q_{12} - 2Q_{66})n^3m + (Q_{12} - Q_{22} + 2Q_{66})nm^3 \\
\bar{Q}_{66} &= (Q_{11} + Q_{22} - 2Q_{12} - 2Q_{66})m^2n^2 + Q_{66}(m^4 + n^4)
\end{aligned}\right\} \quad (8)$$

$$\left.\begin{aligned}
Q_{11} &= \frac{E_1}{1 - \nu_{12}\nu_{21}} \text{ and } Q_{22} = \frac{E_2}{1 - \nu_{12}\nu_{21}} \\
Q_{12} &= \frac{\nu_{12}E_2}{1 - \nu_{12}\nu_{21}} = \frac{\nu_{21}E_1}{1 - \nu_{12}\nu_{21}} \text{ and } Q_{66} = G_{12}
\end{aligned}\right\} \quad (9)$$

$$\left.\begin{aligned}
m &= \cos\theta \\
n &= \sin\theta
\end{aligned}\right\} \quad (10)$$

$$\bar{z} = \frac{h_k + h_{k-1}}{2} \quad (11)$$

Where EI: bending stiffness (N.mm^2), b is the beam width (m), E1, E2: Young modulus (MPa) in longitudinal and transverse direction, ν_{12}, ν_{21}: Poisson's ratio in longitudinal and transverse direction, t: lamina thickness (m), G: shear modulus (MPa).

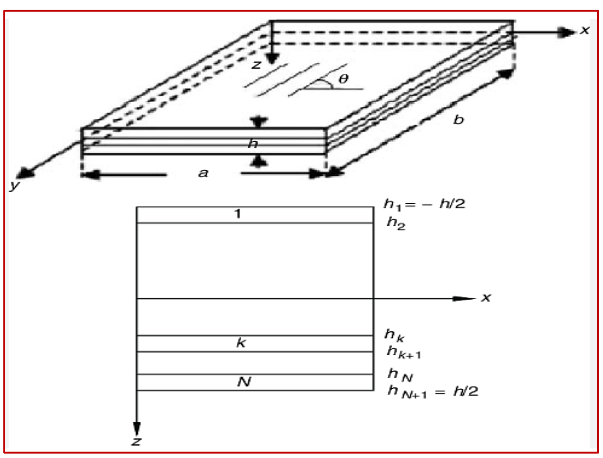

Figure (2): Laminated beam cross section.

The bending stiffness is function of fiber direction (θ), however, for woven glass fiber E_1=E_2 and $\nu_{12} = \nu_{21}$. A preliminary test was performed through computer program by Python version 3.12 software to indicate the effect of fiber direction on the bending stiffness. Table (3) illustrates the values of bending stiffness with respect to fiber direction for symmetric beam lamination with arbitrary number of layers say 20.

Table (3): Effect of fiber direction on the laminated beam stiffness

Fiber direction (θ°)	EI ($N.mm^2$)
$[(0)_{10}]_s$	$1.866*10^7$
$[(25)_{10}]_s$	$1.209*10^7$
$[(\pm30)_{10}]_s$	$0.954*10^7$
$[(\pm45)_{10}]_s$	$0.466*10^7$
$[(\pm60)_{10}]_s$	$0.953*10^7$
$[(\pm75)_{10}]_s$	$1.624*10^7$
$[(90)_{10}]_s$	$1.866*10^7$

From the results listed in Table (3), for woven glass fiber the (0°) direction produced maximum bending stiffness. Therefore, the leaf spring will be laminated with (0°) fiber direction.

2.3. Finite Element Modeling

Almost prior studies used finite element approach for the analysis of metallic and hybrid spring structure as a reliable solution [34-36]. The current design was simulated in Ansys 18.0 software as depicted in Figure (3) so as to perform numerical test to estimate the required thickness (h) based on the induced displacement and bending stress. Element size was refined iteratively during meshing process pending to results convergence at 32829 number of elements as it is clear in Figure (4). The material properties which have utilized in the analysis were calculated experimentally. The simply supported boundary conditions were applied at both ends where the structure motion was constrained to expand only in x-direction, other degrees of freedom were substituted as zero value. A distributed load along the width was applied at the middle of the spring as shown in Figure (5).

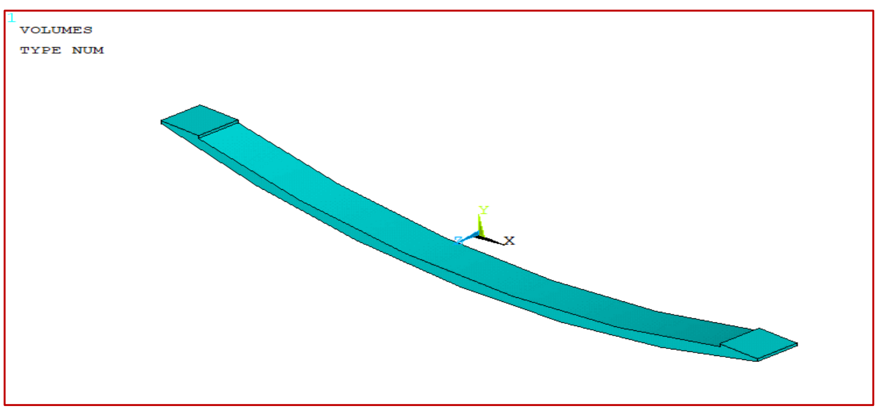

Figure (3): Spring modeling in Ansys software.

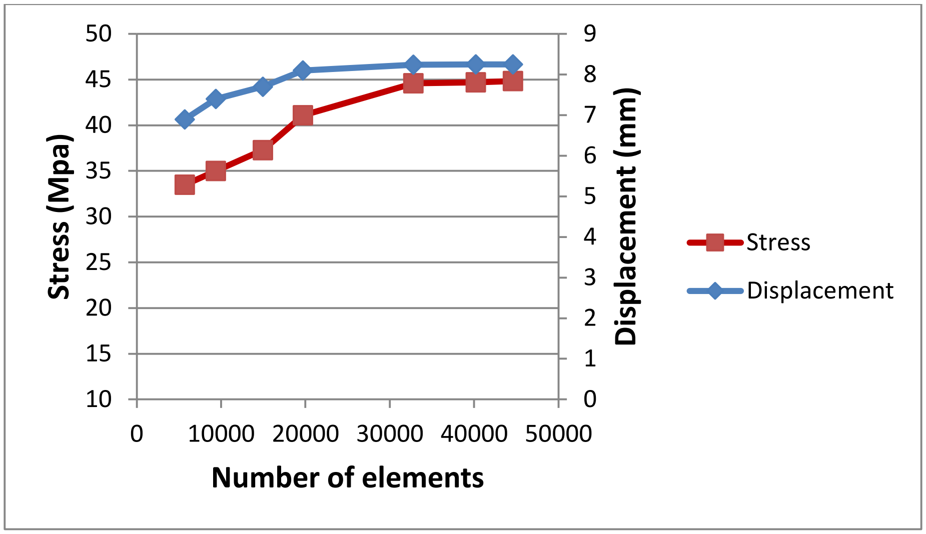

Figure (4): Results convergence at maximum load.

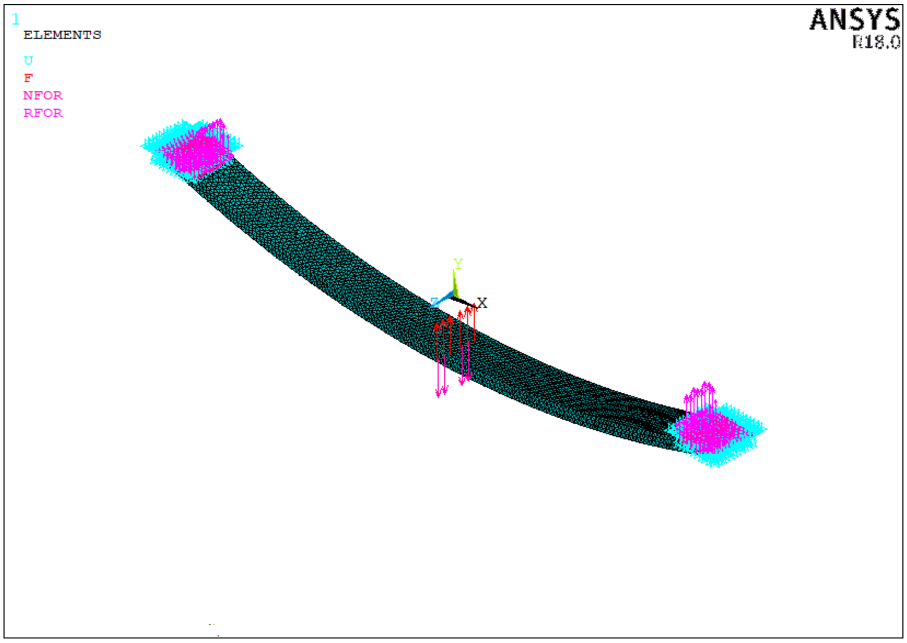

Figure (5): Applied load and boundary conditions during the analysis.

3. Experimental Procedure

3.1. Mechanical Properties

The experimental study has been started by calculating the mechanical properties of the fabric fiberglass and epoxy resin composite, Figure (6) shows the materials used in the hand lamination process. A composite plates were laminated to prepare test specimens. The tensile specimens were machined according to ASTM D3039 standard as explained in Figures (7 & 8).

Figure (6): Materials used for preparing a tensile specimens: (1) Cleaning material, (2) Hardner, (3) Isolation material, (4) Epoxy, and (5) Woven glass fiber.

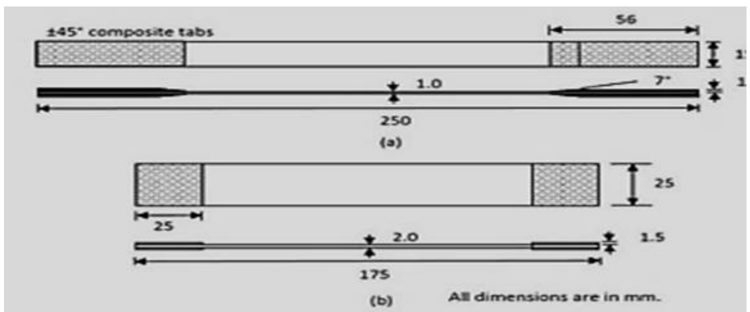

Figure (7): ASTM D3039 tensile specimen standard Dimension (mm): (a) Fiber orientation 0°, (b) Fiber orientation 45° [37].

In this work, the specimen with (0°) fiber direction were made from (3 layers) and the specimen with (45°) fiber direction were made from (6 layers).

Figure (8): Fabricated specimens.

After the tensile test was performed, the shear modulus of the composite was calculated using the following formula [38]:

$$\boldsymbol{G_{12}} = \frac{\mathbf{1}}{\frac{\mathbf{4}}{\boldsymbol{E_X}} - \frac{\mathbf{1}}{\boldsymbol{E_1}} - \frac{\mathbf{1}}{\boldsymbol{E_2}} + \frac{\mathbf{2}\boldsymbol{\nu_{12}}}{\boldsymbol{E_1}}} \qquad (\mathbf{12})$$

Where Ex is the young modulus (MPa) calculated at 45° fiber direction specimen.

3.2. Lamination of the Proposed Model

To fabricate accurate specified dimensions and profile with good surface finish, a lamination mold was designed by means of Solidworks software .The frame mold was manufactured from steel and used in the lamination steps. Figure (9) shows the hand lay-up of the leaf spring. The designed spring thickness is considered to be 18 mm, so 36 woven fiber glass and epoxy layer was laminated for fabricating the specified dimensions. The thickness of each lamina was determined to be 0.5 mm. A digital scale was used to measure the mass of fiber and the mass of resin used in fabrication process. Then, the fiber rate is equal to the mass of fiber divided by the mass of the fabricated composite plate resulting in a value of 0.6 fiber volume fraction. The mounted laminate in the mold was exposed to room temperature for 72 hours for verifying the solidification state. Figure (10) shows the final shape of the fabricated design.

Figure (9): Spring lamination.

Figure (10): The fabricated leaf spring.

3.3. Experimental Stress Analysis

An experimental test was performed on the fabricated structure so as to calculate the induced deflections and stresses under the action of distributed bending load. Towards achieving this goal, a test frame was designed and manufactured for fixing the loaded spring. A hydraulic actuator was used to apply the range of the desired load gradually with constant increment. The resulting deflection was measured by vernier tool with 0.01 mm scale precession. The strain can be estimated in lab experiments via a strain guage sensor and related it theoretically via Hook’s law formulated in Eq. (11), to measure the value of resulting stress due to an applied load. Strain gauge utilization in experimental stress analysis was presented in prior studies of **[**39-42]. Based on this idea, a 120 Ω strain gauge was glued in the mid span of the fabricated spring where the maximum bending stress has occurred as pictured in Figure (11). The sensor was connected to a data acquisition system to display the value of recorded strain. Figure (12) illustrates the current design mounted in the test frame.

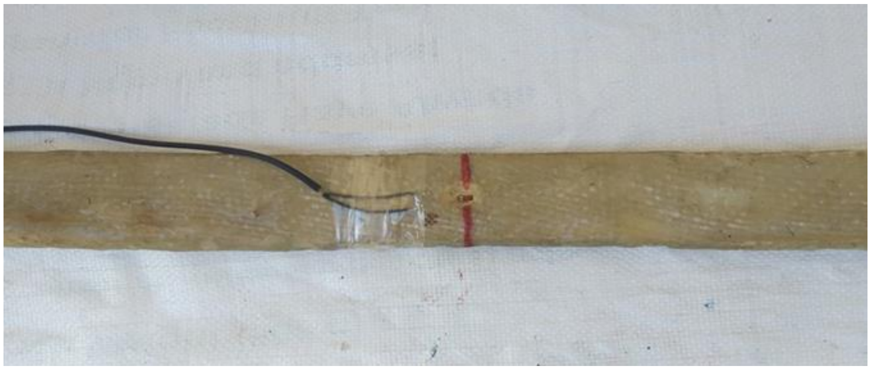

Figure (11): Strain gauge glued at mid span.

Figure (12): Experimental test for calculation the induced stresses and deflections.

The Hooks law was applied to calculate the stress value from gathered strain data as follows:

$$\boldsymbol{\sigma_{exp} = E * \epsilon} \qquad \textbf{(13)}$$

Where E Young modulus (MPa), ϵ strain measured by strain gauge.

4. Results and Discussion

4.1. Stress Analysis Results

The stress analysis was performed iteratively by Ansys software under the range of load began at minimum 250 N and raised by 250 N gradually until the peak estimated load is 3065.625 N. Figures (13 & 14) explain the contour plots for the resulted vertical displacement and Von Mises stress at permissible ultimate load respectively.

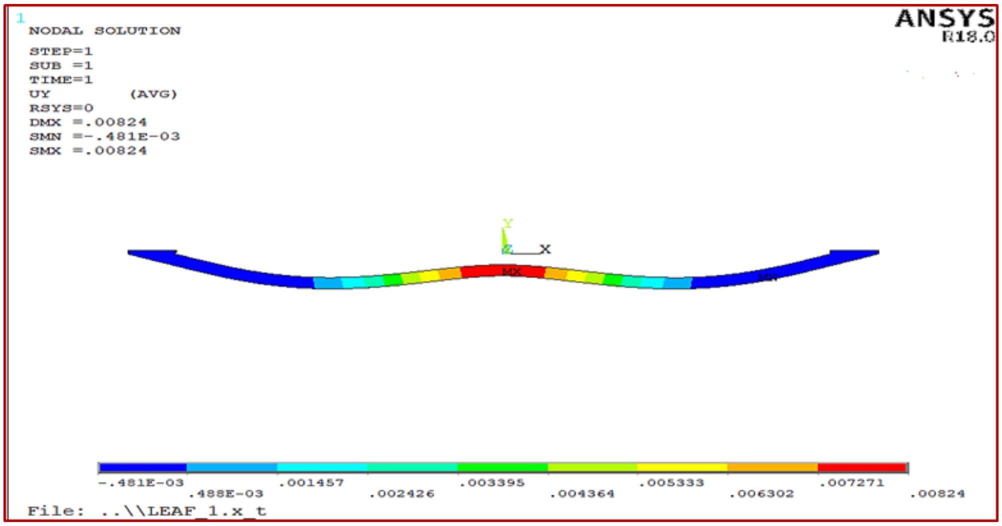

Figure (13): Vertical displacement distribution (m) at peak load.

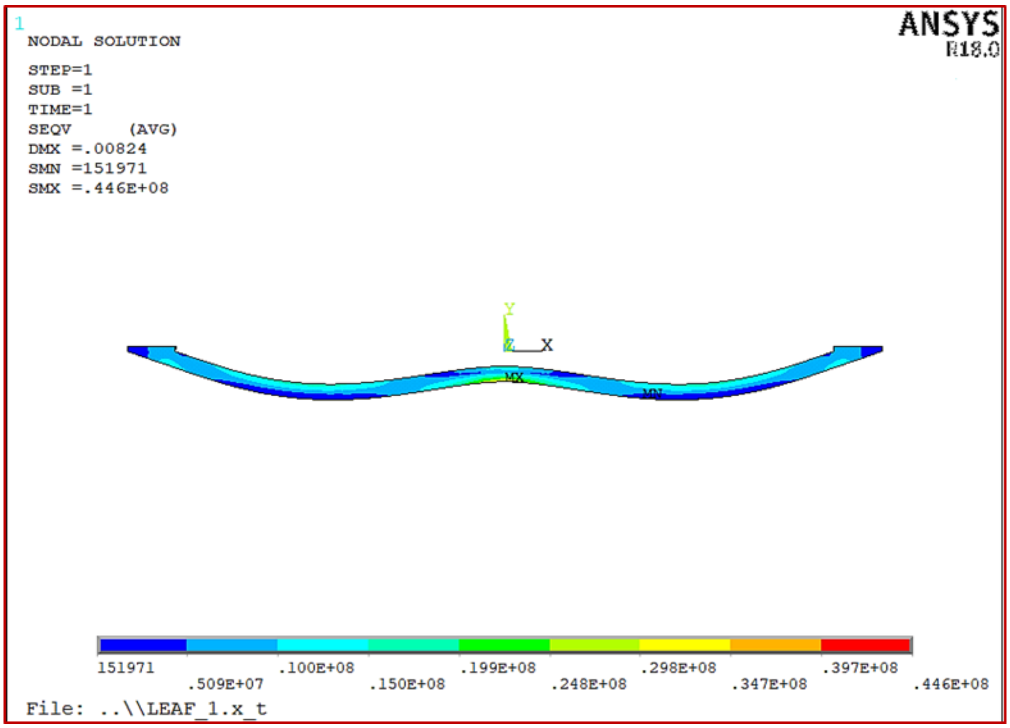

Figure (14): Von Mises stress distribution (Pa) at peak load.

To ensure the outcomes of the numerical solution and to understand the actual behavior of the proposed design, an experimental test data was recorded in Figures (15 & 16) for verification results.

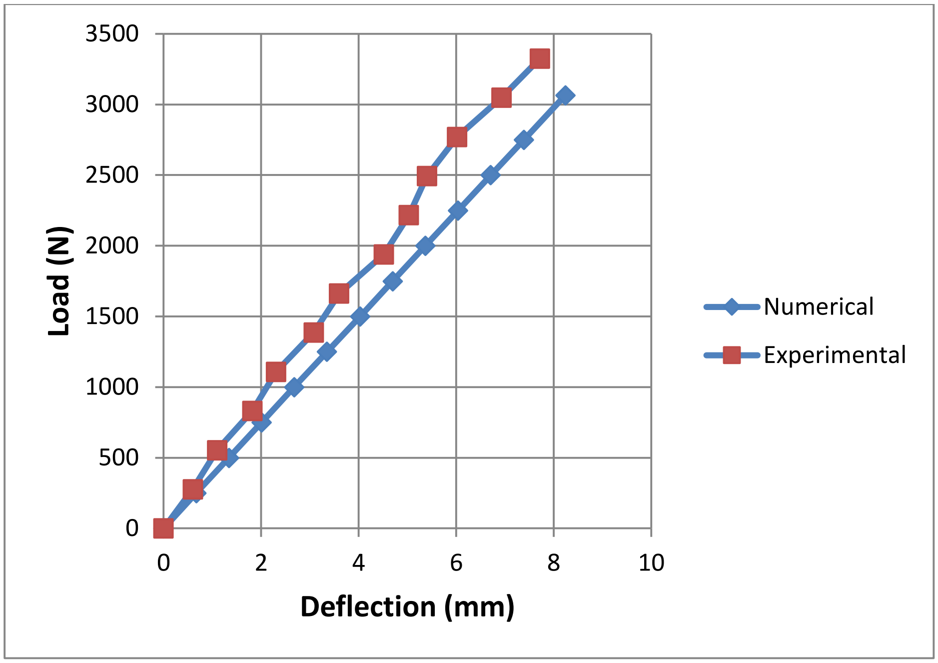

Figure (15): Induced numerical and experimental displacement for various load values.

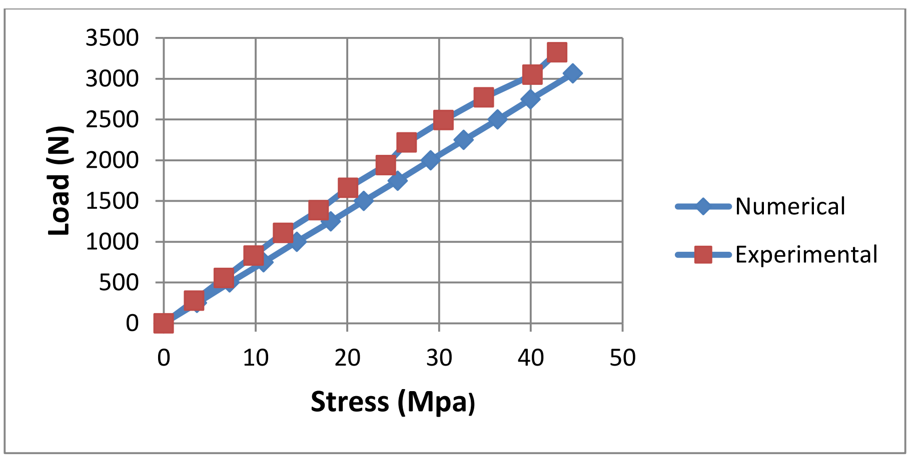

Figure (16): Induced numerical and experimental stresses for various load values.

4.2. Fatigue Results

Glass-fiber-reinforced thermoplastics are typically tested under zero-to-maximum tension or bending. Such composites may have various reinforcement details, such as continuous unidirectional fibers, random chopped fiber mats, or short chopped fibers for injection molding, where [43]:

$$\boldsymbol{R} = \frac{\boldsymbol{\sigma_{min}}}{\boldsymbol{\sigma_{max}}} \qquad (\mathbf{14})$$

If R=0, that means the dynamic load vary from zero to maximum which is considered in this work resulting a $1*10^6$ cycle life as obvious in Figure (17) and a minimum dynamic factor of safety 3.32 as shown in Figure (18).

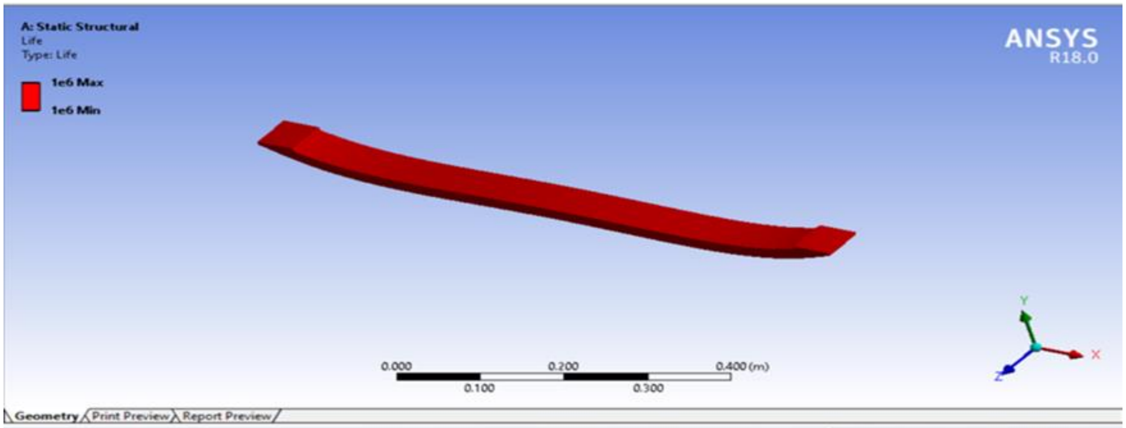

Figure (17): Service life of the proposed design at maximum load.

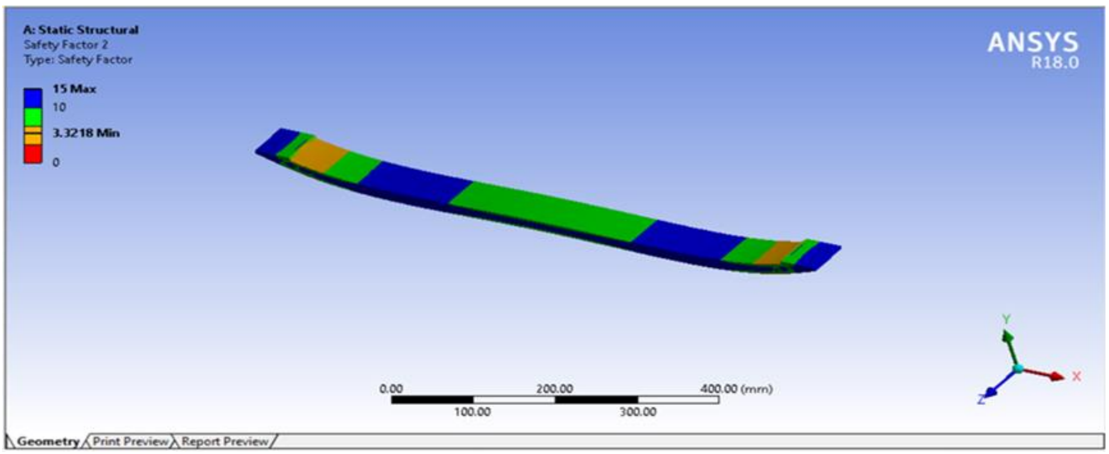

Figure (18): Dynamic factor of safety at maximum load.

Overall, the current work aim is to design a robust and light weight vehicle suspension structure from the benefit of durable composite materials. The design factor (h) was calculated by means of Ansys software through iterative solution to achieve the result that (h=18 mm) as a suitable spring thickness. The numerical solution gives a clear insight about the values of displacements and stresses distribution along the spring span and the critical zones where the induced values are the maximum. The recorded peak deflection observed to be 8.24 mm as shown in Figure (13), which is below the value of spring camber in Table (1). The maximum stress is 44.6 MPa was recorded in the points of load application as it is obvious in Figure (14). However, this value is still below the ultimate tensile strength listed in Table (2). Compared to the numerical solution, the identical boundary conditions have been applied in the experiments and all the results were compared accordingly and as plotted in Figures (15 & 16) which reveal that the fabricated structure is safer when it is subjected to the predicted load. Figure (17) shows that the current design reaches the maximum number of cycle which is $1*10^6$ cycle with minimum factor of safety 3.2 as obvious in Figure (18). The prototype of the actual steel leaf spring for a 1000 kg capacity vehicle was simulated, as shown in Figure (19). Its mass, calculated using FEM software command, is 6.7981 kg. In contrast, the mass of the fabricated woven glass fiber leaf spring is 1.32 kg, achieving an 80% weight reduction compared to traditional steel leaf spring.

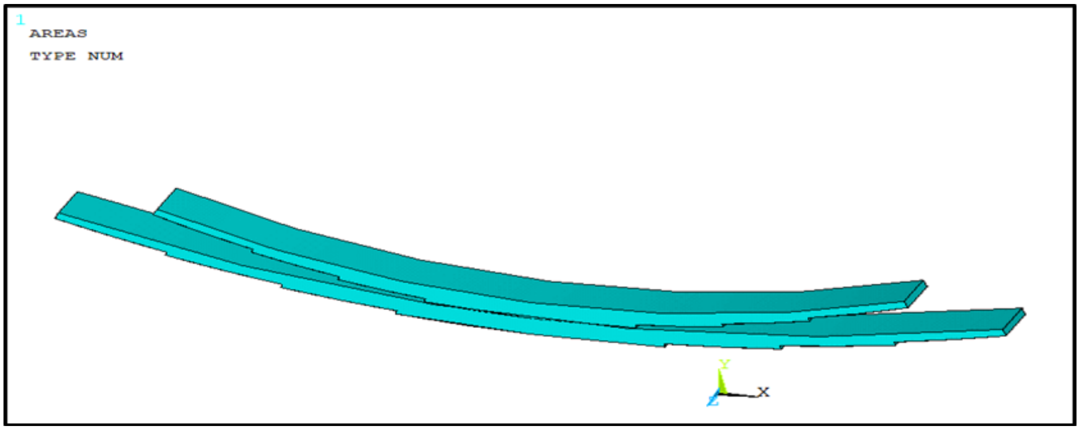

Figure (19): Multi leaf steel spring.

5. Conclusions

The current study is focused on the investment of polymeric composite materials with a suitable lamination for possible using instead of conventional metallic material for suspension leaf spring. Furthermore, the motivation forward such design is the composite materials have good strength to weight ratio also the ability to store energy and release it when the load is removed to give a considerable damping property. The study includes numerical and experimental static evaluation of spring strength and bending displacement under the action of 1000 kg car mass. The numerical and experimental outcomes verified that a woven fiber glass and epoxy spring with thickness of 18 mm, width 56 mm and length 740 mm is efficient to be used in such automobiles. A weight reduction is a clear result in this analysis, the mass of the fabricated structure is just 1.32 kg which is quite lighter if compared to multi leaf steel spring. Also, the composite materials able to withstand the dynamic loading and provide high service life to fatigue, so utilizing the composite materials in industry can be considered as a good solution for weight minimization. For future work, further weight reduction can be achieved by applying modern shape optimization techniques to develop an effective design for the leaf spring. Building on these investigations, future efforts in shape optimization may lead to an optimal design for the composite leaf spring.

Conflict of Interest: The authors declare that there are no conflicts of interest associated with this research project. We have no financial or personal relationships that could potentially bias our work or influence the interpretation of the results**.**

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