Fatigue Analysis and Optimization of A Multi-Leaf Spring: A Review

Anshul Deshmukh[1]
anshuldeshmukh007@gmail.com

Amit Bhende[2]
amitbhendejobs@yahoo.co.in

[1]M. Tech Research Scholar,
[2]Assistant Professor,

Mechanical Engineering Department,
St. Vincent Pallotti College of Engineering, Nagpur, India

Abstract — The suspension system in a vehicle significantly affects the behavior of vehicle, i.e. vibration characteristics including ride comfort, stability etc. Leaf springs are commonly used in the vehicle suspension system and are subjected to millions of varying stress cycles leading to fatigue failure. The advantage of leaf spring over helical spring is that the ends of the spring may be guided along a definite path as it deflects to act as a structural member in addition to energy absorbing device. A lot of research has been done for improving the performance of leaf spring. Now the automobile industry has shown interest in the replacement of steel spring with composite leaf spring, since the composite material has high strength to weight ratio and good corrosion resistance. The aim of this paper is to analyze how failure occurs on a leaf spring and to provide preventive measures for the same. There is a review of some papers on the design and analysis of leaf spring performance and fatigue life prediction of leaf spring. There is also the analysis of failure in leaf spring.

Index Terms — failure analysis, leaf spring, FEM, fatigue analysis

1. INTRODUCTION

Leaf spring is widely used in automotive and one of the components of suspension system. It consists of one or more leaves. As a general rule, the leaf spring must be regarded as a safety component as failure could lead to severe accidents. The leaf springs may carry loads, brake torque, driving torque, etc in addition to shocks. The multi-leaf spring is made of several steel plates of different lengths stacked together. During normal operation, the spring compresses to absorb road shock.

In order to conserve natural resources and economize energy, weight reduction has been the main focus of automobile manufacturer in the present scenario. 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 automobile as it accounts for ten to twenty percent of the unsprung weight. This helps in achieving the vehicle with improved riding qualities. It is well known that springs, are designed to absorb and store energy and then release it. Hence, the strain energy of the material becomes a major factor in designing the springs. The introduction of composite materials has 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 leaf springs bend and slide on each other allowing suspension movement. 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 traveling 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.

2. PROBLEMS IN LEAF SPRINGS

2.1. Fatigue failure

Fatigue failure is the predominant mode of in-service failure of many automobile components such as leaf springs. 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 traveling 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. [1]

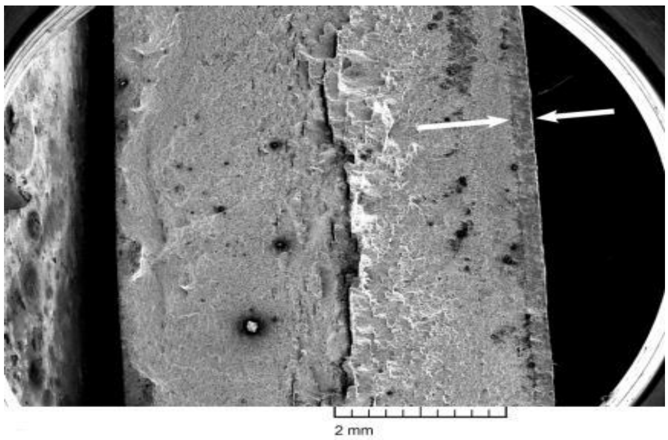

Fig.1 Secondary cracks at the mid-plane

2.2. Central hole failure

The central hole of the leaf spring suffers highest tensile stress levels. Hence it is more prone to failure. The photograph of Fig. 2 is a plan view of the fracture, which occurred in the second leaf after six months of service. The fracture started at the central hole, in a plane normal to the leaf major axis, with no evidence of a prior plastic deformation. [2]

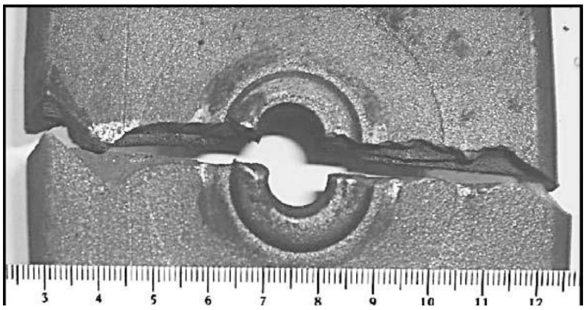

Fig. 2 Photograph of the fractured second leaf of a specimen which failed during service

Morphologically, the fracture surface was typical of fatigue failure. Thus, it consisted of a smooth region exhibiting ring marks extending into the crack origin on both sides of the hole and spanning nearly one half of the fractured area. The remaining material which was unable to withstand the service loads had suddenly broken by effect of overloading. The crack propagated normally to the main axis of the spring leaf. In summary, the fractographic evidence was typical of fatigue fracture. Also, the marks observed suggested that the crack originated in the vicinity of the top corner of the hole front (Fig. 3); this was a region concentrating a high stress owing to its high and low relief, which, as expected, had reduced the fatigue strength of the material. [2]

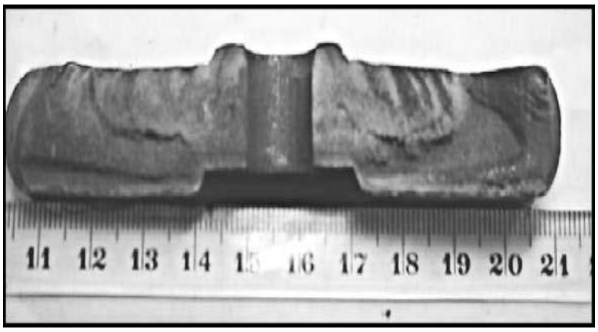

Fig. 3 Photograph of the fracture surface in the second leaf

2.3. Fracture at the eye end

Fracture of the spring occurred at the formed forward eye, as shown in Fig. 4. Comparison of the eye with unbroken springs revealed that it had somewhat unwrapped prior to the failure. The position of the two broken ends in Fig. 2 exaggerates the prior deformation. Striking features of the fracture were the presence of extensive secondary cracking at the mid plane, the stepped nature of the fracture, and “woody fracture” on the stepped surface parallel to the spring surface. [3]

Fig.4 Eye end failure

3. REASONS FOR FAILURE

3.1. Raw materials defect

A typical raw material defect is the existence of a foreign material inside the steel, such as non-metallic inclusions.

In general, there are two types of foreign materials that can become trapped inside the steel solution: large imperfections such as spinells, and smaller imperfections such as inclusions that are caused by alloying elements. ASTM differentiates inclusion types by thin and heavy, in addition to composition and shape. Type A is sulphide-type with a boundary of thin and heavy classification of 4 lm. Type B is aluminate-type with a boundary of 9 lm. Type C is Silicate-type with a boundary of 5 lm, and Type D is globular oxide with a boundary of 8 lm. It is also worth noting that thin inclusion rarely causes a coil spring to fail early. An ideal raw material has the form of ferrite pearlite. However, a raw material can also have local bainite inside the ferrite pearlite matrix. Due to a hardness difference, such raw materials may exhibit internal cracking. [4]

3.2. Surface imperfections

Surface imperfections can occur as small hardening cracks, tool marks, scale embedded to the base material or surface flaws inherited by the raw material. Fig. 5 shows two different surface flaws deep enough to cause a leaf spring to fail early. On the left side, the surface imperfection is inherited from the raw material. This type of defect can occur when the surface flaw detector does not function normally. It is usually easy to determine if such a flaw was inherited from the raw material and not due to manufacturing. A pre-existing defect usually has surrounding decarburization after the raw material is heated during manufacturing, while a surface defect caused by manufacturing is often not accompanied by decarburization; as in the right side of the figure. [4]

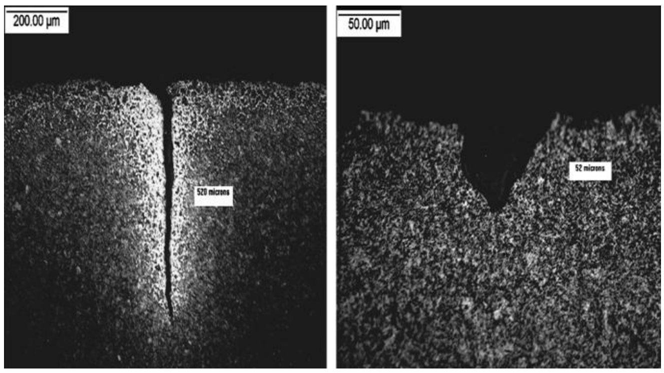

Fig. 5 Inherited from raw material (left) and surface imperfection due to manufacturing (right)

3.3. Improper heat treatment

Improper heat treatment can be easily overlooked since a temperature difference in heating does not relate directly to the hardness of the material. Extensive evaluations are usually needed to identify this problem. Fig. 6 shows a typical example of an improper heat treatment. Prolonged heating can cause the prior austenite grain size to grow significantly.

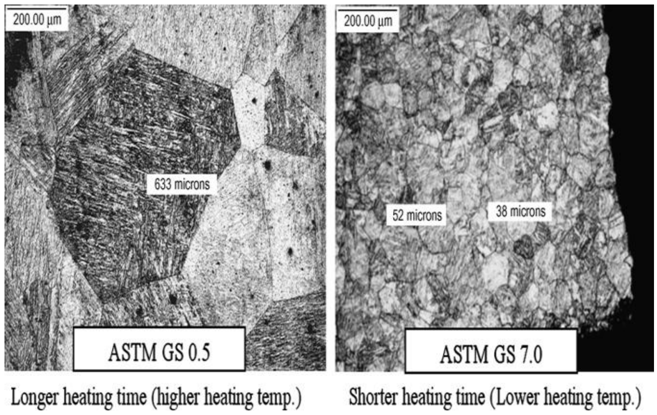

Fig. 6 Identical raw materials heated with different heating patterns

Improper heat treatment can also result in the microstructure becoming pearlite instead of the required martensite. This type of defect is easier to identify due to the clear difference in hardness. This defect usually occurs when the heating system does not operate normally. Again, referring to the figure, the left hand side coil has a much lower lifetime than that of the right side. Bainitic formation is another form of improper heat treatment. Unlike martensite, bainitic ferrite usually contains only slight excess of carbon in ferrite solution. Most of the carbon in a transformed sample of bainite is in the form of cementite particles, which in turn tend to be coarser than those associated with tempered martensite. The effects of tempering are therefore always milder than is the case when the microstructure is martensite. Furthermore, bainitic structures are usually accompanied by a greater percentage of retained austenite than martensitic structures. Tempering induces the decomposition of the retained austenite into mixture of ferrite and carbides. [2, 4]

3.4. Decarburization

Decarburization may be considered as the least severe offender in the entire list of defects. Decarburization is the loss of carbon from the steel surface which will result in a soft leaf surface once heat-treating is complete. This soft layer will not be able to handle the spring stresses and will lead to early failure. Poor steel quality can also influence spring life. If the steel has excessive impurities in it, the fatigue life will be reduced. Partial decarburization is usually permissible in spring, at least to a slight extent. [3]

3.5. Presence of stress concentrators

Fatigue damage started in the vicinity of the leaf central hole by effect of the presence of stress concentrators and in the direction normal to the acting tensile stress. The stress concentrators included (a) the complex geometry of the hole, (b) its sharp corners, (c) fibering of the hole inner walls, (d) notches caused by the bolt thread and (e) various surface defects such as scabs and rolling lines in the starting sheets of an unclean steel. The negative effect of these factors was substantially enhanced by a defective heat treating of the leaves, including steel decarburization, during the manufacturing process, which led to inadequate hardness in the springs and, more important, the local presence of soft products (ferrite) in the material structure. [2, 3]

4. PREVENTIVE ACTIONS

4.1. Minimizing stress concentrators

One effective way of preventing fatigue failure is by minimizing stress concentrators resulting from design, metallurgical or manufacturing factors. The specific measures to be adopted for lengthening spring life begin with the selection of clean steel, free of surface defects. The leaf hole should be round and flat. Moreover, after heat treating the top corners of the major leaves should be trimmed into curved (rounded) form to further decrease the stress-raising action. This operation also eliminates partially the decarburized layer at the most critical hole region. Decarburization of the leaves during the manufacturing process must be prevented. [2]

4.2. Heat treatment

Heat treating should be conducted so as to obtain a pure tempered martensite structure. Additional measurements of assistance with a view to increasing the fatigue strength of the springs include improving the surface quality of the leaves as regards both starting material (steel sheets) and manufacturing process (by avoiding fibering or the formation of inner notches in the hole). The use of a bolt threaded only at its ends might prove effective in this respect. [2]

4.3. Shot peening

Fatigue fracture is instigated by cyclical stresses on the material to induce a compressive stress on the tension surface, which reduces the propagation of the crack which eventually will enhance the fatigue life. Shot peening is a widely used method for fatigue life enhancement. [5] Shot peening is a process in which the surface of a component is bombarded with small spherical media called shot. Each piece of shot, on striking the surface, imparts a small indentation or dimple, all of which jointly deform the surface in tension. The surrounding elastic material, on attempting to return the yield surface to its initial shape, creates a residual compressive stress field within the cold work-hardened surface layer. [5,6]

4.4. Use of composite materials for leaf spring

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. Since, the composite materials have more elastic strain energy storage capacity and high strength to weight ratio as compared with those of steel, multi-leaf steel springs are being replaced by mono-leaf composite springs. Life of composite leaf spring is much higher than that of steel leaf spring. [1]

5. FINITE ELEMENT ANALYSIS

The Analysis involves the following discreitization called meshing, boundary conditions and loading.

5.1. Meshing

Meshing involves division of the entire of model into small pieces called elements. This is done by meshing. It is convenient to select the free mesh because the leaf spring has sharp curves, so that shape of the object will not alter. To mesh the leaf spring the element type must be decided first. [6]

Meshing of spring is done by isomeshing with quadrilateral plate elements. The CQUAD4 is used for modelling plates, shells and membranes. The CQUAD4 can represent in-plane, bending and transverse shear behavior, depending upon data provided on the PSHELL property entry. The CQUAD4 element is a quadrilateral flat plate connecting four grid points. At some junctions, the triangular elements are also introduced to make the frame to behave like stiffeners at those parts. [7]

5.2. Boundary Conditions

The boundary condition is the collection of different forces, pressure, velocity, supports, constraints and every condition required for complete analysis. Applying boundary condition is one of the most typical processes of analysis. A special care is required while assigning loads and constraints to the elements. Boundary condition of the spring involves the one end fix and other end X and Y axis displacement and rotation about Z axis. [8]

The leaf spring is mounted on the axle of the automobile; the frame of the vehicle is connected to the ends of the leaf spring. The ends of the leaf spring are formed in the shape of an eye. The front eye of the leaf spring is coupled directly with a pin to the frame so that the eye can rotate freely about the pin but no translation is occurred. The rear eye of the spring is connected to the shackle which is a flexible link; the other end of the shackle is connected to the frame of the vehicle. The rear eyes of the leaf spring have the flexibility to slide along the X-direction when load applied on the spring and also it can rotate about the pin. The link oscillates during load applied and removed. Therefore the nodes of rear eye of the leaf spring are constrained in all translational degrees of freedom, and constrained the two rotational degrees of freedom. So the front eye is constrained as UX, UY, UZ, ROTX, ROTY and the nodes of the rear eye are constrained as UY, UZ, ROTX, ROTY. [6]

To represent the pivoted boundary condition at front eye, a master node was created at the central axis of front eye. This master node was connected to remaining nodes of eye with rigid body element RBE2. At master node all degrees of freedom except rotational DOF about y-axis were constrained. To represent the boundary condition at rear eye, a master node was created at the central axis of rear eye. This master node was connected to remaining nodes of eye with rigid body element RBE2. At master node all degrees of freedom except rotational DOF about y-axis and translation in x were constrained. [7]

5.3. Loads Applied

The load is distributed equally by all the nodes associated with the center bolt. To apply load, it is necessary to select the circumference of the bolt hole and consequently the nodes associated with it. It is necessary to observe the number of nodes associated with the circumference of the bolt hole, because the applied load need to divide with the number of nodes associated with the circumference of the center bolt. [6]

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 [9] 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 [9], fatigue tests were conducted on steel and composite leaf springs.

Fatigue life prediction is based on knowledge of both the number of cycles the part will experience at any given stress level during that life cycle and another influential environmental and use factors. The local strain-life method can be used pro-actively for a component during early design stage [10, 11].

6.1. Fatigue life prediction methods

Three common fatigue life prediction methods exist: S–N curve based approach, local strain approach, and fracture mechanics approach. Each uses a different load-life relationship (i.e. a relationship between some load-related parameter and fatigue life). The advantages and disadvantages of these methods depend on the simplicity of use, the accuracy of the prediction, and on the scope of the application range.

The S–N curve based approach is simple to use, but the results in fatigue life predictions that are not accurate. The local strain approach is accurate enough and the range of application is wide. However, it can only be applied to the prediction of the crack initiation period. Fatigue life predictions using the fracture mechanics approach are more accurate, but the method can only be applied on the calculation of the stable crack growth period. [11, 12]

7. CONCLUSION

The composite leaf spring is lighter than conventional steel leaf spring with similar design specifications but not always is cost- effective over their steel counterparts. Composite materials have more elastic strain energy storage capacity and high strength to weight ratio as compared with those of steel. Therefore, it is concluded that composite leaf spring is an effective replacement for the existing steel leaf spring in automobile. [13]

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. [8, 12]

E-glass epoxy is better than using Mild-steel as though stresses are little bit higher than mild steel, E-glass epoxy is having good yield strength value. The prior cracking in the spring was extensive enough to reduce the strength of the spring to the point where normal dirt road forces were adequate to produce rupture. [13, 14]

The fatigue life prediction of the leaf spring is performed based on finite element analysis and fatigue life simulation method. FEM gives the prediction of critical areas from the viewpoint of static loading. The results of non-linear static analysis of 2D model of the leaf spring using the commercial solver and analytical results show better correlation [14, 15]

REFERENCES

[1] Mouleeswaran Senthil Kumar, Sabapathy Vijayarangan, "Analytical and Experimental Studies on Fatigue Life Prediction of Steel and Composite Multi-leaf Spring for Light Passenger Vehicles using Life Data Analysis", Journal- ISSN 1392-1320, Materials Science, Vol. 13, No. 2, 2007

[2] J.J.Fuentes et al., "Premature fracture in automobile leaf springs Engineering Failure Analysis", P.P.648–655, 2009

[3] C.K. Clarke and G.E. Borowski, "Evaluation of a Leaf Spring Failure", ASM International p.p. 54-63, 2005

[4] Y. Prawoto et al., "Design and failure modes of automotive suspension springs", Engineering Failure Analysis 15 (2008), pp.1155–1174

[5] M.L Aggarwal, V.P. Agrawal, R.A.Khan "A stress approach model for predictions of fatigue life by shot peening of EN45A spring steel" International Journal of Fatigue 28 (2006), pp. 1845–1853

[6] G Harinath Gowd et al, "Static analysis of leaf spring", International Journal of Engineering Science and Technology (IJEST), Vol. 4 No.08 August 2012, pp. 3795-3803

[7] V.K.Aher et al., "Fatigue Life Prediction of Multi Leaf Spring used in the Suspension System of Light Commercial Vehicle", International Journal on Theoretical and Applied Research in Mechanical Engineering (IJTARME), Volume-1, Issue-1, 2012, pp. 71-77

[8] Sorathiya Mehul et al., "Analysis of composite leaf spring using FEA for light vehicle mini truck", Journal of Information, Knowledge and Research in Mechanical Engineering, Volume – 02, Issue – 02, Nov 12 to Oct 13, pp. 424-428

[9] Spring Design Manual**,** Design and Application of Leaf Springs, AE-11, Society of Automotive Engineer HS-788, 1990.

[10] Lee, Yung-Li, Pan, J., Hathaway, and R., Barkey, "Fatigue testing and analysis, theory and practice", UK: Elsevier Butterworth-Heinemann.

[11] X. Huang, M. Torgeir, W. Cui. 2008, "An engineering model of fatigue crack growth under variable amplitude loading", International Journal of Fatigue, Vol.30, Issue 1, 2-10

[12] M Senthil Kumar and Vijayarangan, "Static analysis and fatigue life prediction of steel and composite leaf spring for light passenger vehicles", Journal of scientific and Industries Research Vol. 66, February 2007, pp 128-134

[13] Baviskar A. C. et al., "Design and Analysis of a Leaf Spring for automobile suspension system: A Review", International Journal of Emerging Technology and Advanced Engineering, Volume 3, Issue 6, June 2013, pp 406-410

[14] R. W. Landgraf and R. C. Francis, "Material and Processing Effects on Fatigue Performance of Leaf Springs", Congress and Exposition Cobo Hall, Detroit, February 26-March 2, Vol.28 No.3 (2009), pp.351-363.

[15] Yohannes Regassa et al., "Failure Analysis of Semi-elliptical Master Leaf Spring of Passenger Car using Finite Element Method", Global Journal of Researches in Engineering Mechanical and Mechanics Engineering, Volume 13, Issue 2 Version 1.0 Year 2013