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DESIGN FOR FATIGUE AND SIMULATION OF GLASS FIBRE/EPOXY COMPOSITE AUTOMOBILE LEAF SPRING

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ABSTRACT

In the present work, steel leaf spring used in passenger cars is replaced with a composite leaf spring made of a glass/epoxy composite The primary objective is to compare fatigue characteristics of SAE1045-450-QT steel and E - Glass/ Epoxy Composite material. Based on the available design data a fatigue analysis is carried out on an ANSYS Workbench v14.0 and the results of the simulation are documented. Factors like fatigue life, fatigue damage, biaxiality indication, rain flow counting and fatigue response are plotted for the composite leaf spring and the fatigue performance is predicted using life data. Therefore the objective of this paper is to present a design and simulation study on the fatigue performance of a glass fibre/epoxy composite leaf spring through design and finite element method and prove the reliability of the validation methods based only on simulation, thereby saving time, material and production costs for a complete product realization.

Keywords: glass fibre/epoxy composite, leaf spring, design for fatigue, finite element method, ANSYS workbench v14.0.

INTRODUCTION

The automobile chassis is mounted on the axles, not direct but with some form of springs. This is done to isolate the vehicle body from the road shocks which may be in the form of bounce, pitch, roll or sway. These tendencies give rise to an uncomfortable ride and also cause additional stress in the automobile frame and body. All the part which performs the function of isolating the automobile from the road shocks are collectively called a suspension system. Leaf spring is a device which is used in suspension system to safeguard the vehicle and the occupants. For safe and comfortable riding i.e., to prevent the road shocks from being transmitted to the vehicle components and to safeguard the occupants from road shocks it is necessary to determine the maximum safe load of a leaf spring. Leaf spring should absorb vertical vibrations due to road irregularities by means of variations in the spring deflection so that potential energy is stored in the spring as strain energy and then released slowly. So, increasing energy storage capability of a leaf spring ensures a more compliant suspension system [1, 2].

The suspension leaf spring is one of the potential items for weight reduction in automobile as it accounts for 10 to 20 percent of the unsprung weight. This helps in achieving the vehicle with improved riding qualities. Since the strain energy in the spring is inversely proportional to density and young's modulus of the material, it is always suggested that the material for leaf spring must have low density and modulus of elasticity. Composite materials are having such properties as compared to the conventional steel. Important characteristics of composites (Springer and Kollar, 2003) that make them excellent for leaf spring instead of steel are higher strength-to weight ratio, superior fatigue strength, excellent corrosion resistance, smoother ride, higher natural frequency, etc. Fatigue failure is the predominant mode of in-service failure of many automobile components, especially the springs used in automobile suspension systems. Fatigue behaviour of Glass fibre/epoxy composite materials has been studied here [2, 3]. The introduction of composite materials has made it possible to reduce the weight of the leaf spring without any reduction in load carrying capacity and stiffness. The present work attempts to analyze Glass fibre/epoxy composite Leaf Spring for the safe load, ride comfort, Stiffness, weight saving and fatigue life compared to Steel leaf spring using ANSYS® Software.

LITERATURE REVIEW

Composite materials are one of the material families which are attracting researchers and being solutions of such issue. As leaf spring contributes considerable amount of weight to the vehicle and needs to be strong enough, a single E-glass/Epoxy leaf spring is designed and simulated following the design rules of the composite materials considering static loading only. The constant cross section design of leaf springs is employed to take advantages of ease of design analysis and its manufacturing process. And it is shown that the resulting design and simulation stresses are much below the strength properties of the material, satisfying the maximum stress failure criterion. The designed composite leaf spring has also achieved its acceptable fatigue life. [4]. Fatigue life prediction was performed based on finite element method and fatigue life simulation method. Using the variable amplitude loading, it predicted the actual case that happen when the vehicle run on the road. Both analysis results were well correlated. This simulation gives the prediction about the damage that occurs and also provides information for the manufacturer to improve the fatigue life [5]. The fatigue strength is strongly influenced by the layer design. 0° laminate results have values 1.5-1.8 times higher than +45°/0°/-45° and +30°/-30°/0° laminates which exhibit similar fatigue strengths (although +30°/ -30°/0° is 10-15% lower than the +45°/0°/-45° case) [6]. Composite leaf springs would offer substantial weight savings by using mono leaf spring in passenger cars. Mono parabolic leaf spring of a Maruti Omni used HM and HS Carbon polymers composite material. Finite

Element analysis (FEA) is carried out at static condition of the spring model so that stress distribution can be observed for analysis of high stress zones. The original steel leaf spring would weigh about 3.5 kgs whereas composite leaf spring would weigh 0.7314 kgs. So, we have observed that almost 65-70% of weight reduction could be achieved by using the carbon composite [7]. Whereas, Design and experimental analysis of composite multi leaf spring using glass fibre reinforced polymer compared to steel spring, 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 performance of the leaf spring is also increased. Ride comfort and life of Composite Leaf Spring are also more when compared to Steel Leaf Spring [2]. Composite leaf spring is lighter than conventional steel leaf spring with similar design specifications but not always is cost effective over their steel counterparts. The life of the spring is an important criterion. In this aspect as well composite leaf spring proves to be much better than EN45 steel leaf spring. The predicted life of the composite leaf spring is 10^9cycles as compared to 10^6 cycles of steel leaf spring [8].

A four-leaf steel spring used in the rear suspension system of light vehicles replaced with an optimized composite one. Main consideration was given to the optimization of the leaf spring geometry to give the minimum weight. The results showed that the optimum spring width decreases hyperbolically and the thickness increases linearly from spring eye towards the axle seat. The natural frequency of composite leaf spring is higher than that of the steel leaf spring and is far enough from the road frequency to avoid the resonance [9]. Composite materials have high elastic strain energy storage capacity and high strength to weight ratio Therefore, it is concluded that composite leaf spring is an effective replacement for the existing steel leaf spring in automobile [10].

SPECIFICATION AND MATERIAL PROPERTIES OF LEAF SPRING

Parameters of the steel leaf spring and Composite leaf spring are listed in Table-1.

Table-1. Specification of existing leaf spring.

Parameters	Value
Total length of the spring (Eye to Eye)	1200 mm
Free camber (At no load condition)	120 mm
Thickness of leaf	8 mm
Width of leaf spring	60 mm
Maximum load given on spring	3250 N
No. of full length leave (Master leaf) E - glass/ epoxy composite	01
No. of full length leaves SAE1045-450-QT	04

Mechanical and Cyclic Properties of SAE1045-450-QT and E - Glass/ Epoxy Composite material are listed in the Tables 2 and 3, respectively [11, 12]

Table-2. Mechanical and cyclic properties of SAE 1045-450- QT

Material properties	Value
Elastic Modulus (E), GPa	207
Yield Tensile Strength , MPa	1515
Ultimate Tensile Strength, MPa	1584
Cyclic Strength Coefficient (K')	1874
Fatigue Strength Coefficient (S_f)	1686
Fatigue Strength Exponent (b)	-0.06
Fatigue Ductility Exponent (c)	-0.83
Fatigue Ductility Coefficient (E_f)	0.79
Cyclic Strain Hardening Exponent (n')	0.09
Density , Kg/m^3	7.7×10^3
Possion's ratio	0.266
Behaviour	Isotropic

Table-3. Mechanical and cyclic properties of E glass/ epoxy composite material.

Material properties	Value
Tensile modulus along X-direction (Ex), MPa	34000
Tensile modulus along Y-direction (Ey), MPa	6530
Tensile modulus along Z-direction (Ez), MPa	6530
Tensile strength of the material, MPa	900
Compressive strength of the material, MPa	450
Shear modulus along XY-direction (Gxy), MPa	2433
Shear modulus along YZ-direction (Gyz), MPa	1698
Shear modulus along ZX-direction (Gzx), MPa	2433
Poisson ratio along XY-direction (NUxy)	0.217
Poisson ratio along YZ-direction (NUyz)	0.366

FINITE ELEMENT MODELLING

To design for fatigue and simulation, SAE 1045-450-QT steel leaf as well as composite leaf spring, stress analysis was performed on simplified equations and trial and error method using FE ANSYS Workbench software. The standard simulation setup for ANSYS software and divided into: pre-processing, solving, and post processing categories. First, 3D geometric model of leaf spring is developed in ANSYS Workbench for Finite Element meshing. Necessary for good simulation result, quality of meshing is optimized.

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ASSUMPTIONS

- SAE1045-450-QT multi leaf and E-Glass Epoxy composite mono leaf spring modelled with constant thickness and constant width design.
- Unidirectional (0°) E-Glass Epoxy composite layup are assumed along the longitudinal direction of spring.
- The constraints parameter i.e. dimensions and boundary condition of SAE1045-450-QT multi leaf spring is same as that of E-Glass Epoxy composite leaf spring.
- Fatigue life predication of leaf spring based on finite element analysis using Stress life approach.

Figures 1 and 2 shows Geometry modeling and meshing is done in ANSYS Workbench 14.0.

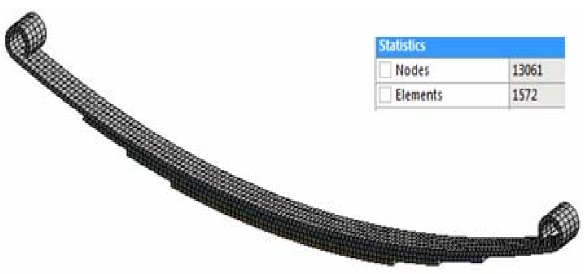

Figure-1. Geometric mesh model - SAE 1045-450-QT leaf spring.

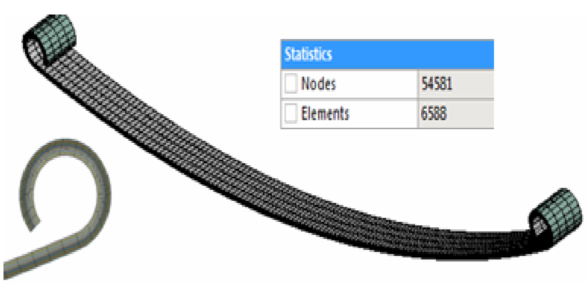

Figure-2. Geometric mesh model - mono composite leaf spring

BOUNDARY CONDITIONS

On the axle of the automobile, the leaf spring is mounted and to the frame of the vehicle, the end of the leaf spring is connected. The boundary conditions were applied at the ends of the leaf spring i.e. eye end.
The Boundary Conditions are listed below:

D.O.F. constrained	Front eye	Rear eye
Translation constrained	X, Y and Z direction	Y and Z direction
Rotation constrained	X and Z direction	X and Z direction
Allowing	Free Y rotation	Free X translation and Y rotation

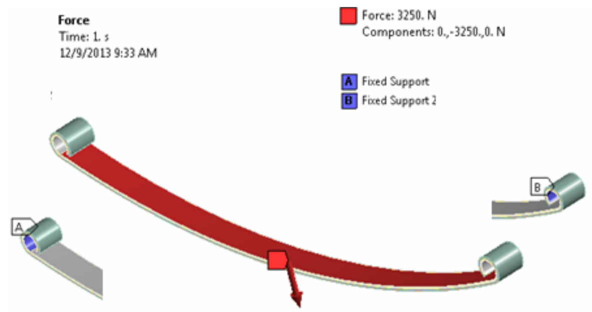

Figure-3. Boundary condition - leaf spring.

FE COMPOSITE ELEMENT MODELLING

E-Glass Epoxy laminated composite leaf spring is assumed to have 10 lamina of 0° degree fiber orientation angle (thickness of each lamina of 0.8mm). The element chosen for the analysis is SHELL 181, is a four-node element with six degrees of freedom at each node: translations in the x, y, and z directions, and rotations about the x, y, and z-axes. SHELL181 may be used for layered applications for modeling composite shells or sandwich construction. The accuracy in modeling composite shells is governed by the first-order shear-deformation theory (usually referred to as Mindlin-Reissner shell theory).

FINITE ELEMENT BASED FATIGUE ANALYSIS

The main purpose of Finite Element Based Fatigue tool using for simulation of leaf spring during the design stage of development process to enable reliable fatigue life calculations. In Finite Element Based Fatigue overview, the three input parameters namely geometry, materials and loading are regarded as input functions. All of these inputs are being discussed below with Figure-4. In practice, most analysis followed following inputs for the fatigue analysis.

- Material properties- during testing, cycle or repeated data is used on constant amplitude.
- Loading histories - Here, term loads used to represent forces, displacements, accelerations, etc. measured or simulated load histories, which is to be applied to a component.
- Geometry information- related to applied load histories to the local stresses and strains at the location of interest. This information is usually taken from finite element (FE) results.

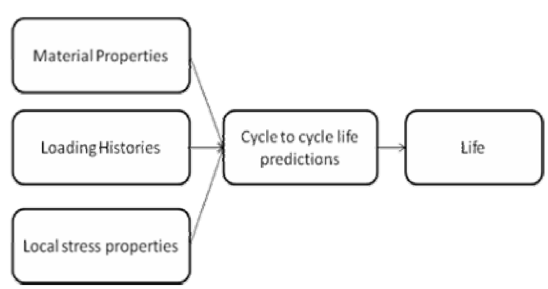

Figure-4. Fatigue analysis prediction strategies.

Firstly, produced stress-time (σ - t) or strain-time (ε - t) history data point from the geometry and loading, then material fatigue properties are introduced to estimate life. In case of may be small changes in structural behaviour which is to be modelled as well as detailed FEM modelling procedures such as meshing and with B.C. & loading, have large effects on predicted stresses. So, it is important to admire greatly the issue of accuracy with FEM Models, while performing fatigue life calculations. Finite Element based calculations should only be undertaken when correlated against test. Engineer's were doing fatigue calculation must have knowledge of dimension involved in various parts of behaviour. Also should have appreciation of material fatigue curves. i.e., S-N Curve.

An integrated Finite Element based fatigue environment analysis is complete analysis of a full load component. Fatigue technique based on generally Stress-Life, Strain- Life or Crack-Propagation estimation methods. But it is important to recognize that, Absolute fatigue life is unobtainable. The schematic diagram of the integrated FE based fatigue life prediction analysis is shown in Figure-5 [11].

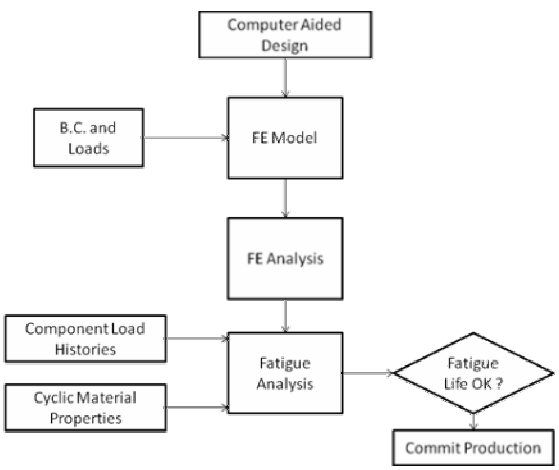

Figure-5. Finite element based fatigue analysis cycle.

FATIGUE LIFE CRITERIA AND S-N CURVES

For E - Glass/ epoxy composite material, Hwang and Han developed an analytical fatigue model to predict the number of fatigue cycles to failure.

Hwang and Han relation:

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

Where, N is the number of cycles to failure;
B = 10.33; C = 0.14012; r = applied stress level

$$r = \frac{\sigma_{max}}{\sigma_u}$$

σ_{max} = maximum stress; σ_u = ultimate tensile strength

The life data analysis is a tool to be used here to predict the fatigue life of mono composite leaf spring. The results are based on analytical result and resulting S-N graph for E - Glass Composite as shown in Figure-6 [2]. E glass-epoxy figure is for transverse loading condition is considered.

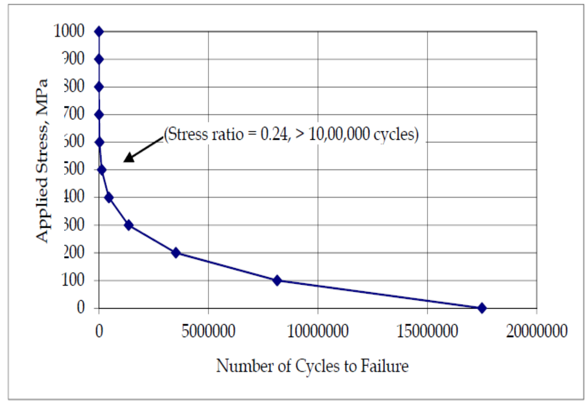

Figure-6. S-N curves for E-Glass/epoxy composite.

The S-N graph: SAE1045-450-QT steel material as shown in Figure-7 [11].

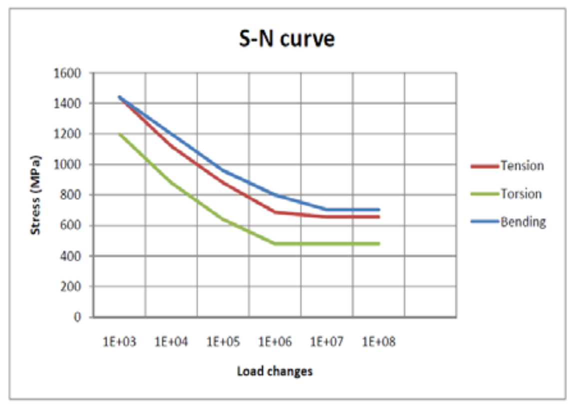

Figure-7. S-N curves for SAE1045-450-QT spring.

RESULTS AND DISCUSSIONS

STATIC ANALYSIS

Since the shear stress (τ_{12} = 6.77 MPa) multiplied by a factor of '9' (9*3 = 60.93 MPa) is much less than the shear strength (S = 68.95 MPa) of the specified composite material, E-glass/Epoxy.

Specifying the criteria (9*τ12< S), design is safe even for the flexural failure.

Table-4. Comparison result of Stress for SAE 1045-450 - QT and E-Glass epoxy composite.

Parameters	**Material**	
	SAE1045-450-QT	**E-Glass epoxy composite**
Maximum load in N	3250	3250
Absolute maximum stress , MPa	724.52	715
Stiffness, N/mm	24.33	53.59

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MODAL ANALYSIS FOR RIDE COMFORT

To avoid resonant condition, leaf spring has to be designed with respect to road frequency in such way that, its natural frequency should be maintained to provide ride comfort to passenger. The road irregularities usually have the maximum frequency of 12 Hz (Yu and Kim, 1988) [7]. Therefore more the natural frequency of leaf spring required. In modal analysis only boundary conditions are applied and no load is acted on the leaf spring.

Table-5. Natural frequency of SAE 1045-450-QT and E-Glass epoxy composite material.

Modes	SAE1045-450- QT frequency (Hz)	E-Glass epoxy frequency (Hz)
1	13.13	17.15
2	54.55	56.16
3	78.59	72.19
4	116.89	119.36
5	178.49	202.78
6	243.27	288.43

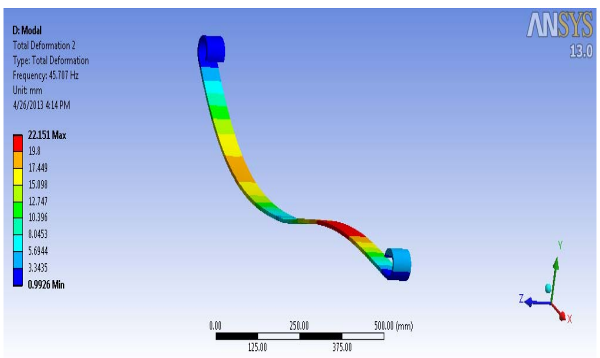

Figure-8. Mode shape second of E- glass epoxy composite leaf spring.

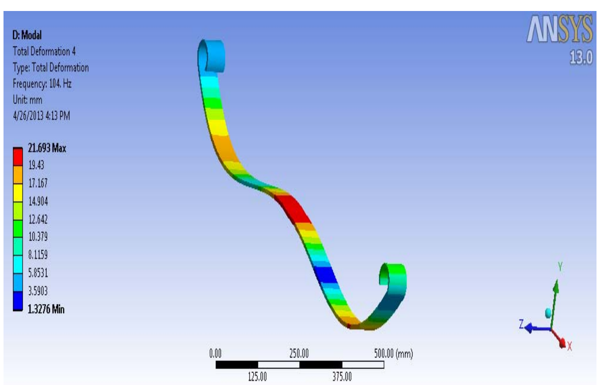

Figure-9. Mode shape fourth of E- glass epoxy composite leaf spring.

FATIGUE LIFE

According to assumptions, if loading is of constant amplitude in stress life analysis, this represents the number of cycles upto leaf spring will fail due to fatigue. When leaf spring subjected to high cycle fatigue, where stresses are mainly elastic, the fatigue total-life (S-N) approach is used for the life prediction.

Fatigue life can be calculated, number of cycle to failure, of mono composite leaf spring using equation (1).

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

$$r = \frac{\sigma_{max}}{\sigma_u}$$

Where

$$\sigma_{max} = \frac{6\,FL}{bh^2}$$

It uses the material stress-life curve and employs fatigue notch factors to account for stress concentrations, empirical modification factors for surface finish effects and analytical equations such as modified Goodman and Gerber equations are given below [11].

$$\frac{\sigma_a}{S_e} + \frac{\sigma_m}{S_u} = 1$$

$$\frac{\sigma_a}{S_e} + \left(\frac{\sigma_m}{S_u}\right)^2 = 1 \qquad (2)$$

Where σ_a, S_e, σ_m and S_a are the alternating stress and mean stress, alternating stress for equivalent completely reversed loading, and the mean stress and the ultimate tensile strength, respectively.

In ANSYS Workbench, fatigue analysis is generally conducted by four approaches namely Goodman's approach, Gerber's approach, mean stress approach and Soderberg's approach , by applying a load of 3250 N, with a loading condition from history data - SAE Transmission. The results obtained using ANSYS Workbench.

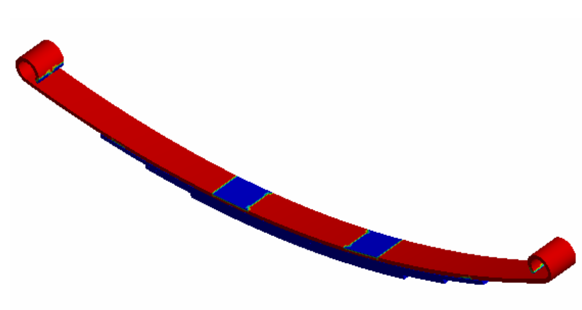

Figure-10. Fatigue life distribution of SAE 1045-450-QT.

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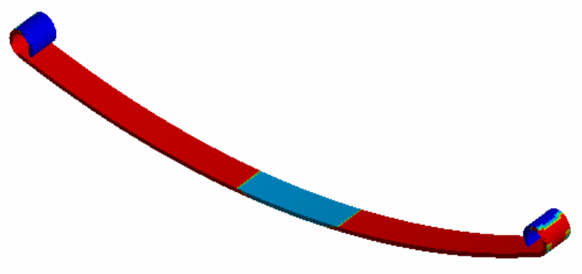

Figure-11. Fatigue life distribution of E- glass epoxy composite.

From the above said approaches it is seen that according to Total life approach shows a maximum value of life for E- Glass Epoxy Composite were 1.725×10^{9} cycles as compared to maximum value of life for SAE 1045-450-QT were 1.025×10^{5} which is represented in blue colour in the life data Figure and the least value of life is shown in red colour. Hence it is most preferred in the analysis so that we can increase the safety of the leaf springs.

FATIGUE SENSITIVITY

This plot represents the variation of fatigue results as a function of the loading at the critical location on the leaf spring model. Sensitivity generally found for life, damage, or factory of safety. Figures 12(a) and (b) shows Fatigue sensitivity plot for E- Glass Epoxy material and SAE 1045-450-QT, respectively.

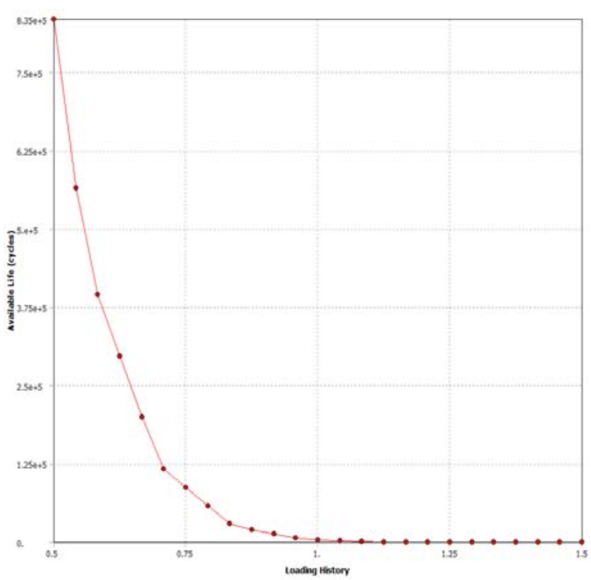

Figure-12(a). Fatigue sensitivity Plot - E- glass epoxy.

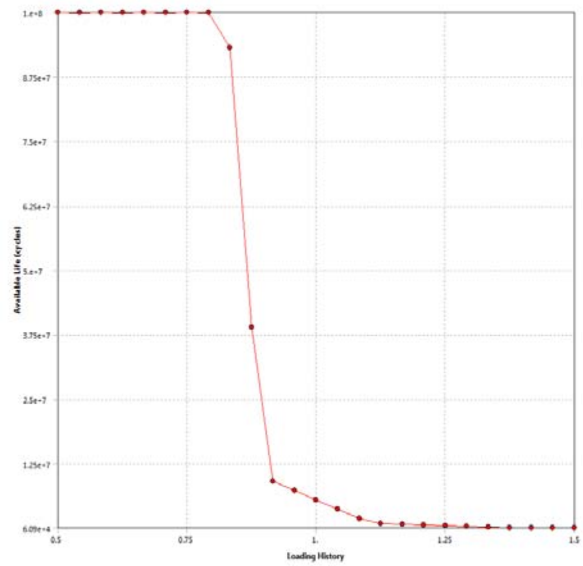

Figure-12 (b). Fatigue sensitivity plot -SAE 1045-450-QT0.

BIAXIALITY INDICATION

Biaxiality indication is defined as the smaller principal stress divided by the larger principal stress with the principal stress nearest zero ignored. A biaxiality of 0 shows uniaxial stress. A value of -1 for pure shear and value of 1 corresponds to a pure biaxial state. Figure-13 shows Biaxiality Indication plot for E- Glass Epoxy material.

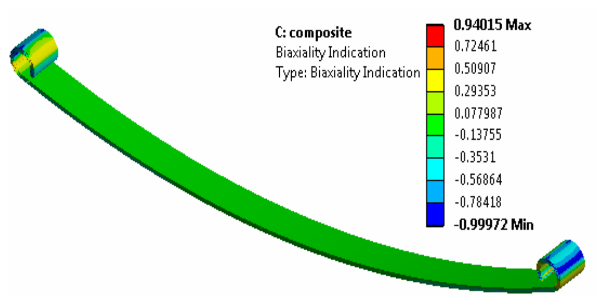

Figure-13. Biaxiality indication plot - E glass epoxy.

RAINFLOW MATRIX CHART

In this 3-D cycle histogram bins get plotted here by dividing alternating and mean stress, where Z axis nothing but counts for given alternating and mean stress bin. It consists of cycle correspond to low stress range and higher stress range. High stress range gives most of damage. This is a plot of the Rainflow matrix at the critical location. This results nothing but measure of the composition of a loading history.

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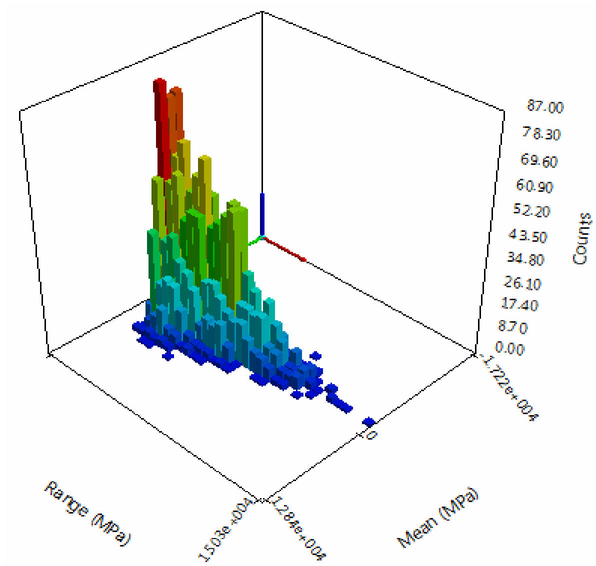

Figure-14. Rainflow matrix chart.

FATIGUE DAMAGE

At resulted design life, is a contour plot of the fatigue damage. Fatigue damage is defined as the design life divided by the available life. Figure-15 shows Fatigue Damage plot for E- Glass Epoxy material.

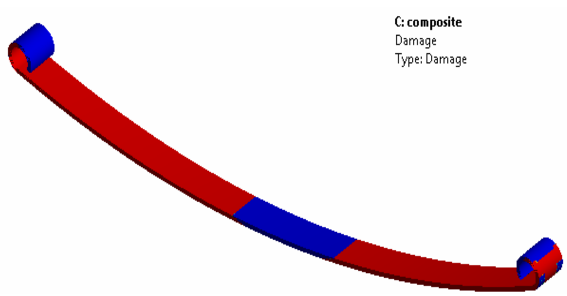

Figure-15. Plot of fatigue damage - E glass epoxy

FATIGUE SAFETY FACTOR

At resulted design life, this is factor of safety with respect to a fatigue failure. The maximum Factor of Safety displayed is 15. For Fatigue safety factor, values less than < 1 indicate failure before the design life is reached.

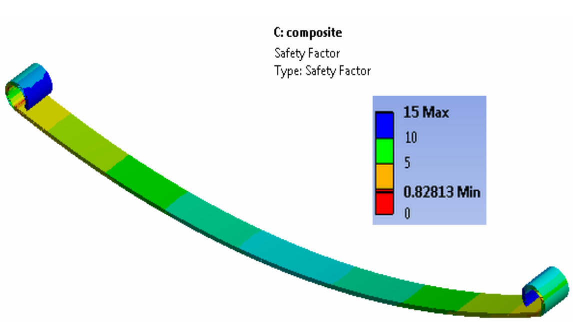

Figure-16. Fatigue safety factor.

CONCLUSIONS

- By using Stress Life approach, Absolute Maximum Principal Stress used basis for calculating E- Glass Epoxy Composites leaf springs life for passenger vehicles.
- Due to Weight reduction and stress, stiffness criteria, multi steel leaf spring is proposed to be replaced with E- Glass Epoxy composite leaf springs.
- In application to Finite Element leaf spring models, linear elastic stresses from Finite element analysis can be used directly to calculate fatigue damage.
- It can be shown that, design and simulation stresses satisfying maximum stress failure criterion; hence design is safe.
- In ANSYS Workbench 14.0, fatigue analysis analyzed using Fatigue Tool predicting CAE result in terms of Fatigue life, Fatigue Sensitivity, Fatigue Damage, Biaxiality Indication, Rainflow matrix and Fatigue Safety factor.
- Using the constant amplitude loading and stress life approach, the fatigue damage and life of the spring has been predicted. From the damage contour, the highest damage value is inacceptable range;
- Ride comfort of both Steel SAE1045-450-QT Leaf Spring and unidirectional E- Glass Composite Leaf Spring was found to be 1.3 times more than the 12Hz produced on road which decreases resonance. This is compared by using modal analysis for increasing ride comfort.
- According to total life approach, the fatigue life of E - Glass Epoxy mono composite leaf spring is higher than that of SAE1045 -450-QT multi leaf spring.

Finite element method using CAE tool like ANSYS Workbench prove the reliability of the validation methods based only on simulation, thereby saving time, material and production costs for a complete product realization. It's important to remember for design engineer, the simulation result. This paper will help to understand linear static behaviour of the composite leaf spring and simulation data for the researcher's to improve the fatigue life of the leaf spring using Computer Aided Engineering tool.

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