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Analytical and Experimental Studies on Fatigue Life Prediction of Steel and Composite Multi-leaf Spring for Light Passenger Vehicles Using Life Data Analysis

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This paper describes static and fatigue analysis of steel leaf spring and composite multi leaf spring made up of glass fibre reinforced polymer using life data analysis. The dimensions of an existing conventional steel leaf spring of a light commercial vehicle are taken and are verified by design calculations. Static analysis of 2-D model of conventional leaf spring is also performed using ANSYS 7.1 and compared with experimental results. Same dimensions of conventional leaf spring are used to fabricate a composite multi leaf spring using E-glass/Epoxy unidirectional laminates. The load carrying capacity, stiffness and weight of composite leaf spring are compared with that of steel leaf spring analytically and experimentally. The design constraints are stresses and deflections. Finite element analysis with full bump load on 3-D model of composite multi leaf spring is done using ANSYS 7.1 and the analytical results are compared with experimental results. Fatigue life of steel leaf spring and composite leaf is also predicted. Compared to steel spring, the composite leaf spring is found to have 67.35 % lesser stress, 64.95 % higher stiffness and 126.98 % higher natural frequency than that of existing steel leaf spring. A weight reduction of 68.15 % is also achieved by using composite leaf spring. It is also concluded that fatigue life of composite is more than that of conventional steel leaf spring.
Keywords: composite multi leaf spring, E-glass/Epoxy, static analysis and fatigue life, ride comfort.

1. INTRODUCTION

In the present scenario, weight reduction has been the main focus of automobile manufactures. The suspension leaf spring is one of the potential items for weight reduction in automobiles as it accounts for ten to twenty percent of the unsprung weight, which is considered to be the mass not supported by the leaf spring. The introduction of composite materials made it possible to reduce the weight of the leaf spring without any reduction on the load carrying capacity and stiffness. Studies were conducted on the application of composite structures for automobile suspension system [1, 2]. A double tapered beam for automotive suspension leaf spring has been designed and optimized [3]. Composite mono leaf spring has also been analyzed and optimized [4].

The leaf spring should absorb the vertical vibrations and impacts due to road irregularities by means of variations in the spring deflection so that the potential energy is stored in spring as strain energy and then released slowly. So, increasing the energy storage capability of a leaf spring ensures a more compliant suspension system. According to the studies made [3, 4], a material with maximum strength and minimum modulus of elasticity in the longitudinal direction is the most suitable material for a leaf spring. Fortunately, composites have these characteristics [5].

Fatigue failure is the predominant mode of in-service failure of many automobile components. This is due to the fact that the automobile components are subjected to variety of fatigue loads like shocks caused due to road irregularities traced by the road wheels, the sudden loads due to the wheel travelling over the bumps etc. The leaf springs are more affected due to fatigue loads, as they are a part of the unsprung mass of the automobile.

The fatigue behavior of Glass Fiber Reinforced Plastic (GFRP) epoxy composite materials has been studied in the past [6]. Theoretical equation for predicting fatigue life is formulated using fatigue modulus and its degrading rate. This relation is simplified by strain failure criterion for practical application. A prediction method for the fatigue strength of composite structures at an arbitrary combination of frequency, stress ratio and temperature has been presented [7]. These studies are limited to mono-leaf springs only.

In the present work, a seven-leaf steel spring used in passenger cars is replaced with a composite multi leaf spring made of glass/epoxy composites. The dimensions and the number of leaves for both steel leaf spring and composite leaf springs are considered to be the same. The primary objective is to compare their load carrying capacity, stiffness and weight savings of composite leaf spring. Finally, fatigue life of steel and composite leaf spring is also predicted using life data.

2. EXISTING STEEL LEAF SPRING

Design parameters of the existing seven-leaf steel spring used in this work includes: total length (eye-to-eye), 1150 mm; arc height at axle seat (camber), 175 mm; spring rate, 20 N/mm; number of full length leaves, 2; number of graduated leaves, 5; width of the leaves, 34 mm; thickness

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of the leaves, 5.5 mm; full bump loading, 3250 N; spring weight, 13.5 kg. This spring is symmetrical, so only one half is considered for the analysis to save the calculation time.

Experimental results from testing the steel leaf spring under full bump loading containing the stresses and deflections are listed in the Table 1.

Table 1. Stress analysis of steel leaf spring using experimental, analytical and FEM

Parameters	Experiment	Analytical	FEM
Load (N)	3250	3250	3250
Maximum stress (MPa)	680.05	982.05	744.32
Maximum deflection (mm)	155	133.03	134.67
Maximum stiffness (N/mm)	20.96	24.43	24.13

2.1 Finite element analysis of steel leaf spring

A stress analysis is performed using finite element method (FEM). All the calculations are done using the version 7.1 of ANSYS [8]. The finite element model for the leaf spring is two-dimensional [9]. A plane strain solution is obtained because of the high ratio of width to thickness of a leaf. The model is restrained to the right half part only because the spring is symmetric. The contact between leaves is emulated by interface elements. Nodes are created based on the values of co-ordinates calculated and each pair of coincident nodes is joined by the interface elements that simulate the action between the neighboring leaves. The element that is selected for this analysis is SOLID 42 [9], which behaves as the spring, and the interface elements CONTA174 and TARGE170 are used to represent contact and sliding between adjacent surfaces of leaves. An average coefficient of friction 0.03 is taken between surfaces [10].

The axle seat is assumed to be fixed and loading is applied at eye end. A finite element stress analysis is performed under full bump loading. Also, analytical solution is obtained out using the SAE standard design formulas for leaf springs [10]. The results of experimental, analytical and finite element methods are shown and compared in Table 1. Maximum normal stress σ_{11} from finite element analysis is compared to the experimental solution under full bump loading and has 8.63 % error. There is a good correlation for stiffness in all three methods.

3. COMPOSITE LEAF SPRING

The theoretical design details of composite mono-leaf spring are explained in many literatures. In some designs, width is fixed and in each section the thickness is varied hyperbolically so that it has minimum thickness at two edges and maximum thickness at the middle [3]. Another design in which the width and thickness are fixed from eyes to the middle of spring and towards the axle seat the width decreases hyperbolically and thickness increases linearly has been presented [4]. In their design the curvature of spring and fiber misalignment in the width and thickness direction are neglected. A double tapered composite leaf spring has been designed and tested and optimized its size for minimum weight [11]. The mono-leaf spring is not easily replaceable on its catastrophic failure. Hence, in this work, a composite multi leaf spring is designed, fabricated and tested for its load carrying capacity and stiffness using a more realistic situation. Fatigue life is also predicted.

3.1. Material selection

Based on the specific strain energy of steel spring and some composite materials [4], the E-glass/epoxy is selected as the spring material. Many attempts have been made to substitute more economic resins for the epoxy but all attempts to use polyester or vinyl ester resins have been unsuccessful to date [1]. The stored elastic strain energy in a leaf spring varies directly with the square of maximum allowable stress and inversely with the modulus of elasticity both in the longitudinal and transverse directions according to:

$$S = \frac{1}{2}\frac{\sigma_t^2}{\rho E}\ , \tag{1}$$

where S is the strain energy, σ_t is the allowable stress, E is the modulus of elasticity and ρ is the density. E-glass/epoxy in the direction of fibers has good characteristics for storing strain energy. So, the unidirectional lay up along the longitudinal direction of the spring is selected which also helped in fabricating process using filament-winding machine. E-glass/epoxy is selected as the spring material having following mechanical properties: modulus of elasticity, E_{11}, 38.6 GPa and E_{22}, 8.27 GPa; modulus of shear, G_{12}, 4.14 GPa; Poisson ratio, 0.26; tensile strength, σ_{t11}, 1062 MPa; tensile strength, σ_{t22}, 31 MPa; compressive strength, σ_{c11}, 610 MPa; compressive strength, σ_{c22}, 118 MPa; and shear strength, τ_{12}, 71 MPa.

3.2. Design and finite element analysis of composite leaf spring

The dimensions of the composite leaf spring are taken as that of the conventional steel leaf spring. The number of leaves is also the same for composite leaf spring. The design parameters selected are as follows: each composite leaf consists of 20 layers; thickness of a single layer is 0.275 mm; width of each leaf, fiber and resin is kept at 34 mm; thickness of each leaf, fiber and resin are 5.5 mm, 0.2 mm and 0.075 mm respectively. Since the properties of the composite leaf spring vary with the directions of the fiber, a 3-D model of the leaf spring (Fig. 1) is used for the analysis in ANSYS 7.1. The loading conditions are assumed to be static. The element chosen is SOLID46, which is a layered version of the 8-node structural solid element to model layered thick shells or solids [8]. The element allows up to 250 different material layers. To establish contact between the leaves, the interface elements CONTACT174 and TARGET170 are chosen.

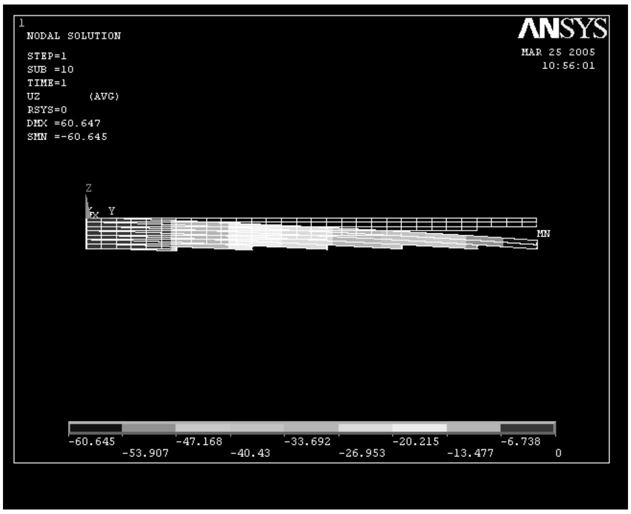

Fig. 1. FEM model of composite leaf spring

4. STATIC TESTING AND RESULTS

The individual leaves are fabricated using a filament-winding machine. A fiber volume fraction of 0.6 is used. All individual leaves are assembled together using a center bolt and four side clamps. Also metal spring eyes are fixed at both the ends.

After the fabrication, the composite multi leaf spring was tested with the help of an electro-hydraulic leaf spring test rig. Steel leaf spring weighs 13.5 kg whereas composite leaf spring weighs only 4.3 kg. For a light passenger vehicle with a camber height of 175 mm, the static load to flatten the leaf spring is theoretically estimated to be 3250 N. Therefore a static vertical force of 3250 N is applied to determine the load-deflection curves (Fig. 2).

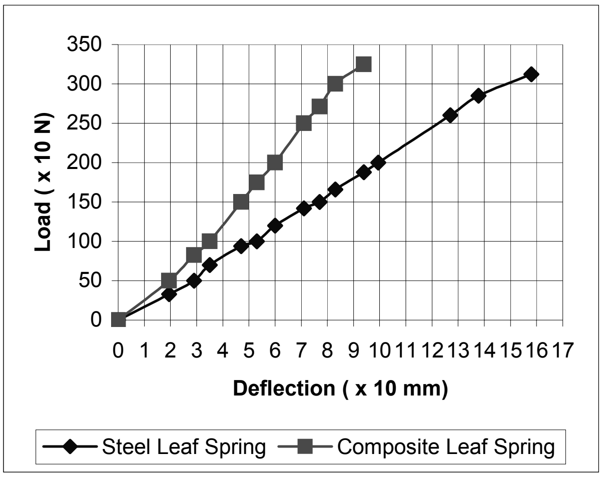

Fig. 2. Load-deflection curves for steel and composite leaf springs

During the full bump load test, the experimental stress measurement is carried out to verify the result of FEM analysis. The experimental results are shown in Fig. 3 and the maximum stress developed was found to be 222 MPa. FEM results show that the maximum stress developed is 217 MPa. It is found that the experimental results and FEM results showed good agreement. E-glass/epoxy composite leaf spring has spring constants 34.57 N/mm - 53.59 N/mm. Thus, all the data of spring constants for composite leaf springs are greater than the design value, 20 N/mm.

The leaf spring is analysed under bending loading condition and the normal stresses are important. The longitudinal compression strength of composite used in this analysis is less than its longitudinal tensile strength, so failure criterion stress is longitudinal compression stress. Fig. 3 shows that the maximum longitudinal compression stress is about 222 MPa. At a same loading, the maximum stress developed in the steel leaf spring is about 680.05 MPa from Table 1. The compression strength of fiber glass/epoxy is 610 MPa and the yielding stress of the steel is 1175 MPa. So, the factor of safety in steel spring is 1.73 while in the composite spring it is 2.75. The deflection of spring under full bump loading is 94 mm (Fig. 2), which is less than the maximum value 175 mm, which shows 64.95 % increase in stiffness. Figs. 4 and 5 show the variation of longitudinal stress of experimental and FEM results for steel and composite leaf spring respectively. FEM and experimental results showed good agreement.

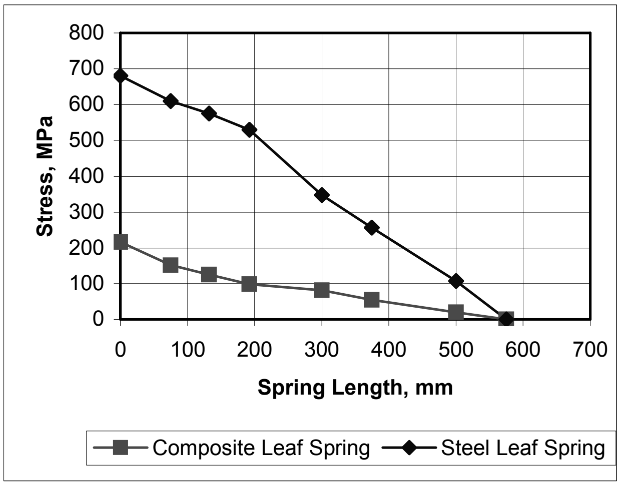

Fig. 3. Variation of experimental stress of steel and composite springs

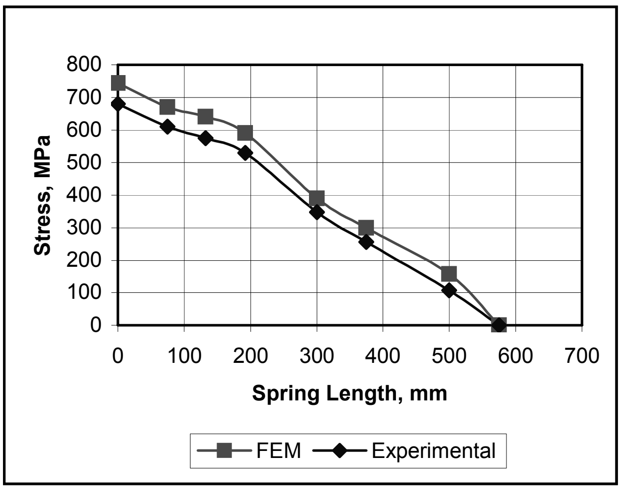

Fig. 4. Variation of longitudinal stress of steel leaf spring

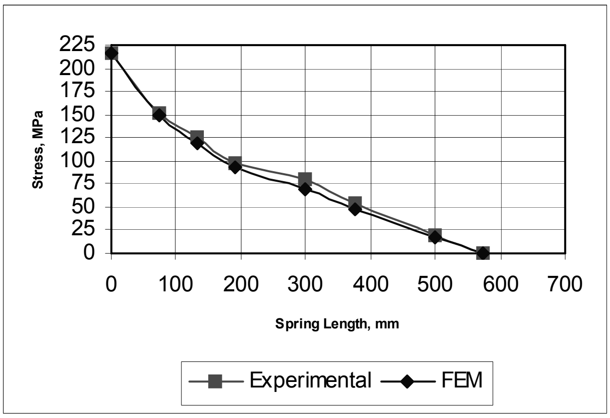

Fig. 5. Variation of longitudinal stress of composite leaf spring

5. PASSENGER RIDE COMFORT

The leaf spring of light passenger vehicles has to be designed in such a way that its natural frequency is maintained to avoid resonance condition with respect to road frequency to provide good ride comfort. The road irregularities usually have the maximum frequency of 12 Hz [3]. Therefore the leaf spring should be designed to have a natural frequency, which is away from 12 Hz to avoid the resonance (poor ride comfort zone). The first natural frequency of the steel leaf spring is found to be 6.3 Hz whereas that of composite leaf spring is 14.3 Hz. It is found that the first natural frequency of composite leaf spring is nearly 1.2 times the maximum road frequency and therefore resonance will not occur. Therefore it is obvious that composite leaf spring provides improved ride comfort.

6. FATIGUE ANALYSIS

The main factors that contribute to fatigue failures include number of load cycles experienced, range of stress and mean stress experienced in each load cycle and presence of local stress concentrations. Testing of leaf springs using the regular procedure consumes a lot of time. Hence SAE [10] suggests a procedure for accelerated tests, which give quick results, particularly for steel leaf springs. The results of the accelerated tests can be extrapolated to get the actual fatigue life under normal working conditions. Following the procedure outlined by the references [10, 12], fatigue tests were conducted on steel and composite leaf springs.

6.1. Fatigue life of steel leaf spring

Fatigue life calculation of steel leaf spring is given as follows: stroke available in fatigue testing machine, 0 mm – 200 mm; initial deflection of the spring, 100 mm; initial stress (measured by experiment), 420 MPa; final deflection of the spring (camber), 175 mm; maximum stress in the final position (measured by experiment), 805 MPa. Fatigue life cycles predicted for steel leaf spring is less than 1000,000 cycles by the procedure outlined in [10].

6.2. Fatigue life of composite leaf spring

A load is applied further from the static load to maximum load with the help of the electro-hydraulic test rig, up to 3250 N (175 mm deflection), which is already obtained in static analysis. The test rig is set to operate for a deflection of 75 mm. This is the amplitude of loading cycle, which is very high. The frequency of load cycle is fixed at 33 mHz, as only 20 strokes/min is available in the test rig used. This leads to high amplitude low frequency fatigue test.

The maximum and minimum stress values obtained at the first cycle of the composite leaf spring are 222 MPa and 133 MPa respectively. As the cycles go on increasing, the stress settling is happening only after 25000 cycles. These maximum and minimum operating stress values are 240 MPa and 140 MPa respectively. Because of very low stress level, the fatigue life of the composite leaf spring is very high under simulated conditions.

6.2.1. Life data analysis

Life data analysis [13] which is a statistical approach is used to make predictions about the life of composite leaf springs by fitting a statistical distribution to life data from representative sample units. For the GFRP leaf spring, the life data is measured in terms of the number of cycles to fail for the four leaf springs and are presented in Table 2.

Table 2. Number of cycles to failure for composite leaf spring

Leaf spring No.	Cycles to fail	Stress level
1	10,800	0.65
2	6,950	0.65
3	19,240	0.65
4	14,350	0.65

6.2.2. Life time distribution

Weibull life distribution model is selected which has previously been used successfully for the same or a similar failure mechanism. The Weibull distribution is used to find the reliability of the life data and it helps in selecting the particular data that is to be used in life prediction model. The Weibull distribution uses two parameters 'b' and 'θ' to estimate the reliability of the life data. 'b' is referred to as shape parameter and 'θ' is referred to as scale parameter.

The reliability of Weibull distribution is given by

$$R(t) = 1 - \exp(-x/\theta)^{b} , \tag{2}$$

where, x is the life; b is the Weibull slope or 'shape' parameter and θ is the characteristic life or 'scale' parameter.

The parameters of the Weibull distribution are calculated using probability plotting [13]. The life cycles of leaf spring are arranged in increasing order and the median rank is calculated using the Equation (3) and are shown in Table 3.

$$\text{Mediarank} = 100 \cdot (j - 0.3)/(N + 0.4), \tag{3}$$

where, j is the order number and N is the total quantity of sample.

The value of θ is found to be 14,600 cycles. The reliability of the life data is calculated and shown in Table 4. It is found that the reliability of 3rd GFRP spring is higher than that of other leaf springs and the fatigue life data of 3rd GFRP spring has been considered for fatigue life prediction.

Table. 3. Median rank of composite leaf springs

Order No.	Cycles to fail	Median rank
1	6,950	15.9
2	10,800	38.5
3	14,350	61.4
4	19,240	84.1

Table. 4. Reliability of fatigue life data

Leaf spring No.	Life (cycles)	Median rank	Reliability (%)
1	10,800	38.5	43
2	6,950	15.9	39
3	19,240	84.1	73
4	14,350	61.4	62.7

The fatigue test is conducted up to 20000 cycles and it is examined that no crack initiation is visible. The details of test results at 0 and 20000 cycles are as follows: maximum load cycle range, 1850 N – 3250 N; amplitude, 75 mm; frequency, 33 mHz; spring rate, 27.66 N/mm; maximum operating stress, 240 MPa; minimum operating stress, 140 MPa and time taken 17 h. The experimental results are available only up to 20000 cycles. With no crack initiation, there is a necessity to go for analytical model for finding number of cycles to failure from analytical results. Hwang and Han [6] have developed an analytical fatigue model to predict the number of fatigue cycles to failure for the components made up of composite material. They have proposed two constants in their relation on the basis of experimental results. It is proved that the analytical formula predicts the fatigue life of component with E-glass/epoxy composite material.

Hwang and Han relation:

$$N = \{B(1-r)\}^{1/C}, \tag{4}$$

where, N is the number of cycles to failure; $B = 10.33$; $C = 0.14012$; $r = \sigma_{max}/\sigma_u$; σ_{max} is the maximum stress; σ_u is the ultimate tensile strength and r is the applied stress level. Equation (4) is applied for different stress levels and fatigue life is calculated for the composite leaf spring. The results are obtained based on the analytical results and the resulting S-N graph is shown in Fig. 6. From Fig. 6, it is observed that the composite leaf spring, which is made up of E-glass/epoxy is withstanding more than 10 Lakh cycles under the stress level of 0.24.

The test is conducted for nearly 17 hours to complete 20000 cycles. The variations in stress level are reduced to very low level after 20000 cycles. There is no crack initiation up to 20000 cycles. The stress level of 0.24 is obtained from experimental analysis. This is very much helpful for the determination of remaining number of cycles to failure using fatigue model [6]. According to this fatigue model, the failure of the composite leaf spring takes place only after 10 Lakh cycles. Since the composite leaf spring is expected to crack only after 10 Lakh cycles, it is required to conduct the leaf spring fatigue test up to 10 Lakh cycles for finding type and place of crack initiation and propagation. For completing full fatigue test up to crack initiation with the same frequency, nearly 830 hours of fatigue test is required.

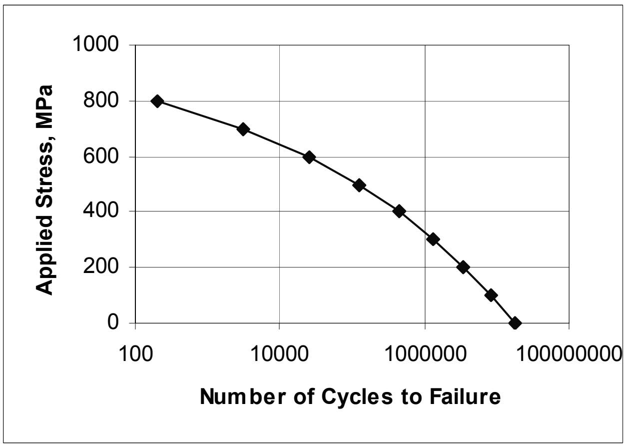

Fig. 6. S-N curve for composite leaf spring

7. CONCLUSIONS

Design and experimental fatigue analysis of composite multi leaf spring using glass fibre reinforced polymer are carried out using life data analysis. Compared to steel spring, the composite leaf spring is found to have 67.35 % lesser stress, 64.95 % higher stiffness and 126.98 % higher natural frequency than that of existing steel leaf spring. The conventional multi leaf spring weighs about 13.5 kg whereas the E-glass/Epoxy multi leaf spring weighs only 4.3 kg. Thus the weight reduction of 68.15 % is achieved. Besides the reduction of weight, the fatigue life of composite leaf spring is predicted to be higher than that of steel leaf spring. Life data analysis is found to be a tool to predict the fatigue life of composite multi leaf spring. It is found that the life of composite leaf spring is much higher than that of steel leaf spring.

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