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Optimization of Leaf Spring for Strength Using Composite Material for Light Commercial Vehicle

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Abstract : Safety, energy saving and environmental protection are the important trends in case of an automobile. Lightweight has become an important goal of vehicle development. The leaf spring is about 5% to 10% of the total mass of vehicles as the vehicle suspension elastic element. So leaf spring is one of the important components to achieve vehicle lightweight. It can be easily observed that material having lower modulus and density will have a greater specific strain energy capacity. 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. A material with maximum strength and minimum modulus of elasticity in the longitudinal direction will be the most suitable material for a leaf spring. To meet the need of natural resources conservation, automobile manufacturers are attempting to reduce the weight of vehicles in recent years. Weight reduction can be achieved primarily by the introduction of better material, design optimization and better manufacturing processes. The suspension leaf spring is one of the potential items for weight reduction in automobiles unsprung weight. This achieves the vehicle with more fuel efficiency and improved riding qualities. The introduction of composite materials has made it possible to reduce the weight of leaf spring without any reduction on load carrying capacity and stiffness.

Keywords: Leaf Spring,Composite Material, Weight Reduction, Modulus of Elasticity, Elastic Strain Energy

INTRODUCTION

Originally called ‘laminated’ or ‘carriage spring’, a leaf spring is a simple form of spring commonly used for the suspension in wheeled vehicles. It is also one of the oldest forms of springing, dating back to medieval times. Sometimes referred to as a semi-elliptical spring or cart spring, it takes the form of a slender arc-shaped length of spring steel of rectangular cross-section. The centre of the arc provides location for the axle, while tie holes are provided at either end for attaching to the vehicle body. For very heavy vehicles, a leaf spring can be made from several leaves stacked on top of each other in several layers, often with progressively shorter leaves.

Leaf springs can serve locating and to some extent damping as well as springing functions. While the interleaf friction provides a damping action, it is not well controlled and results in stiction in the motion of the suspension. For this reason manufacturers have experimented with mono-leaf springs.

A leaf spring can either be attached directly to the frame at both ends or attached directly at one end, usually the front, with the other end attached to a shackle, a short swinging arm. The shackle takes up the tendency of the leaf spring to elongate when compressed and thus makes for softer springiness. Some springs terminated in a concave end, called a spoon end (seldom used now), to carry a swiveling member.

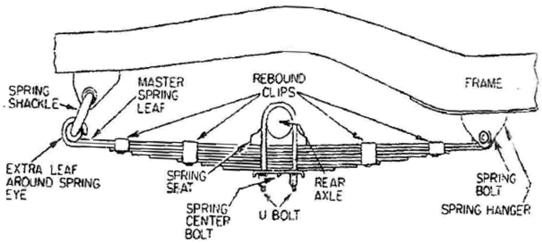

FIG. 1 CONVENTIONAL LEAF SPRING

LITERATURE REVIEW

Kong et al. [1] have simulated the fatigue life of a parabolic leaf spring design under variable amplitude loading (VAL). VALs carry the road signal that provokes fatigue failure on leaf spring. In order to seek for comprehensive leaf spring fatigue assessment, VALs signal were gathered through measurements from various road conditions such as highway, curve mountain road and rough rural area road. Subsequently, fatigue life of particular leaf spring design was predicted using finite element (FE) stress–strain model together with VALs signal as load input. For more conservative way, Morrow and Smith Watson To per (SWT) mean stress correction methods were also applied. The results indicate that fatigue life of leaf spring is lowest during rough road mission, followed by curve mountain road and smooth highway road respectively. Additional design modification to prolong the fatigue life of the parabolic leaf spring is compulsory. The road VALs has provided even more realistic fatigue life estimation of parabolic leaf spring design when compared to traditional controlled laboratory method. Parabolic leaf spring experiences repeated cyclic loading during operating condition. Fatigue life assessment of the parabolic leaf spring is a significant aspect during the component design stage.

Malaga et al. [2] have studied the replacement of multi-leaf steel spring with mono composite leaf spring. Suspension system in an automobile determines the riding comfort of passengers and the amount of damage to the vehicle. The main function of leaf spring assembly as suspension element is not only to support vertical load, but also to isolate road-induced vibrations. The behavior of leaf spring is complicated due to its clamping effects and inter-leaf contact etc. Since the composite materials have more elastic strain energy storage capacity and high strength-to-weight ratio as compared to those of steel. It is possible to reduce the weight of the leaf spring without any reduction on load carrying capacity and stiffness. The design constraints were limiting stresses and displacement. Modeling and analysis of both the steel and composite leaf springs have been done using analysis software.

The introduction of composite materials was made it possible to reduce the weight of the leaf spring without any reduction on load carrying capacity and stiffness. Since, the composite materials have more elastic strain energy storage capacity and high strength-to-weight ratio as compared to those of steel. The introduction of fiber reinforced plastics made it possible to reduce the weight of a machine element without any reduction of the load carrying capacity.

Murathan et al. [3] have studied the fiber reinforced composite compared with steel leaf springs based on endurance rig tests. The conventional leaf springs, designed for the optimized performance together with safety factors, are made of steel. However, it is considered that the steel leaf springs are replaced by lighter ones in order to fulfill the specified requirements. Fiber reinforced composite materials with polymer based matrix offer a great potential for manufacturing leaf springs with lightweight, high mechanical and fatigue performance. Therefore, leaf spring manufacturers have great interest on those materials to replace steel parts with the composite ones and an increasing number of studies have been published in the literature in recent years. Leaf spring system affects the weight of the vehicle in addition to driving performance and security. Seeking materials, which are lightweight and high performance, instead of steel has been continued in recent years and it has been accelerated in last few years all over the world due to recent regulations. Composite materials have the highest potential to become an alternative candidate material for this purpose. In addition to their lightweight, composite materials are suited to manufacture leaf springs due to their excellent fatigue performance, higher corrosion and chemical resistance and their process flexibility as compared to steel.

Abdul Rahim Abu Talib et al. [4] demonstrated that composite elliptical springs can be used for light and heavy trucks with substantial weight reduction. Suspension system is designed to provide both safety and comfort for the vehicle occupants. In this study, finite element models were developed to optimize the material and geometry of the composite elliptical spring based on the spring rate, log life and shear stress parameters.

Fiber-reinforced polymers have been vigorously developed for many applications, mainly because of the potential for weight savings. Other advantages of using fiber-reinforced polymers instead of steel are: (a) the possibility of reducing noise, vibrations and ride harshness due to their high damping factors; (b) the absence of corrosion problems, which means lower maintenance costs; and (c) lower tooling costs, which has favorable impact on the manufacturing costs.

The shear stress was calculated for the composite elliptic spring model, and a different set-up was applied for 30 layer altogether at different fiber orientation angles. At 450, the stresses in the principal coordinates of an equal-layer-thickness [±h] angle-layer laminate, under uniform axial loading as a function of the fiber orientation, are shown in Fig. 2, which represent the variation of the shear stress from 00 until 900. It appears the lowest shear stress occurs in the range from 200 to 600.

Mahmood and Rezaei [5] have studied methodology to obtain a spring with minimum weight that is capable of carrying given static external forces without failure The finite element results showing stresses and deflections verified the existing analytical and experimental solutions. Using the results of the steel leaf spring, a composite one made from fiberglass with epoxy resin is designed and optimized using ANSYS. Main consideration is given to the optimization of the spring geometry.. The design constraints were stresses (Tsai– Wu failure criterion) and displacements. The results showed that an optimum spring width decreases hyperbolically and the thickness increases linearly from the spring eyes towards the axle seat. Compared to the steel spring, the optimized composite spring has stresses that are much lower, the natural frequency is higher and the spring weight without eye units is nearly 80% lower.

Gary and Khoa [6] have studied the fundamentals of multi-leaf spring design as determined through beam theory offers a general perspective on how finite element analysis works. Additionally, the fundamentals of combining dissimilar materials require a basic knowledge of how the combined equivalent modulus affects the overall stiffness characteristics of multi-leaf design. By capturing these basic fundamentals into finite element modelling, an analysis of a steel-composite multi-leaf contact model relative to an idealized steel-composite multi-leaf model shows the importance of contact modelling. The results demonstrate the important differences between an idealized non-contact models relative to a complete contact model.

S. Rajesh et al. [7] showed that by properly selecting the % of reinforcement and its orientation it is possible to achieve higher order stiffness and consequently higher natural frequency. In fact unlike homogenous metallic material. GFRP composite will exhibit increased stiffness with load application. When a seven leafs spring was replaced by mono composite leaf spring under the static condition of design parameters and optimization, appreciable weight-reduction was reported. The joint strength plays an important role in the functioning of leaf spring in vehicle suspension. Leaf springs were shaped by short, and long glass fiber reinforced polypropylene and unreinforced polypropylene and the joint performance in both static and dynamic conditions was assessed. This study illustrates that the possibility of replacing existing conventional steel-leaf spring by the leaf spring made by tailoring the layup of composite laminates. The dimensions of the existing conventional middle leaf (spring) of a commercial vehicle were chosen for the design and manufacture of die for moulding the composite leaves. Accordingly, suspension springs of composites of different layups with glass and carbon were fabricated and tested for flexure response. It is to be noted here that the cross sectional area of the composite leaf spring was the same as of the conventional leaf spring. By using universal testing machine, load per deflection and maximum load for each of the composite leaf springs were evaluated. The low frequency impact on the composite leafs was effected with a laboratory loading set-up in a milling machine. Experimental results indicated the superior flexure response of the hybrid composites and suggested possible alternative on comparison with the conventional spring.

Franklin and Edward [8] have investigated the traditional steel multi-leaf spring pack which has been a low cost widely utilized suspension system in vehicles for decades. Applications are typically load carrying orientated, from light trucks to heavy construction equipment. Improvements to the basic design in terms of stress reduction, fatigue resistance and significant weight reduction can be achieved through the cladding of composite material to the existing steel main spring. Testing was conducted using standard test methods where available to compare the durability of a standard Multi leaf Steel Pack to a Hybrid Mono Leaf Spring. The Hybrid Spring demonstrated significant improvements in the areas of ultimate deflection, fatigue and creep resistance. Testing to date confirms the benefit of the reduced stress in the outer most fibres that is an inherent feature of the Fiberglass Mono-leaf Hybrid Spring. In the areas of automotive fluid exposure the coating faired well, brake fluid causing the most degradation. The gravel meter testing when comparing painted composite to the elastomeric coating exhibited improved results.

Gulur and Sambagam [9] have studied increased interest of automobile industry in the replacement of steel spring with fiberglass composite leaf spring due to high strength to weight ratio.This research study aims to present a low cost fabrication of complete mono composite leaf spring and mono composite leaf spring with bonded end joints. Also, general study on the analysis and design. A single leaf with variable thickness and width for constant cross sectional area of unidirectional glass fibre reinforced plastic (GFRP) with similar mechanical and geometrical properties to the multi-leaf spring, was designed, fabricated (hand-layup technique) and tested. Computer algorithm using C-language has been used for the design of constant cross-section leaf spring. The results showed that a spring width decreases hyperbolically and thickness increases linearly from the spring eyes towards the axle seat. The finite element results using ANSYS software showing stresses and deflections were verified with analytical and experimental results. The design constraints were stresses (Tsai-Wu failure criterion) and displacement. Compared to the steel spring, the composite spring has stresses that are much lower, the natural frequency is higher and the spring weight is nearly 85 % lower with bonded end joint and with complete eye unit.

J.P. Hou et al. [10] have described three designs of eye-end attachment for composite leaf springs. The material used is glass fibre reinforced polyester. Static testing and finite element analysis have been carried out to obtain the characteristics of the spring. Load– deflection curves and strain measurement as a function of load for the three designs tested have been plotted for comparison with FEA predicted values. The main concern associated with the first design is the delamination failure at the interface of the fibres that have passed around the eye and the spring body, even though the design can withstand 150 KN static proof load and one million cycles fatigue load. FEA results confirmed that there is a high inter laminar shear stress concentration in that region. The second design feature is an additional transverse bandage around the region prone to delamination. Delamination was contained but not completely prevented. The third design overcomes the problem by ending the fibres at the end of the eye section.

Mahadi and Hamouda [11] have investigated that the fiber type and ellipticity ratio significantly influenced the spring stiffness. After 1.15 million fatigue cycles, composite semi-elliptical suspension spring‟s useful stroke is reduced. The relaxation of the composite elliptic spring found to be very sensitive to the compression rate. Among the chassis components, the first major structural application of fiber-reinforced composites is the rear leaf spring; introduced first in 1981. For spring such as in cars or trucks, the service life would probably be based on a certain minimum level of stiffness. This study introduces a new composite semi-elliptical suspension spring by utilizing fiber reinforced composite strength in principal direction instead of shear direction. Three types of composites were tested. Typical behaviors of their compression, tension, torsion and cyclic tests are discussed in this research study.

Kueh and Faris [12] have studied the effects of material composition and its fiber orientation on the static and fatigue behaviors of leaf spring. The design constraints were bending stresses, deflection and fatigue life. Compared to the steel leaf spring, the designed composite spring has much lower bending stresses and deflections and higher fatigue life cycles. The reduction in unsprung weight can improve the riding quality and increase fuel efficiency significantly. Since fiber reinforced plastics (FRPs) composite material has a high elastic strain energy storage capacity, it is possible to use FRP material to replace the conventional multi-leaf steel spring in order to achieve weight reduction without any reduction of the load carrying capacity. Therefore, this research study is aimed at the design of optimized leaf spring where better stiffness and durability represent the real advantages in the use of composite leaf spring. Also study has been done on static and fatigue behaviors of steel and composite multi-leaf spring using analysis software. The dimensions of an existing conventional leaf spring of a light commercial vehicle were used. The same dimensions were used to design composite multi-leaf spring for the two materials.

Jiashi Wang et al. [13] have studied the composite leaf spring with the rectangular cross section designed for the commercial vehicle and was analyzed by using the finite element software and the experimental tests had been conducted to confirm the finite element analysis. Weight reduction can be achieved primarily by the introduction of better material, design optimization and better manufacturing processes. Because of the higher strength-to-weight ratio, superior fatigue strength and excellent corrosion resistance, the fiber reinforce plastics (FRP) has shown increased interest in the replacement of steel spring. When the spring is made of FRP, such as E-Glass/Epoxy, the weight of the spring can reduce 60–70 %, which can leads to reduction of the unsprung weight. The reduction of the unsprung weight could help in achieving the vehicle with improved riding qualities and increased the fuel efficiency. Therefore, the using of composite leaf spring not only leads to the weight reduction, but also improves the riding qualities. In this study composite leaf spring with rectangle cross section with constant thickness and width is 28 × 80 mm is designed for the Commercial vehicle with 15,000 N full load for one spring. The finite element (FE) method is used for the analysis of stress state, computation of numerical spring rate and the maximum load capacity. Meantime, for the validity of the designed spring, the experiment is conducted on the composite leaf spring fabricated by the hot molding process. The measured spring rate and the maximum load capacity are compared with the FE analysis results and it can be seen that the error is 1.56 % for the spring rate and 0.82 % for the maximum capacity load, and the main performances of fabricated composite leaf spring meet the designed requirements.

Ekbote et al. [14] have proposed to replace the existing steel spring with composite spring. With the results of the steel leaf spring, a mono leaf composite spring made & its geometry is optimized by finite element analysis. The design variables are the width and the thickness of the composite spring. The design constraints were stress and displacement. The objective was to obtain a spring with minimum weight capable of carrying intended static external force without failure. The optimized spring will have its width decreasing and thickness increasing hyperbolically from the spring eye towards the axle seat. An approximate spring model is assumed and its analytical solution is also presented. Compared to steel spring, the optimized composite mono leaf spring has much lower stress and the spring weight without eye units is nearly 65% lower than steel spring. This research study is aimed to develop a double tapered polymer fibre reinforced composite mono leaf spring to replace the existing nine leaf steel spring used in the rear suspension system of a small passenger vehicle (Ambassador car). The main consideration is given to the optimal design of the composite leaf spring geometry by accommodating the installation constraints.

Stephan Krall and Richard Zemann [15] have investigated and compared three different composite leaf springs. The composite leaf spring design is calculated via classical lamination theory and the manufacturing was done by hand lay-up and autoclave. An important aspect for spring elements is the behavior at different thermal conditions. Therefore one of the test bodies was investigated at low temperature. At last the suitability of the analytical calculation of the Euler – Bernoulli beam theory was investigated and compared with the experimental results. In this research study the investigation of the dynamic behavior of composite leaf springs shell reveal the potential of such products. Another novelty for leaf springs is the use of CFRP instead of GFRP, which is the standard work piece material for this type of application. This situation is based on the higher breaking strain of glass fibres and the associated higher travel of the spring. Higher stiffness of carbon fibres would reduce the volume of the part in comparison to glass fibre thus leading to less weight. An important aspect is that except of the price for the raw material, there are no additional expenses for the processing of carbon fibres instead of glass fibres.

CHARACHTERISTICS OF LEAF SPRING

1. The leaf spring acts as a linkage for holding the axle in position and thus separate linkage are not necessary. It makes the construction of the suspension simple and strong.
2. As the positioning of the axle is carried out by the leaf springs so it makes disadvantageous to use soft springs i.e. a spring with low spring constant.
3. Therefore, this type of suspension does not provide good riding comfort.
4. The inter-leaf friction between the leaf springs affects the riding comfort.
5. Acceleration and braking torque cause wind-up and vibration. Also wind-up causes rear end squat and nose diving.
6. The inter-leaf friction damps the spring's motion and reduces rebound, which until shock absorbers were widely adopted was a great advantage over helical springs.

The suspension leaf spring is one of the potential items for weight reduction in automobile as it accounts for 10-20% of the un-sprung weight. The introduction of composites helps in designing a better suspension system with better ride quality if it can be achieved without much increase in cost and decrease in quality and reliability. The relationship of the specific strain energy can be expressed as it is well known that springs, are designed to absorb and store energy and then release it slowly. Ability to store and absorb more amount of strain energy ensures the comfortable suspension system. Hence, the strain energy of the material becomes a major factor in designing the springs.

The relationship of the specific strain energy can be expressed as,

$$U=\sigma^2/ 2\rho E$$

Where,
σ is the strength in……… N/mm2
ρ is the density in……….. kg/mm3
E is the Young's Modulus of the spring material……. MPa

SPRING STIFFNESS OF COMPOSITE SPRING

The rapid growth in utilization of composite materials and structures can be attributed to their properties which have achieved high performance and tailoring capability in aerospace and other engineering applications where maximum performance index and merit rating can be achieved. Further substantial growth is expected to be in the general commercial application sectors where the high strength and stiffness to weight ratios as well as the structural effectiveness can be of advantage.

Fibre reinforced composite springs have been considered as viable replacements for steel springs in the automobile industry [1]. The experimental leaf springs of Robertson et al. [2] and the Liteflex composite leaf spring of Frommann and Kirkham [3] represent some early investigations conducted by vehicle manufacturers for weight saving purposes. Theformer springs were tested both in the laboratory and on a Ford Econoline van and acceptable fatigue results were reported. The Liteflex springs were also found to be successful and have been applied in the front and rear suspensions of the Chevrolet Corvette. Although fibre reinforced plastic composites have higher energy storage capacity than steel, they have, in general, poor resistance against shear stresses. Thus, direct application of these materials in coil springs would require an increase in coil diameter. This may override the weight saving advantage of a composite coil spring over its steel counterpart. In order to overcome this disadvantage, the ''Sulcated Spring'' was introduced and the test data showed it to be a very promising concept [4,5]. At the same time, composite elliptic springs were also being studied [6]. Several elliptic spring elements constructed from unidirectional E-glass fibre reinforced epoxy tapes were mounted in series and tested in quasi-static compression. It was observed that the primary failure was due to interlaminar shear [7].

In order to utilise the high tensile strength of the fibre reinforced plastic in spring systems, which must functionin the same vertical deflection mode and within the same space of a steel coil spring, coil spring in braided carbon fibre reinforced plastics were developed by National Engineering Laboratory [8]. However, sophisticated braiding technique and equipment are of paramount importance. An analytical study using the energy method to evaluate the spring constants of elliptic composite rings was undertaken by Akasaka et al. [9]. Spring constants in the directions of the principal axes and for bending-shear and bending-torsion were measured for elliptic rings made of carbon fibre reinforced thermoplastics. Good agreement was obtained between experimental and the predicted results. Concurrently, the mechanical behaviour of composite cylindrical springs with mid-surface symmetry has been investigated [10]. The theory was developed on the basis of a linear elasticity, and the stress–strain distributions around the ring were evaluated. The spring constant in the diametrical direction was accurately predicted. Most recently, studies of the diametrical, Ky , the in-plane bending-shear, Kxy , and the
bending-torsional, Kxz, spring constants of filament wound composite circular rings were also investigated [11]. Closed-form solutions from complementary strain energy were derived for the spring stiffness's of mid surface symmetric, 45 and 75 of odd numbers of covers E-glass/epoxy filament-wound, composite circular rings under unidirectional loading. A three-dimensional finite element analysis including the effects of transverse shear has also been applied to study the problem.

The diametrical stiffness and stress–strain characteristics of mid-surface symmetric, laminated woven circular springs with extended flat contact surfaces under uniform-end-shortening loading configuration were investigated and verified by experimental testing [12]. In order to exploit fully the potential of composite springs with extended flat contact surfaces, it is necessary to characterize the spring constants in the other two directions and under different loading configurations. In the present work, a theory is developed from complementary strain energy and Castigliano's second theorem to predict the spring stiffnesses of mid-surface symmetric, woven composite circular springs with extended flat contact surfaces under unidirectional line and surfaceloading configurations. A three-dimensional finite element model taking into consideration of transverse shear deformation effects has also been employed to investigate the mechanical characteristics of the candidate springs. The analytical and numerical results arE compared with experimental data. The relationships between the spring stiffnesses of woven composite springs with extended flat contact surfaces under different loading configurations and geometry are also illustrated.

CONCLUSIONS

In the recent studies it is found that a comparative study should be done between steel and composite leaf spring with respect to strength and weight. Above study shows that composite mono leaf spring reduces the weight of vehicle suspension system by 85% for different composite materials for e.g. E-Glass/Epoxy, 94.18% for Graphite/Epoxy, and 92.94 % for Carbon/Epoxy over conventional leaf spring. While the stresses in the composite leaf spring are much lower than that of the steel spring.

Observations made shows that compared to the steel leaf spring (9.2 kg) the optimized composite leaf spring without eye unit's weights nearly 80% less than the steel spring. From the results, it is observed that the composite leaf spring is lighter and more economical than the conventional steel spring with similar design specifications. Adhesively bonded end joints enhance the performance of composite leaf spring for delamination and stress concentration at the end in compare with bolted joints.

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