Finite Element Analysis of Stresses and Deflections in Multi Leaf Springs

Dissertation

Submitted in partial fulfilment of the requirement for the award of degree of

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in

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Submitted

by

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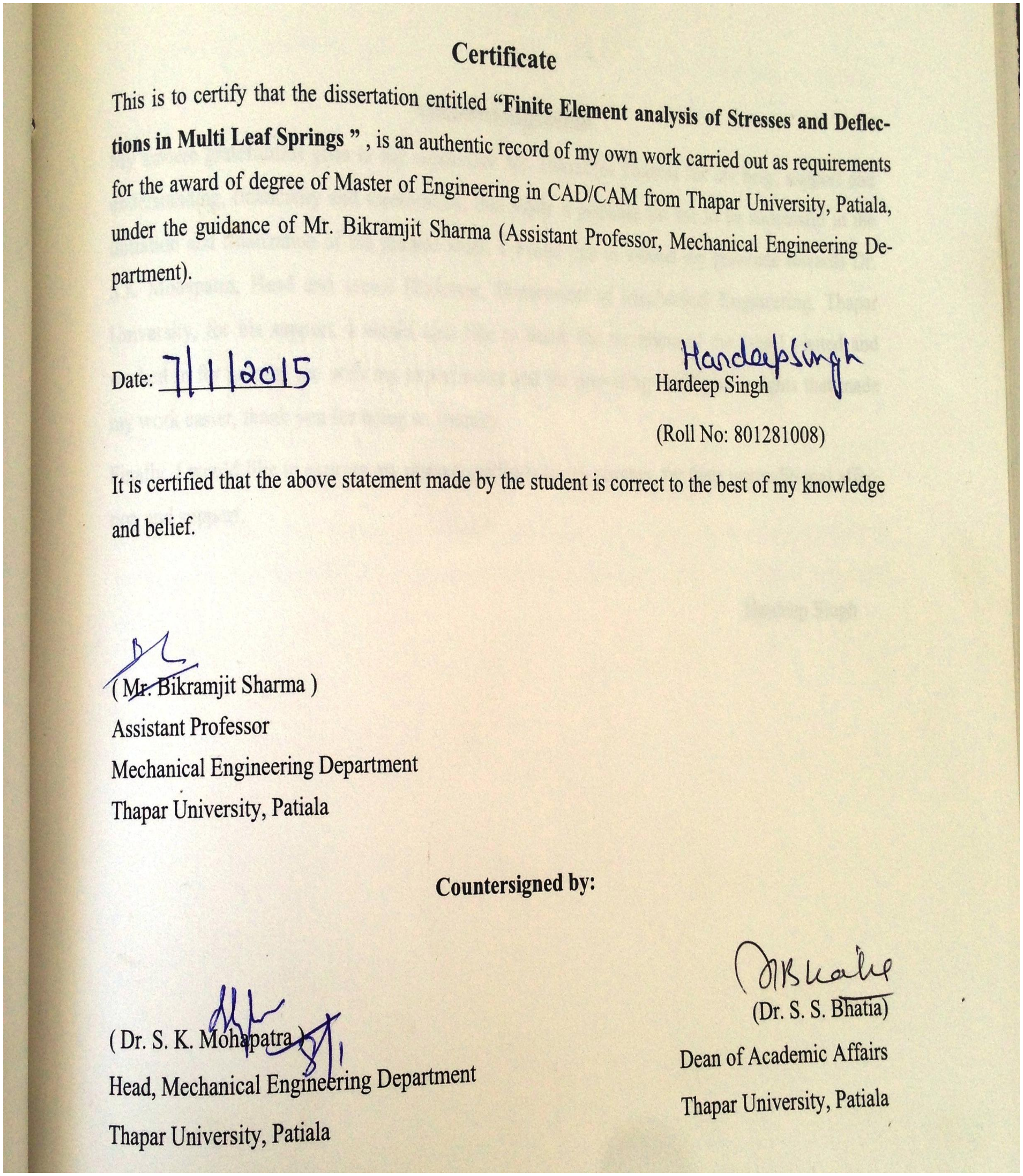

Certificate

This is to certify that the dissertation entitled **"Finite Element analysis of Stresses and Deflections in Multi Leaf Springs"**, is an authentic record of my own work carried out as requirements for the award of degree of Master of Engineering in CAD/CAM from Thapar University, Patiala, under the guidance of Mr. Bikramjit Sharma (Assistant Professor, Mechanical Engineering Department).

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It is certified that the above statement made by the student is correct to the best of my knowledge and belief.

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Hardeep Singh

Abstract

Leaf spring in an automobile provides a good suspension and plays a vital role in carrying loads and absorbing vibrations. The 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. Mainly leaf springs are made of isotropic steel. The automobile industry has shown great interest in replacement of steel parts with composite materials. Owing to high strength and stiffness to weight ratios the requirement of computer aided analysis arises because of anisotropy of composites which makes calculations quite intensive and large number of variables on which the mechanical properties of composite depends. For example fiber material, matrix material, fiber orientation in a ply, layup of a laminate etc. In the present work stress and deflection analysis of leaf spring are calculated by finite element analysis. The leaves of the spring are assigned properties of steel or fiber reinforced composites. The leaf springs are analyzed in ABAQUS 6.10 for stresses and deflections. The results indicate that for the same load carrying capacity there is lowering of induced stresses and deflections when steel leaves are replaced by fibrous composite leaves.

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Chapter 1 Introduction

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 vehicle improved riding qualities. The springs are designed to absorb, store and release energy. Therefore, the strain energy of the material becomes a major factor in designing the springs. In every automobile, leaf spring is one of the main components that provides a good suspension and plays a vital role in supporting- lateral loads, shock loads, brake torque, and driving torque. The composite materials have more elastic strain energy storage capacity and high strength-to- weight ratio as compared to steel. Introduction of composite materials made it possible to reduce the weight without any increase in load carrying capacity and stiffness of the leaf spring. Automobile-sector is showing an increased interest in the area of composites due to their high strength to weight ratio. Therefore analysis of composite material leaf springs has become essential in showing the comparative results with conventional leaf springs. Advantages of leaf spring over helical spring are that the ends of the springs are guided along a definite path so as to act as a structural member in addition to shock absorbing device. This is the reason why leaf springs are still used widely in a variety of automobiles.

1.1. Leaf 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 center 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.

Figure 1.1: Leaf spring assembled at rear axle of automotive [1]

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 through a shackle, a short swinging arm. The shackle takes up the tendency of the leaf spring to elongate when compressed. Leaf springs also known as flat spring are made out of flat plates. Leaf springs are designed two ways: multi-leaf and mono-leaf. The leaf springs may carry loads, brake torque, driving torque, etc. in addition to shocks, they also act as structural member. The multi-leaf spring is made of several steel plates of different lengths stacked together. The leaf springs bend and slide on each other allowing suspension movement.

1.1.1. Construction of leaf spring

The leaves are usually given an initial curvature or cambered so that they will tend to straighten under the load. The leaves are held together by means of band shrunk around them at the centre or by a bolt passing through center. Since, the band exerts stiffening and strengthening effect, therefore effective length of the spring for bending will be overall length of the spring minus width of the band.. The spring is clamped to the axle housing by means of U-bolts. The longest leaf known as main leaf or master leaf has its ends formed in the Shape of an eye through which the bolts are passed to secure the spring to its supports. The other leaves of the spring are known as graduated leaves. In order to prevent digging in the adjacent leaves, the ends of the graduated leaves are trimmed in various forms.

1.1.2. Parts of a leaf spring

Master leaf-They have the advantage of spreading the load more widely over the vehicle's chassis, whereas coil springs transfer it to a single point. The longest leaf known as main leaf or master leaf has its ends formed in the shape of an eye through which the bolts are passed to secure the spring to its supports.

Graduated leaves- The other leaves of the spring are known as graduated leaves. In order to prevent digging in the adjacent leaves, the ends of the graduated leaves are trimmed in various forms. The leaves are usually given an initial curvature or cambered so that they will tend to straighten under the load.

Rebound Clip-It is used for binding master and graduated leaves together. Rebound clips are located at intermediate positions in the length of the spring, so that the graduated leaves also share the stress induced in the full length leaves when spring rebounds.

Center Bolt-It is used for fixing each leaf together on center hole. The leaves are held together by means of band shrunk around them at the centre or by a bolt passing through center. Since, the band exerts stiffening and strengthening effect, therefore effective length of the spring for bending will be overall length of the spring minus width of the band. In case of a center bolt, two-third distance between centers of U-bolt should be subtracted from the overall length of the spring in order to find effective length.

1.1.3. Nipping in leaf spring

The master leaf of a laminated spring is hinged to the supports. The support forces induce, stresses due to longitudinal forces and stresses arising due to possible twist. Hence, the master leaf is more stressed compared to other the graduated leaves. Methods to reduce additional stresses could be,

1 Master leaf is made of stronger material than the other leaves.

2 Master leaf is made thinner than the other leaves. This will reduce the bending stress as evident from stress equation.

3 Another common practice is to increase the radius of curvature of the master leaf than the next leaf.

The last method is explained through the following diagram:

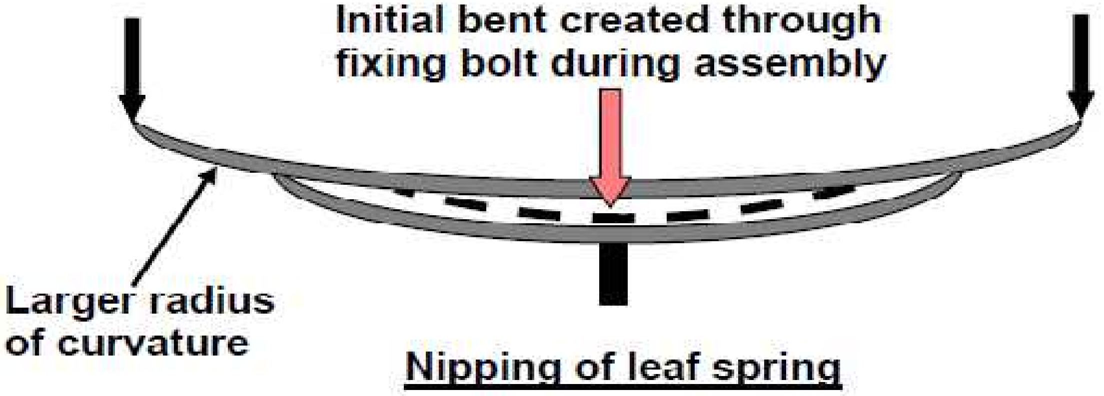


Figure 1.2: Nipping in leaf spring[2]

The master leaf has a larger radius of curvature compared to the additional leaf that is placed below so obviously a gap will be created between the two leaves as indicated in the figure. Now, an initial bent is created during assembly by tightening the central bolt. Therefore, some amount of compressive stress will be produced at the inside curvature of the master leaf. Similarly, at the outside curvature of the master leaf tensile stress will be produced. Both these stresses are initial stresses in the master leaf. However, by such operation of tightening the central bolt, the additional leaf that is placed beneath the master leaf has a tendency to flatten out and as a result the stress pattern of the additional leaf will be reverse of that of the master leaf, tensile stress is produced at the inner curvature and compressive stress is produced at the outer curvature. Hence, when the spring is loaded, for both the master leaf and the additional leaf, tensile stress will be produced at the inner curvature and compressive stress will be produced at the outer curvature. Therefore, due to opposite nature of initial stress and loading stress, the master leaf will experience lesser stress on both the surfaces. However, due to same nature of initial stress and loading stress, the additional leaf is stressed more compared to the master leaf. But, it is to be noted that the higher stress on the additional leaf is actually shared between all other leaves than the master leaf. This practice of stress relief in the master leaf is known as nipping of leaf spring. As a matter of fact, all the leaves of a laminated leaf spring do have certain amount of nipping, so that there will be gaps between the leaves, as a result the stresses will be uniformly distributed and accumulated dusts can also be cleaned.

1.2. Stress and deflection analysis

In order to have an idea of working principle of a leaf spring, let us think of the diving board in a swimming pool. The diving board is a cantilever with a load, the diver, at its free end. The diver initiates a to and fro swing of the board at the free end and utilizes the spring action of the board for jumping. The diving board basically is a leaf spring.

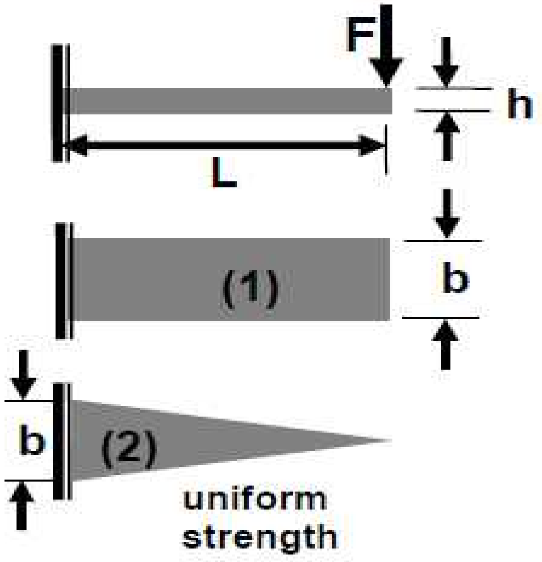


Figure 1.3: Cantilever approach [3]

The leaf springs are widely used in suspension system of railway carriages and automobiles. But the form in which it is normally seen is laminated leaf spring. A simple cantilever type leaf spring is shown in the Fig below. In the cantilever beam type leaf spring, for the same leaf thickness, h, leaf of uniform width, b (case 1) and, leaf of width, which is uniformly reducing from b (case 2) is considered. From the basic equations of bending stress and deflection, the maximum stress σ_{max} and tip deflection δ_{max}, can be derived.

For case 1(uniform width)

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

$$\delta_{max} = \frac{4FL^3}{Ebh^3}$$

Where, **E** is the Elastic modulus of the spring material.

For case 2(non uniform width)

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

$$\delta_{max} = \frac{6FL^3}{Ebh^3}$$

In the second case it is observed that instead of uniform width leaf, if a leaf of varying width (triangular one as shown in the figure) is used, the bending stress at any cross section is same and equal to $\sigma_{\mathbf{max}}$. This is called as leaf of a uniform strength. Moreover, the tip deflection being more, comparatively, it has greater resilience than its uniform width counterpart. Resilience, as we know, is the capacity to absorb potential energy during deformation. However, one should keep in mind that in order to withstand the shear force the tip has to have some width. This is shown as a red zone in the figure. In one way non uniform width leaf is a better design than a uniform width leaf.

Figure 1.4: Cantilever plate [3]

The spring is assumed to be a double cantilever beam, even though the leaf spring is simply supported at the ends. Also, this spring is geometrically and materially symmetrical so that only one half is considered with cantilever beam boundary conditions for the analysis to save the calculation time.

1.3. Composite materials

Composite materials are the combination of two or more constituent materials which have different chemical and physical properties but after combination produce a material with different characteristics. The composite material has the number of characteristic properties like low weight, high temperature performance, high stiffness, high Strength, high hardness and conductivity and good corrosion resistance.

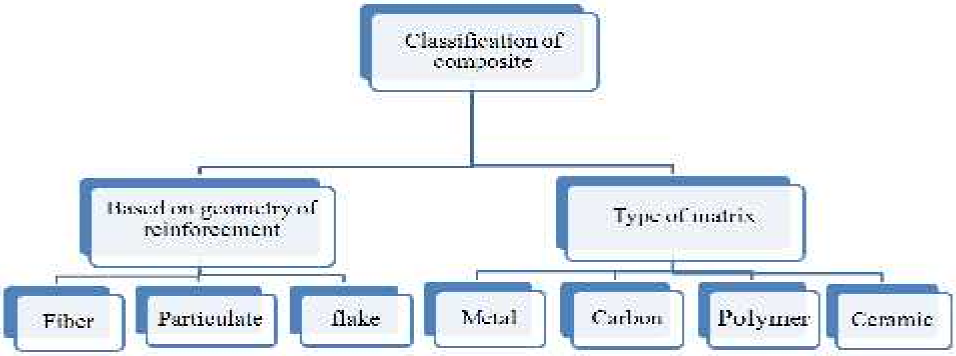


Figure 1.5: Classification of composite

1.3.1. Classification based on reinforcement geometry

According to the reinforcement geometry, composites are classified into three groups namely:

1. Particulate composites
2. Flake composites
3. Fiber composite

Particulate composites: Particulate composite strengthen by matrices those are composed by alloy particles and ceramics particles as shown in figure1. 6. There are some advantages of Particulate composite such as oxidation resistance, improved strength and increased operating temperature. Examples - silicon particles in aluminum matrix, aluminum particles in rubber matrix.

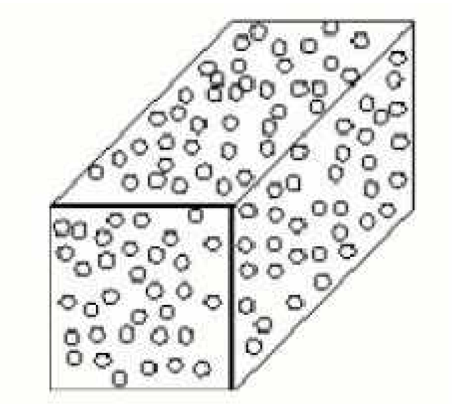


Figure 1.6: Particulate composite[4]

Flake composites: Flake composites made with flake shaped reinforcement such as silica, silver, glass, mica etc as shown in figure 1.7. Flake composite has advantages such as higher strength and low cost.

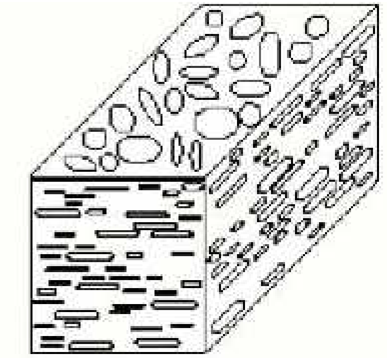


Figure 1.7: Flake composite [4]

Fiber composites: Fiber composites made with short (discontinuous) or long (continuous) fibers as shown in Figure. Examples - resins epoxy, aluminum and ceramics, calcium-alimino silicate.

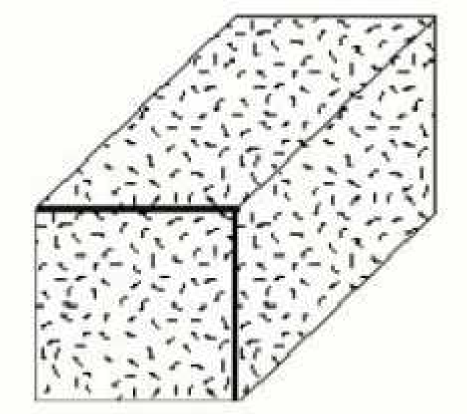


Figure 1.8: **Short discontinuous fiber** [4]

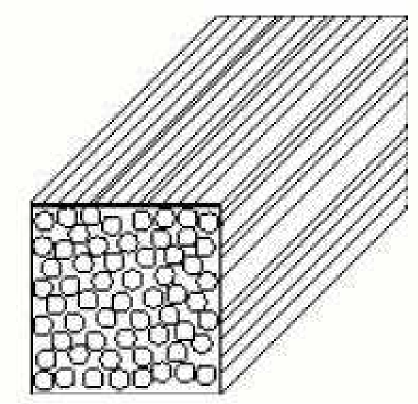


Figure 1.9: Long fiber [4]

1.3.2. Classification based on matrix

Based on the type of matrix, Composites may be classified as:

1. Polymer matrix composite (PMC)
2. Metal matrix composite (MMC)
3. Ceramic matrix composite (CMC)
4. Carbon-carbon composite

Polymer matrix composite (PMC): These are the most common advanced composites consisting of polymer (epoxy, polyester, urethane etc) reinforced by thin diameter fibers (graphite, boron etc). Graphite/Epoxy composites are approximately five times stronger than steel on a weight for-weight basis. They are commonly employed due to their low cost, high strength and simple manufacturing. Main drawbacks of polymer Laminate Composites (PMCs) include low operating temperature, high coefficient of thermal and moisture expansion and low elastic properties in certain directions. However, their advantages are high strength, low cost, high chemical resistance and good insulating property.

Metal matrix composite (MMC): It consists of metal matrix such as aluminum, magnesium and titanium etc. reinforced with fibers such as carbon, silicon carbide etc. Metals are reinforced to increase or decrease their properties to suit the design needs. For example, the elastic stiffness and strength of metals can be increased, while large coefficients of thermal expansion and thermal and electric conductivities of metal can be reduced by addition of fibers such as silicon carbide. MMCs are mainly used to provide advantages over monolithic alloy/metals such as steel and aluminum. These advantages include higher specific strength and specific modulus achieved by incorporation of reinforcement in low density metal matrix such as aluminum and titanium. MMCs possesses several advantages over polymer matrix composite such as higher elastic properties, higher service temperature, insensitive to moisture, higher electric and thermal conductivity, better fatigue and flow resistance. However, the drawbacks of MMCs over PMCs include higher processing temperature and higher densities

Ceramic matrix composite (CMC): Ceramic matrix composites (CMCs) have a ceramic matrix such as alumina, calcium alumino-silicate reinforced by fibers such as carbon or silicon carbide. Their main advantages include high strength and hardness, high service temperature, chemical inertness and low density. CMCs are finding extensive applications in high temperature areas where MMCs and PMC s cannot be used.

Carbon-Carbon Composite: Carbon-carbon composites have carbon fiber reinforced in matrix of carbon. Carbon-carbon composites are used in very high temperature environments up to 6000oF (3315oC) and are 20 times stronger and 30% lighter than graphite fibers. Their advantages include ability to withstand high temperatures, low creep at high temperature, low density, good tensile and compressive strength, high fatigue resistance, high thermal conductivity and high coefficient of friction. Their disadvantages include high cost, low shear strength and susceptibility to oxidations at high temperature. These composites find application in space shuttle nose cone, aircraft brakes, mechanical fasteners etc.

1.4. Introduction to FEA

FEA consists of a computer model of a material or design that is stressed and analyzed for specific results. It is used in new product design, and existing product refinement. A coMPany is able to verify a proposed design will be able to perform to the client's specifications prior to manufacturing or construction. Modifying an existing product or structure is utilized to qualify the product or structure for a new service condition. In case of structural failure, FEA may be used to help determine the design modifications to meet the new condition.

There are generally two types of analysis that are used in industry: 2-D modeling, and 3-D modeling. While 2-D modeling conserves simplicity and allows the analysis to be run on a relatively normal computer, it tends to yield less accurate results. 3-D modeling, however, produces more accurate results while sacrificing the ability to run on all but the fastest computers effectively. Within each of these modeling schemes, the programmer can insert numerous algorithms (functions) which may make the system behave linearly or non-linearly. Linear systems are far less complex and generally do not take into account plastic deformation. Non-linear systems do account for plastic deformation, and many also are capable of testing a material all the way to fracture.

FEA uses a complex system of points called nodes which make a grid called a mesh . This mesh is programmed to contain the material and structural properties which define how the structure will react to certain loading conditions. Nodes are assigned at a certain density throughout the material depending on the anticipated stress levels of a particular area. Regions which will receive large amounts of stress usually have a higher node density than those which experience little or no stress.. The mesh acts like a spider web in that from each node, there extends a mesh element to each of the adjacent nodes. This web of vectors is what carries the material properties to the object, creating many elements. A Finite Element analysis consist of three separated stages; Preprocessing, processing, and postprocessing. A complete finite element analysis is a logical interaction of these three stages.

1.4.1. Preprocessing

As the name indicates, preprocessing is something which is done before processing your analysis. The Preprocessing involves the preparations of data, such as nodal coordinates, connectivity, boundary conditions and loading and material information. The preparation of data require considerable effort if all data are to be handled manually. If the model is small, the user can often just write a text file and feed it into the processor, but as the complexity of the model grows and the number of elements increase, writing the data manually can be very time consuming and error-prone. Therefore it is necessary with a computer preprocessor which help with mesh plotting and boundary conditions plotting. we can change loads, boundary conditions, mesh and element properties and material. All this is done graphically to minimize the chance of error. The only limitation is that you cannot draw your own geometry, you have to select one of the pregenerated geometries.

1.4.2. Processing

The processing stage involves stiffness generation, stiffness modification, and solution of equations, resulting in the evaluation of nodal variables. This is a typical "black box"-operation, as the user will see little of what is going on. We feed data from the preprocessor, and get data out.

1.4.3. Postprocessing

The postprocessing stage deals with the representation of results.Typically, the deformed configuration, mode shapes, temperature, and stress distribution are computed and displayed at this stage.

AL-Qureshi (2001) presented a general study on the analysis, design and fabrication of composite leaf springs. The suspension spring of compact car (jeep) was selected as a prototype. A single leaf with variable thickness spring of glass fiber reinforced plastic was designed, fabricated and tested. The testing was performed experimentally in the laboratory and was followed by a road test. Comparison between GFRP and Steel multi leaf spring was done.

Shokrieh *et al. (*2003) compared the steel and composite leaf spring to obtain a spring with minimum weight that is capable of carrying given static external forces without failure. 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.

Shankar *et al.* (2003) presented a low cost fabrication of complete mono composite leaf spring and mono composite leaf spring with bonded end joints. A single leaf with variable thickness and width of constant cross sectional area of unidirectional glass fiber reinforced plastic (GFRP) with similar mechanical and geometrical properties to the multileaf spring, was designed, fabricated and tested. Computer algorithm using C-language has been used for the design of constant cross-section leaf spring. The results showed that 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.

Mahdi *et al.* (2006) studied the influence of ellipticity ratio on spring rate and load carring capacity. The influence of ellipticity ratio on performance of woven roving wrapped composite elliptical springs has been investigated both experimentally and numerically. A series of experiments was conducted for composite elliptical springs with ellipticity ratios (a/b) ranging from one to two. In general, this study demonstrated that composites elliptical spring can be used for light and heavy trucks and meet the requirements, together with substantial weight saving. The results showed that the ellipticity ratio significantly influenced the spring rate and failure loads. Composite elliptic spring with ellipticity ratios of a/b=2.0 displayed the highest spring rate.

Hou *et al.* (2007) presented the design evolution process of a composite leaf spring for freight rail applications. Three designs of eye-end attachment for composite leaf springs were described. The material used was glass fibre reinforced polyester. Static testing and finite element analysis had 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 had been plotted for comparison with FEA predicted values. The main concern associated with the first design was 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 interlaminar 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.

Abdullah *et al*. (2009) analyzed and evaluated the capability of parabolic spring to replace the multi leaf in suspension system. Finite element analysis had been performed to analyze the stress distribution and behavior for both type of springs. Finally, comparison between simulation and experimental result had been made for validating purpose. Multi leaf can hold much more load then parabolic spring, but in terms of material usage and space requirement, parabolic spring has the advantages. For multi-leaf, the stress was concentrated at the center part, while for parabolic, stress was distributed well at the both side of the part.

Yinhuan *et al.* (2011) analyzed the mechanics characteristic of a composite leaf spring made from glass fiber reinforced plastics using the ANSYS software. Considering interleaf contact, the stress distribution and deformation were obtained. Taking the single spring as an example, comparison between the performance of the GFRP and the steel spring was presented. The comparison results showed that the composite spring has lower stress and much lower weight. Then the automotive dead weight is reduced observably.

Turan *et al.* (2011) evaluated the effects of joint geometry and fiber orientation on the failure loads and failure modes, parametric studies were performed experimentally and numerically. A numerical study was performed by using 3D APDL codes with ANSYS fem software and Hashin Failure Criteria was used for predicted failure mode and failure load. The experimental and numerical results showed that the failure loads of composite plates were increased with increasing E/D and W/D ratios.

Gebremeskel *et al.* (2012) designed a single E-glass/Epoxy leaf spring and simulated following the design rules of the composite materials. And it was shown that the resulting design and simulation stresses are much below the strength properties of the material satisfying the maximum stress failure criterion. This particular design was made specifically for light weight three wheeler vehicles. Its prototype was also produced using hand lay-up method.

Ekbote *et al.* (2012) analyzed nine-leaf steel spring used in the rear suspension system of a light duty vehicle by finite element method using ANSYS software. 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 was assumed and its analytical solution was 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.

FARIS *et al.* (2012) investigated the static and fatigue behaviors of steel and composite multi-leaf spring using the ANSYS V12 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 or the two materials-glass fiber/epoxy and E-glass fiber/vinyl ester, which are of great interest to the transportation industry. Main consideration was given to 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.

Kothari *et al.* (2012) studied static and fatigue life analysis of conventional leaf springs made of respectively SUP 9 & EN 45. Comparison for maximum stress, deflection and stiffness as well as fatigue life was done. The CAD models were prepared in CATIA and analyzed by using ANSYS 12.1. Computer algorithm using C++ language had been used in calculating maximum stress, deflection and stiffness. Calculated results were compared with FEA result. SUP 9 springs has lower value of maximum stress, deflection and stiffness in compare to EN45 spring.

Krishan *et al.* (2012) designed a multi leaf spring made of steel and stress-deflection analysis was carried out by finite element approach using CAE tools i.e CATIA, ANSYS. When the leaf spring is fully loaded, a variation of 0.632 % in deflection is observed between the experimental and finite element analysis result, and same in case of half load, which validated the model and analysis. On the other hand, bending stress in both the cases was also close to the experimental results. The maximum value of equivalent stresses was below the Yield Stress of the material that the design was safe from failure.

Raghavedra *et al.* (2012) compared laminated composite leaf spring and steel leaf spring with respect to weight, stiffness and strength. By employing a composite leaf spring for the same load carrying capacity, there was a reduction in weight of 73%-80%**,** natural frequency of composite leaf springs are 27%~67% higher than steel leaf spring and 23~65% stiffer than the steel spring**.** Based on the results, it was inferred that carbon/epoxy laminated composite mono leaf spring has superior strength and stiffness and lesser in weight compared to steel and other composite materials considered in this investigation. From the results, it is observed that the laminated composite leaf spring is lighter and more economical than the conventional steel spring with similar design specifications.

Radha *et al.* (2013) studied the material optimization of existing steel, carbon fiber and boron fibers were evaluated and optimized the best one in concern with their performance. The boron fiber composite material can be replaceable with existing steel for master leaf spring. The master leaf spring was modeled in Pro/E (Wild Fire) 5.0 and analysis was carried out by using ANSYS 13.0 for better understanding. The objective of this project was to present modeling, stress analysis and material optimization of master leaf spring and comparison of deformation and stress results between steel leaf spring and composite leaf springs under same conditions.

Suhas *et al.* (2013) experimentally done investigation on E glass/Epoxy Resin hybrid composites lead to the following conclusions. For the compositions of 50:50%, 40:60%, 30:70% by volume of E-glass/Epoxy, 40:60% composition yielded maximum tensile strength, impact strength and flexural strength. The entire fabrication of composite leaf spring was done with 40:60% of E-Glass/Epoxy composition. A comparative study made between composite and steel leaf springs with respect to weight and strength showed that composite leaf spring has more load carrying capacity and is lighter compared to Steel leaf spring. The study demonstrated that composites can be used for leaf springs in light weight vehicles.

Increasing competition in automobile sector tends to modify the existing products or replacing old products by new and advance materials. The suspension leaf spring is one of the potential items for weight reduction in automobile vehicles. The automobile industry has shown great interest in replacement of steel parts with composite materials. The advantages of using composite material include high strength to weight ratio. In the present work, a geometric model of multi leaf spring consisting of nine leaf was created in solid works and finite element analysis was carried out in ABAQUS 6.10. The objective of the present work is to:-

1. Perform stress and deflection analysis of leaf spring made of steel, glass fiber/epoxy composite, carbon fiber/epoxy composite.
2. Comparison between stresses and deflections in a steel and composite leaf springs.
3. Determine the effect of fiber orientation on stresses and deflection induced in composite leaf springs

3.1. Design methodology

1. Modeling of mutli-leaf spring was done in SOLID WORKS 2012.
2. Geometric Model of the multi leaf spring is imported in ABAQUS 6.10.
3. Finite element analysis of multi leaf spring has been done using three different materials (steel, carbon/epoxy and glass/epoxy).
4. Stresses and deflections are obtained from finite element analysis for three different materials are compared and conclusions are drawn.

3.2. Design variables of multi leaf spring

Following dimensions are taken for steel as well as composite leaf spring.

Table 3.1: Dimensions of leaf spring [17]

Parameter Name	Value
Span length(eye to eye)	1450 mm
Number of full length leaves	2
Number of graduated length leaves	7
Width of leaves	70 mm each
Thickness of leaves	12 mm each
Length of full length leaves(L1 and L2)	1450 mm
Length of graduated leaves (L3, L4, L5, L6, L7, L8, L9)	1320, 1140, 940, 800, 640, 464, 244 mm

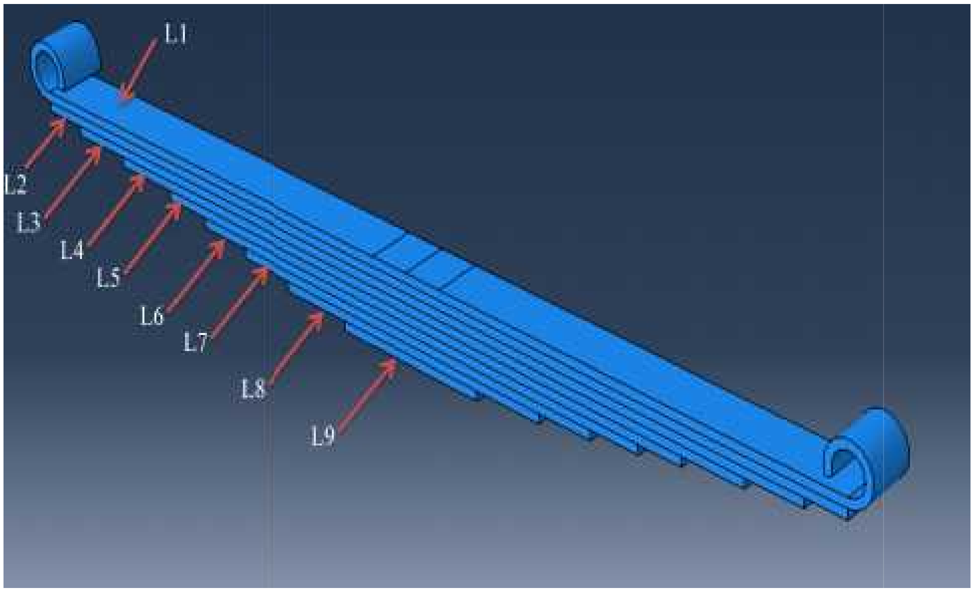


Figure 3.1: Multi Leaf Spring

3.3. Material properties

Material properties of steel, glass fiber/epoxy and carbon fiber/epoxy composites are taken from research paper.

Table 3.2: Material properties of glass fiber/epoxy composite [14]

PROPERTY	VALUE
Tensile modulus along X-direction (E_x), MPa	36040
Tensile modulus along Y-direction (E_y), MPa	5195
Tensile modulus along Z-direction (E_z), MPa	5195
Tensile strength of the material, MPa	900
Compressive strength of the material, MPa	450
Shear modulus along XY-direction (G_{xy}), MPa	2127
Shear modulus along YZ-direction (G_{yz}), MPa	1550
Shear modulus along ZX-direction (G_{zx}), MPa	2127
Poisson ratio along XY-direction (γ_{xy})	0.26
Poisson ratio along YZ-direction (γ_{yz})	0.29
Poisson ratio along ZX-direction (γ_{zx})	0.26

Table 3.3: Material properties of carbon fiber/epoxy composite [12]

PROPERTY	VALUE
Tensile modulus along X-direction (E_x), MPa	172821
Tensile modulus along Y-direction (E_y), MPa	10797
Tensile modulus along Z-direction (E_z), MPa	10797
Tensile strength of the material, MPa	1400
Compressive strength of the material, MPa	800
Shear modulus along XY-direction (G_{xy}), MPa	5000
Shear modulus along YZ-direction (G_{yz}), MPa	3500
Shear modulus along ZX-direction (G_{zx}), MPa	3500
Poisson ratio along XY-direction ($Ɣ_{xy}$)	0.32
Poisson ratio along YZ-direction ($Ɣ_{yz}$)	0.25
Poisson ratio along ZX-direction ($Ɣ_{zx}$)	0.25

Table 3.4: Material properties of steel

Parameter Name	**Value**
Material selected	SUP9
Young modulus of elasticity, MPa	210000
Poisson's ratio	0.26
Tensile strength ultimate, MPa	1272
Tensile strength yield, MPa	1158
Behavior	Isotropic
Density	0.785

3.4. CAD modeling of multi leaf spring

CAD modeling software is dedicated for the specialized job of 3D-modeling. The model of the multi leaf spring structures also includes many complicated parts. Modeling of multi leaf spring is done in SOLID WORKS. All the nine leaves are modeled separately in the part module of solid works and assembled in assembly module. The multi leaf spring is modeled in a position having maximum deflection i.e. all leaves are in flat position and then load is applied in the reverse direction to attain its original shape i.e. semi-elliptical. The modeling process is same for steel as well as composite leaf spring. First of all 2-D geometry was created in sketch of part module and it is then extruded to get the required 3-D geometry. These steps are repeated for all the nine leaves followed by assembly in the assembly module.

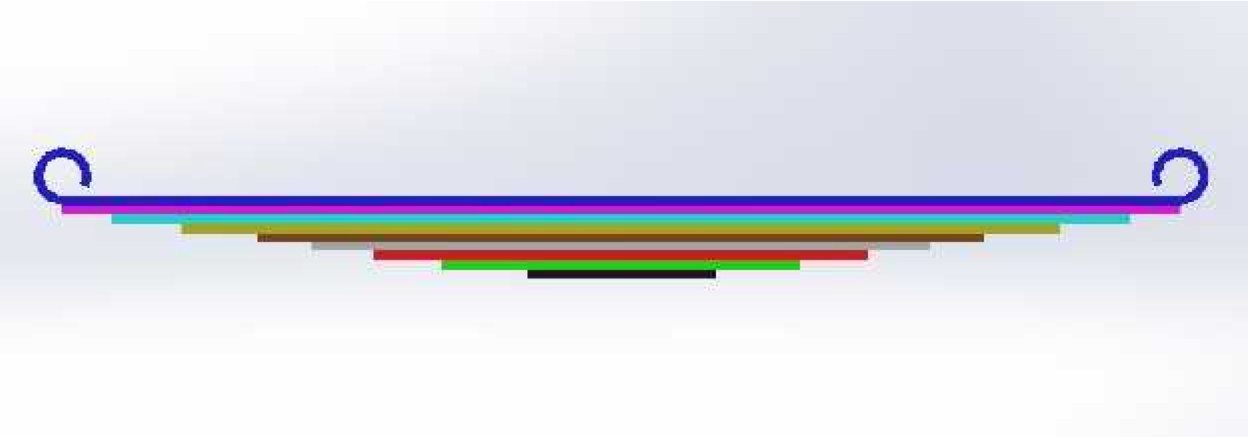


Figure 3.2: CAD Model of multi leaf spring

After doing the modeling of multi leaf spring in solid works, the model has been imported in ABAQUS 6.10. The following steps are performed thereafter:

1. Computer model generation.
2. Assigning material properties to all the nine leaves.
3. Inserting plies in the leaves made of composite material.
4. Applying boundary conditions.
5. Applying load.
6. Assigning interaction property between the leaves.
7. Mesh generation.
8. Creating the job to get output data file(.odb)
9. Opening the .odb file to see the results.

All the above steps were done for the analysis of leaf spring made of steel as well as composite leaf spring only the difference was there is no insertion of plies in multi leaf spring made of steel

4.1 Computer model generation

After doing the assembly of all the leaves of leaf spring in SOLIDWORKS 2012 it was saved with extension as parasolid. Then it was imported in ABAQUS 6.10 and the finite element model was automatically generated.

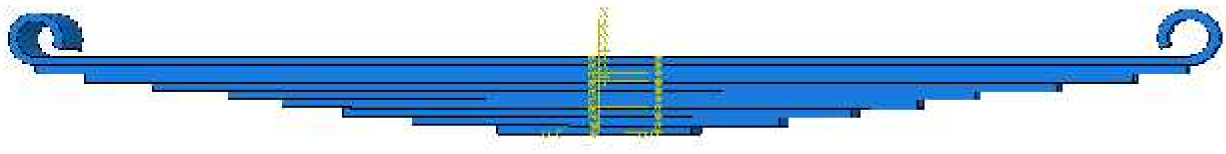
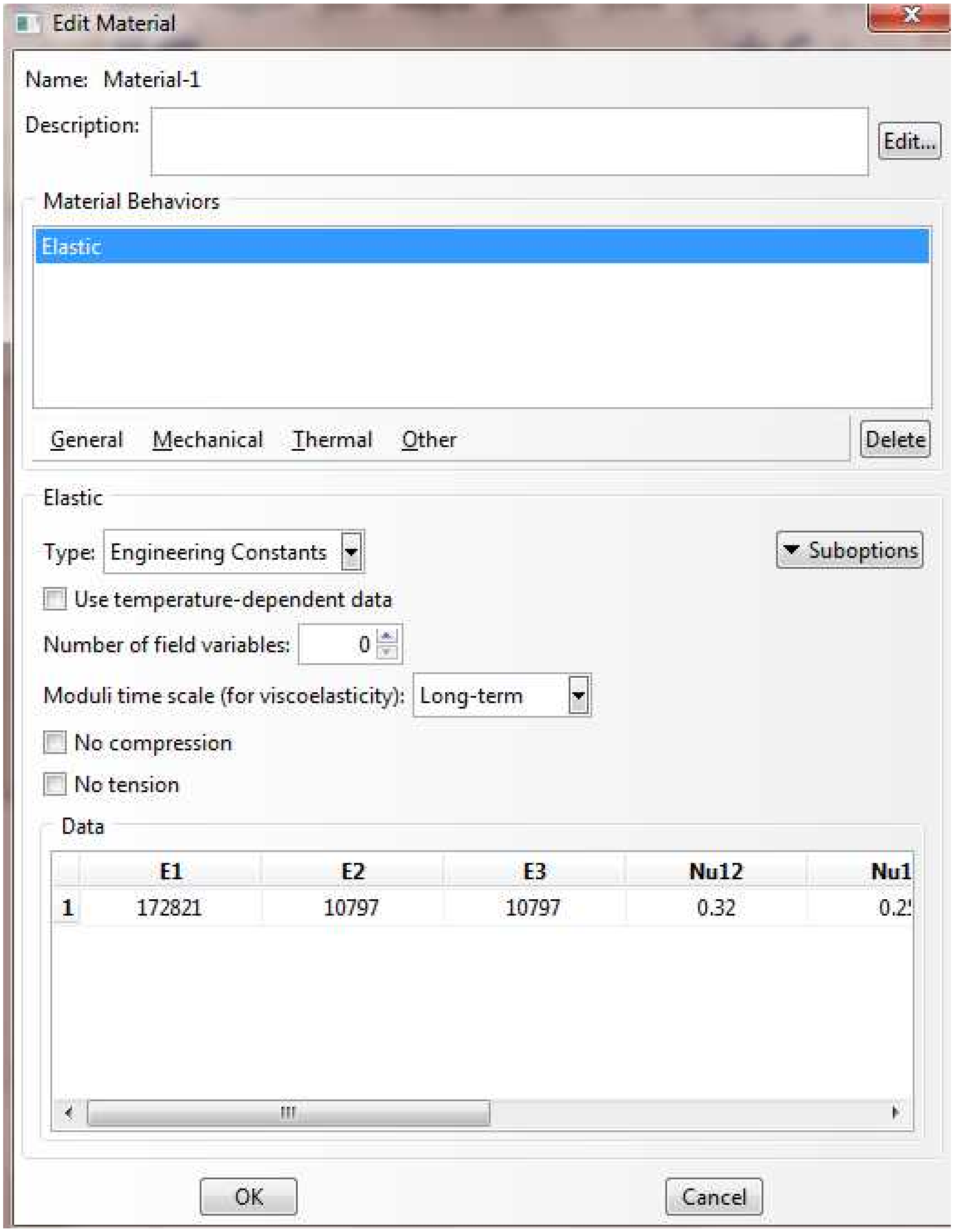


Figure 4.1: Geometry generation

4.2. Assigning the material properties

In material properties of steel, carbon/epoxy, glass/epoxy were assigned as shown in the material property box. The properties of the above materials were taken from the research paper and are shown figure 4.2.



Name: Material-1

Description:

Material Behaviors

Elastic

Elastic

Type: Engineering Constants

☐ Use temperature-dependent data

Number of field variables: 0

Moduli time scale (for viscoelasticity): Long-term

☐ No compression

☐ No tension

Data

	E1	E2	E3	Nu12	Nu1
1	172821	10797	10797	0.32	0.2

Figure 4.2: Assigning material property

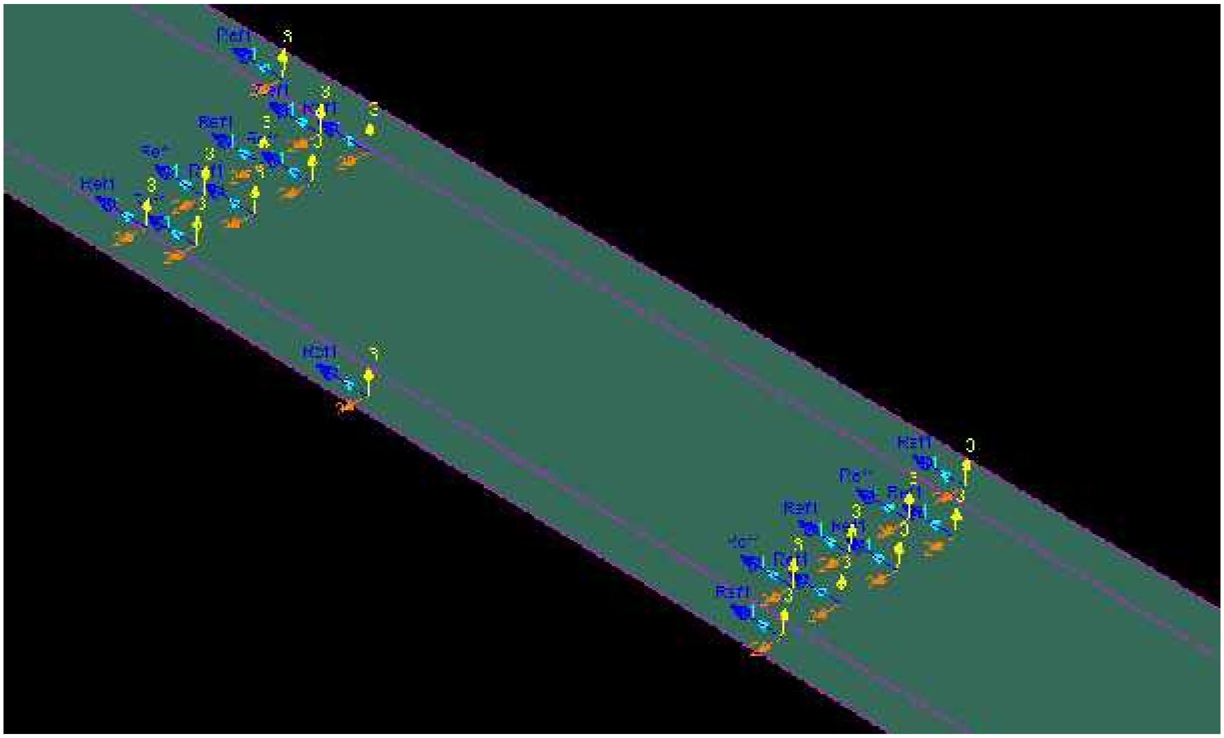


Figure 4.3: Ply orientation in 0^0

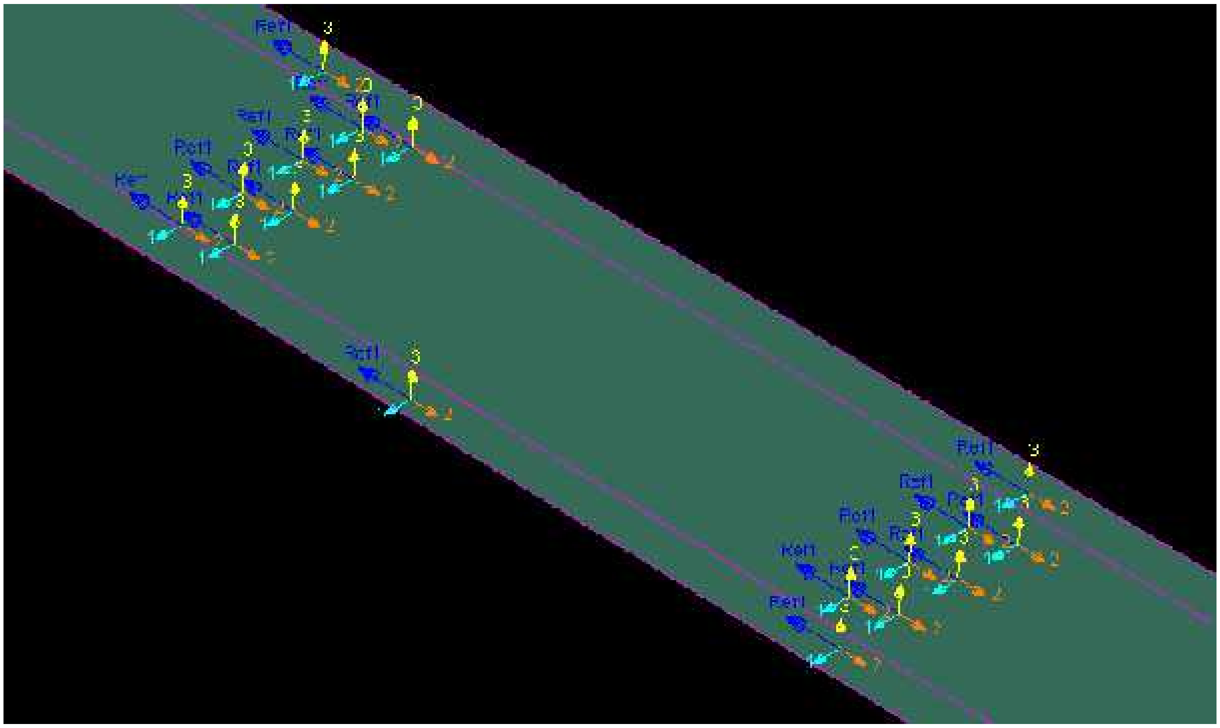


Figure 4.4: Ply orientation in 90^0

4.3. Plies insertion in composites

Inserting the plies only for multi leaf spring made of composite material (glass/epoxy and carbon/epoxy). There are no plies in case steel.

1. There are 30 plies in each leave.
2. Width of each ply is 0.4mm.
3. Fiber orientation in plies is also varied.
4. Stacking of plies was done in z direction

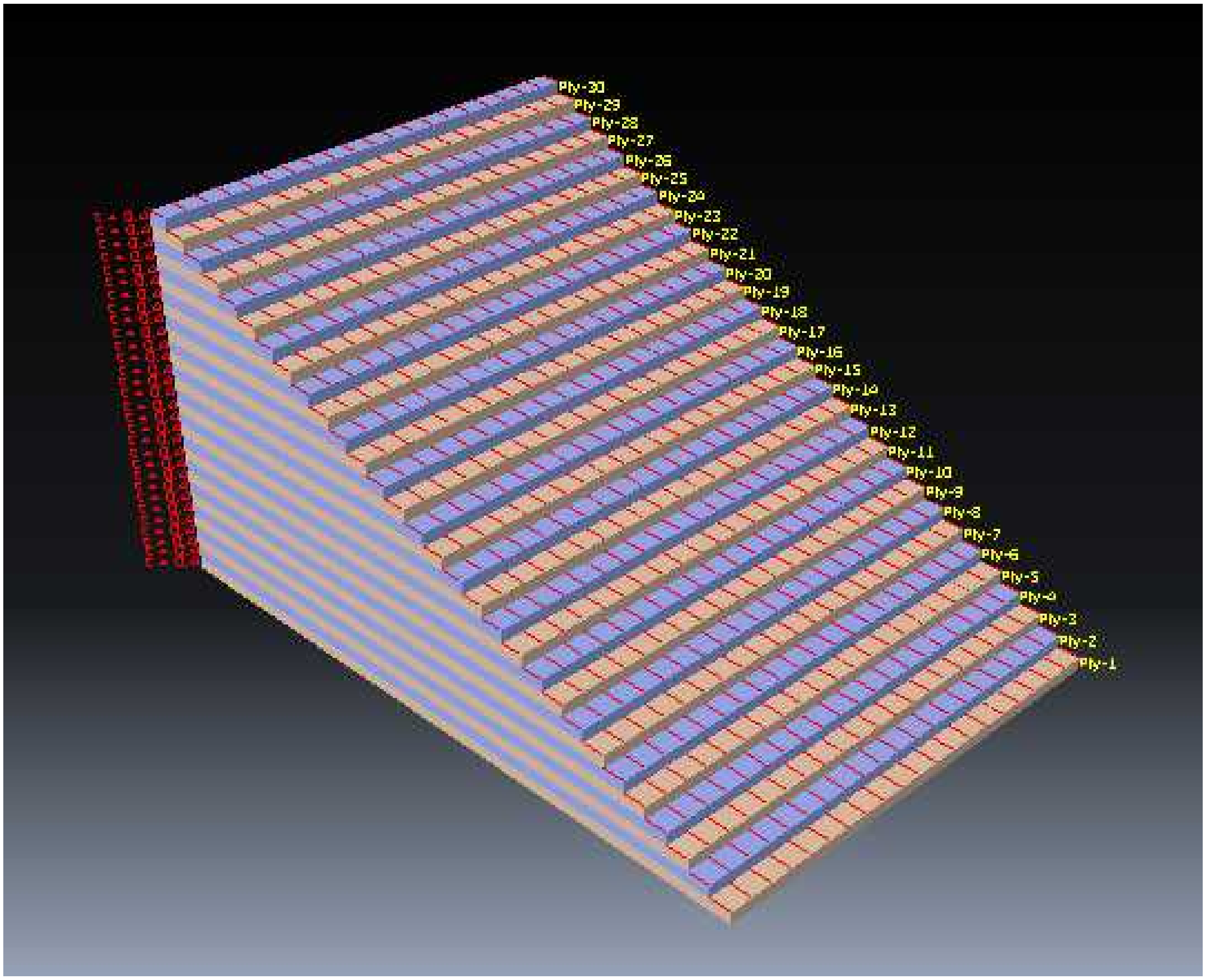


Figure 4.5: Ply Layup with fibre direction(0 degree)

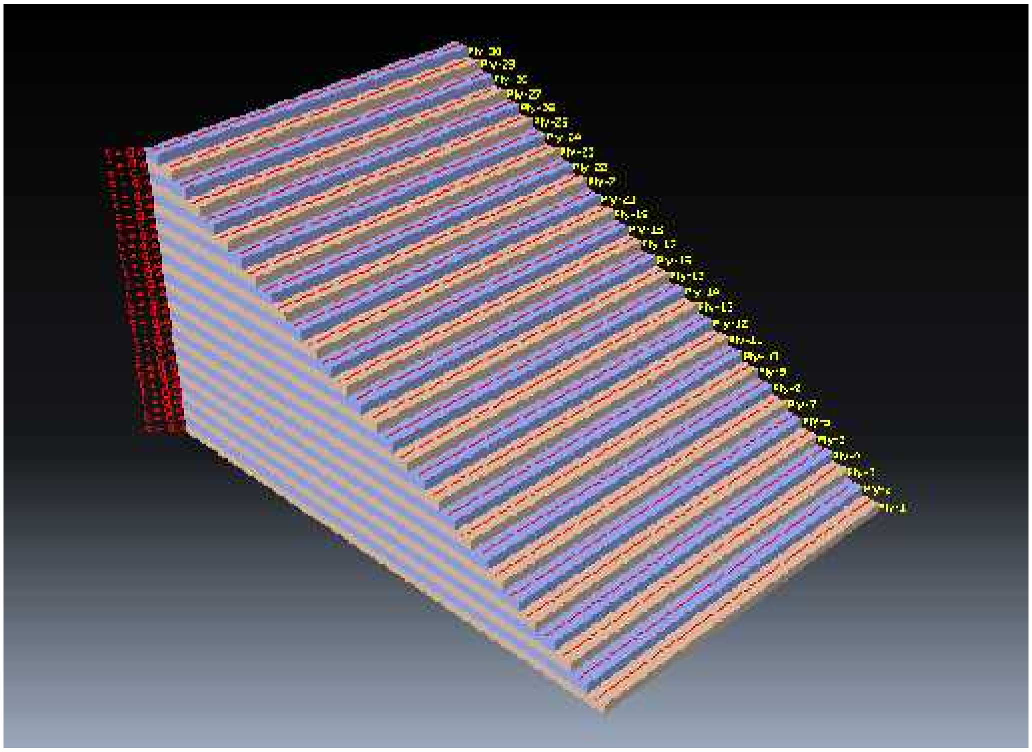


Figure 4.6: Ply stack with fibre direction(90 degree)

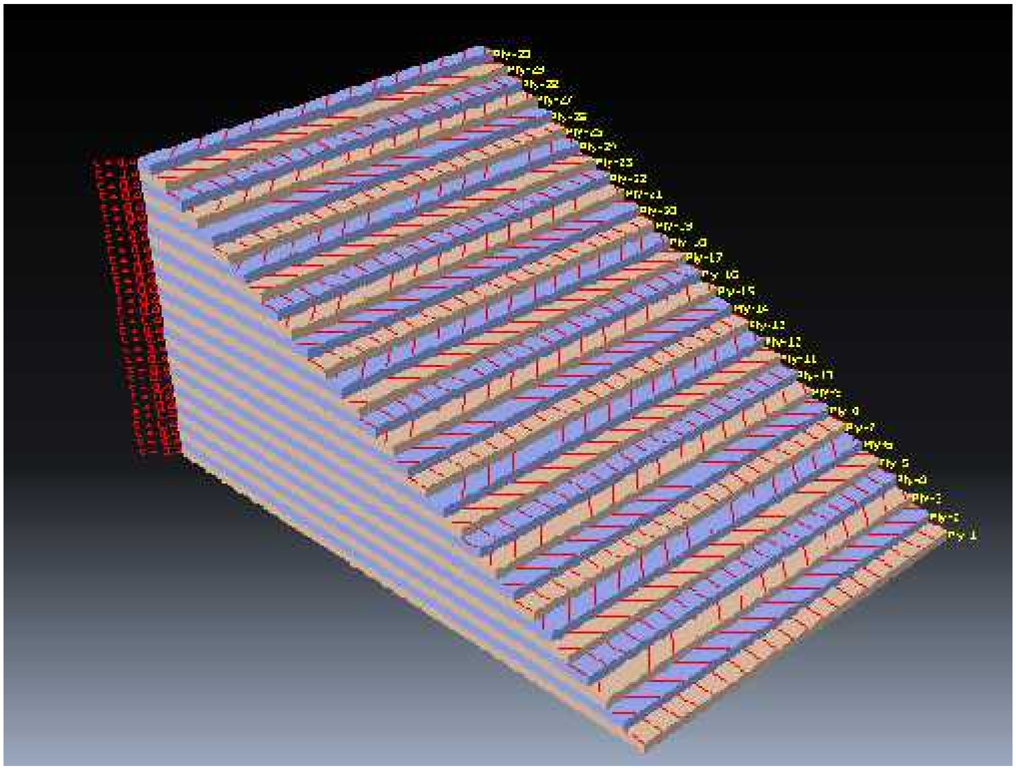
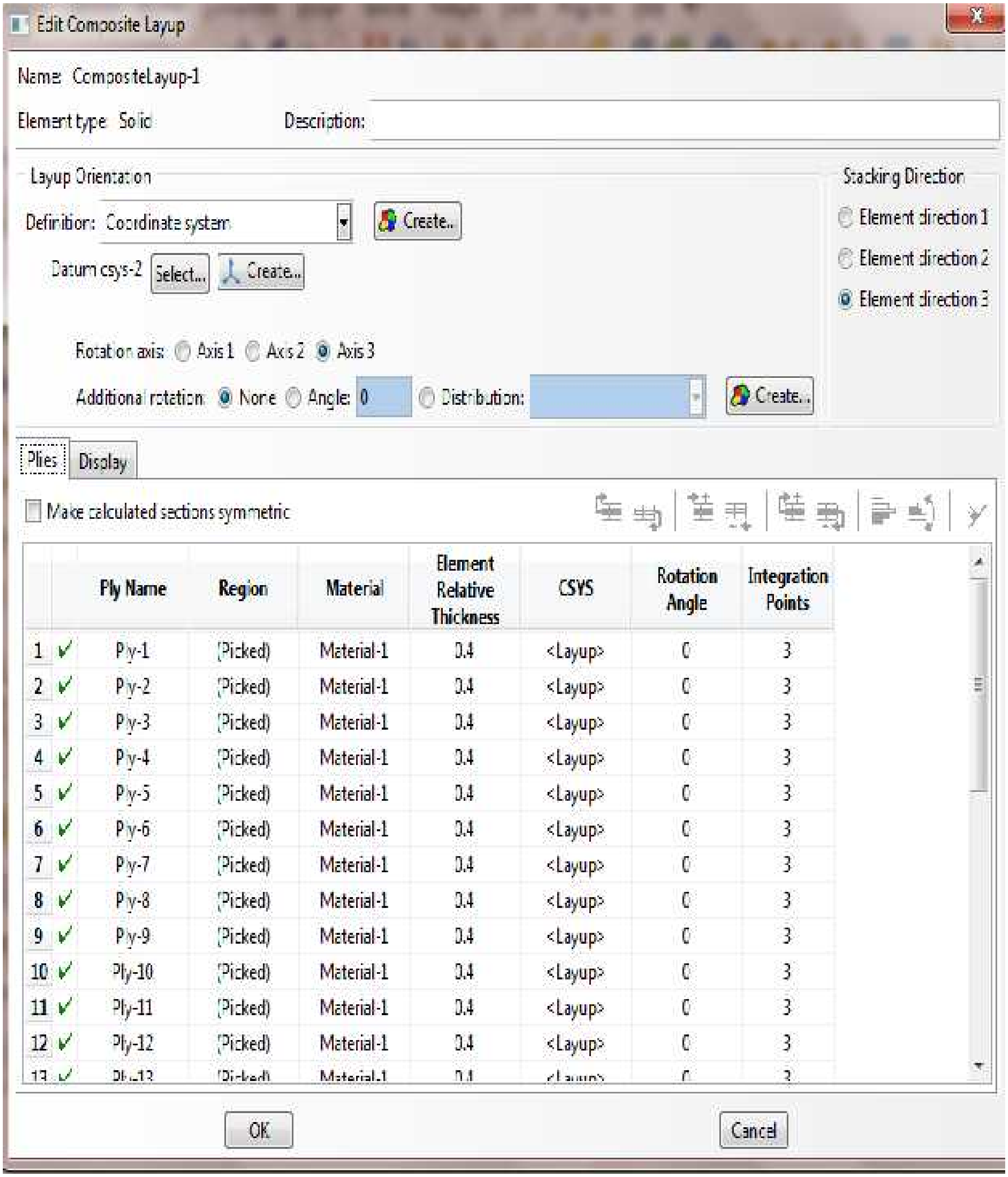


Figure 4.7: Ply stack with fibre direction(0,45,-45 degree)

4.4. Ply layup for composite leaf spring

In composite layup module, stacking direction and orientation of each ply along with the thickness is given to each leaf separately.



Edit Composite Layup

Name: CompositeLayup-1

Element type: Solid

Description:

Layup Orientation

Definition: Coordinate system

Datum csys-2

Rotation axis: ○ Axis 1 ○ Axis 2 ● Axis 3

Additional rotation: ● None ○ Angle: 0 ○ Distribution:

Stacking Direction

○ Element direction 1

○ Element direction 2

● Element direction 3

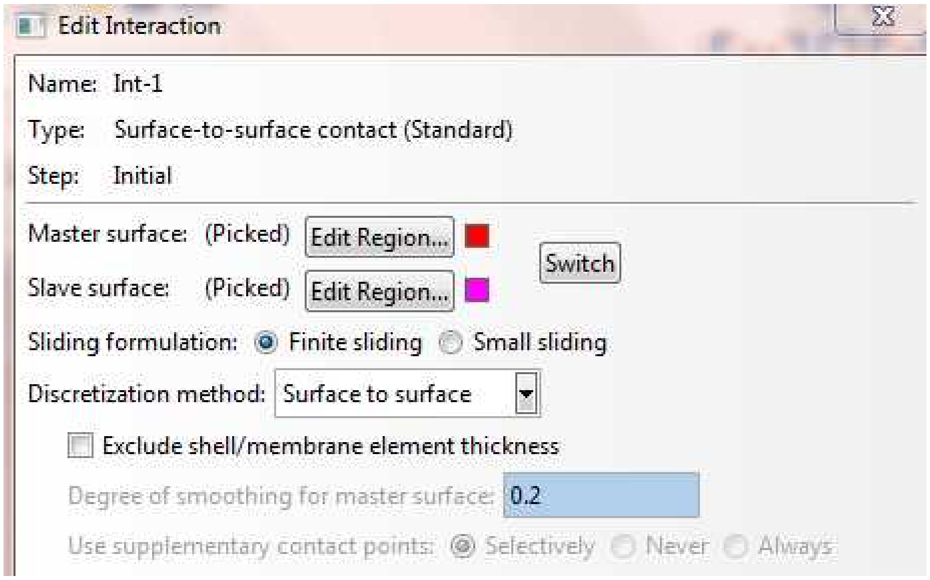
☐ Make calculated sections symmetric

		Ply Name	Region	Material	Element Relative Thickness	CSYS	Rotation Angle	Integration Points
1	✓	Ply-1	(Picked)	Material-1	0.4	<Layup>	0	3
2	✓	Ply-2	(Picked)	Material-1	0.4	<Layup>	0	3
3	✓	Ply-3	(Picked)	Material-1	0.4	<Layup>	0	3
4	✓	Ply-4	(Picked)	Material-1	0.4	<Layup>	0	3
5	✓	Ply-5	(Picked)	Material-1	0.4	<Layup>	0	3
6	✓	Ply-6	(Picked)	Material-1	0.4	<Layup>	0	3
7	✓	Ply-7	(Picked)	Material-1	0.4	<Layup>	0	3
8	✓	Ply-8	(Picked)	Material-1	0.4	<Layup>	0	3
9	✓	Ply-9	(Picked)	Material-1	0.4	<Layup>	0	3
10	✓	Ply-10	(Picked)	Material-1	0.4	<Layup>	0	3
11	✓	Ply-11	(Picked)	Material-1	0.4	<Layup>	0	3
12	✓	Ply-12	(Picked)	Material-1	0.4	<Layup>	0	3
13	✓	Ply-13	(Picked)	Material-1	0.4	<Layup>	0	3

Figure 4.8: Showing Ply Layup with orientation

4.5. Assigning interaction property

Surface to surface interactions were assigned between the two intersecting leaves as shown in fig below. This property is same for leaves made of composite as well as steel material



Name: Int-1
Type: Surface-to-surface contact (Standard)
Step: Initial
Master surface: (Picked) 🟥
Slave surface: (Picked) 🟪
Sliding formulation: ● Finite sliding ○ Small sliding
Discretization method: Surface to surface
☐ Exclude shell/membrane element thickness
Degree of smoothing for master surface: 0.2
Use supplementary contact points: ● Selectively ○ Never ○ Always

Figure 4.9: Interaction Property

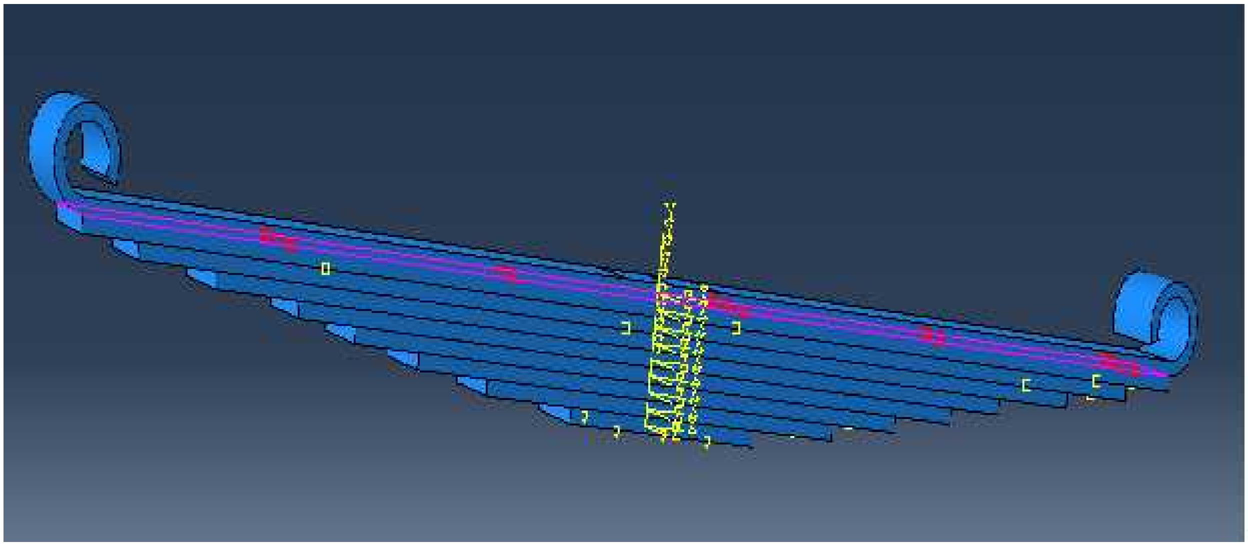


Figure 4.10: Showing Interaction between upper two leaves

4.6. Mesh generation

Mesh generation is one of the most critical aspects of engineering simulation. Too many cells may result in long solver runs, and too few may lead to inaccurate results. In the mesh module in ABAQUS meshing of all the nine leaves of leaf spring was done. The element used for meshing is an 8-node linear brick element(C3D8R). The seeds were given global size of 50.

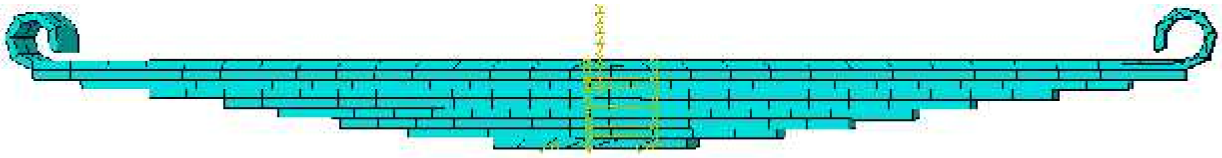
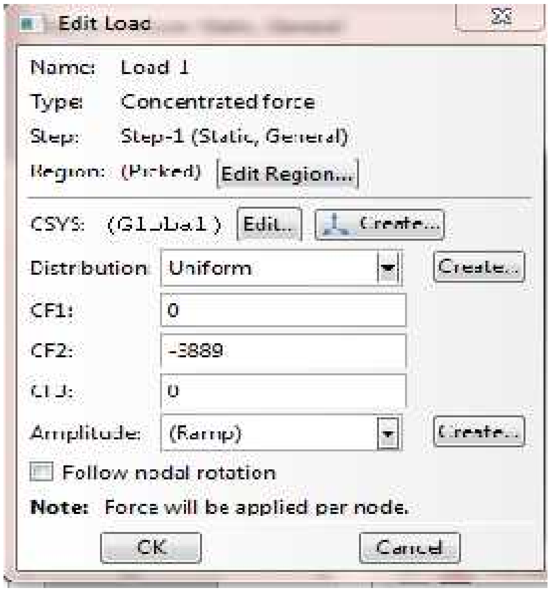


Figure 4.11 : Mesh Generation

4.7. Applying load

A load of 35KN is applied in the downward direction that is negative y-direction. This is same for all the three leaf springs made of steel, glass fiber/epoxy composite and carbonfiber/ epoxy composite.



Edit Load

Name: Load 1
Type: Concentrated force
Step: Step-1 (Static, General)
Region: (Picked)
CSYS: (Global)
Distribution: Uniform
CF1: 0
CF2: -3889
CF3: 0
Amplitude: (Ramp)
☐ Follow nodal rotation
Note: Force will be applied per node.

Figure 4.12: Load Module

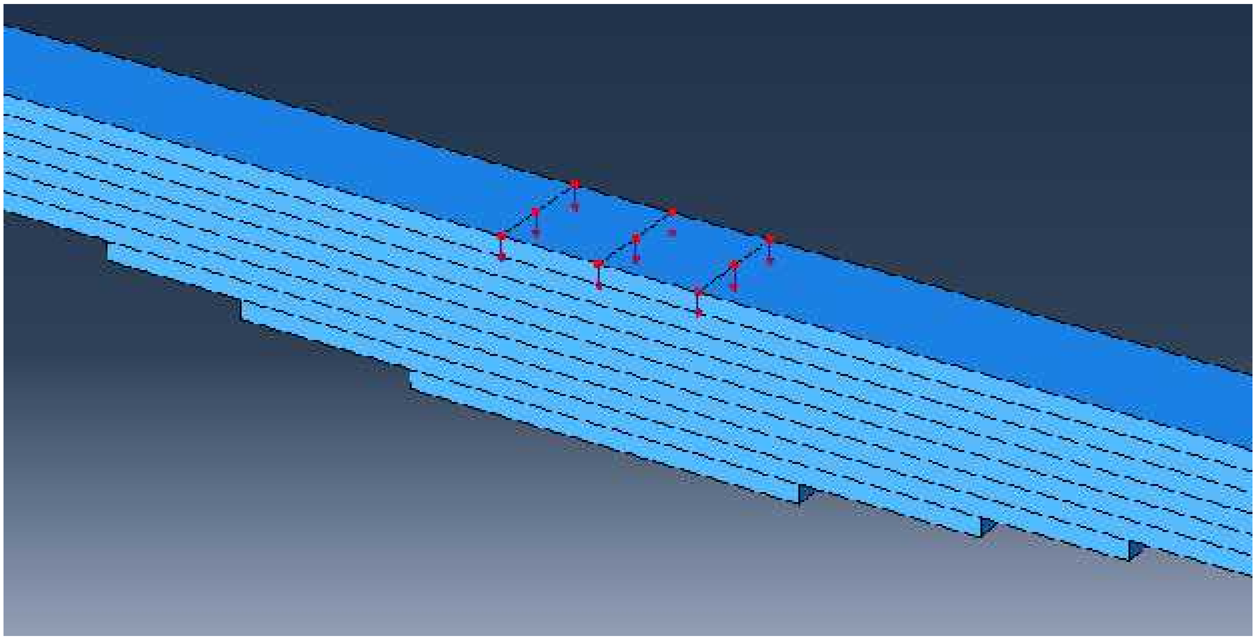
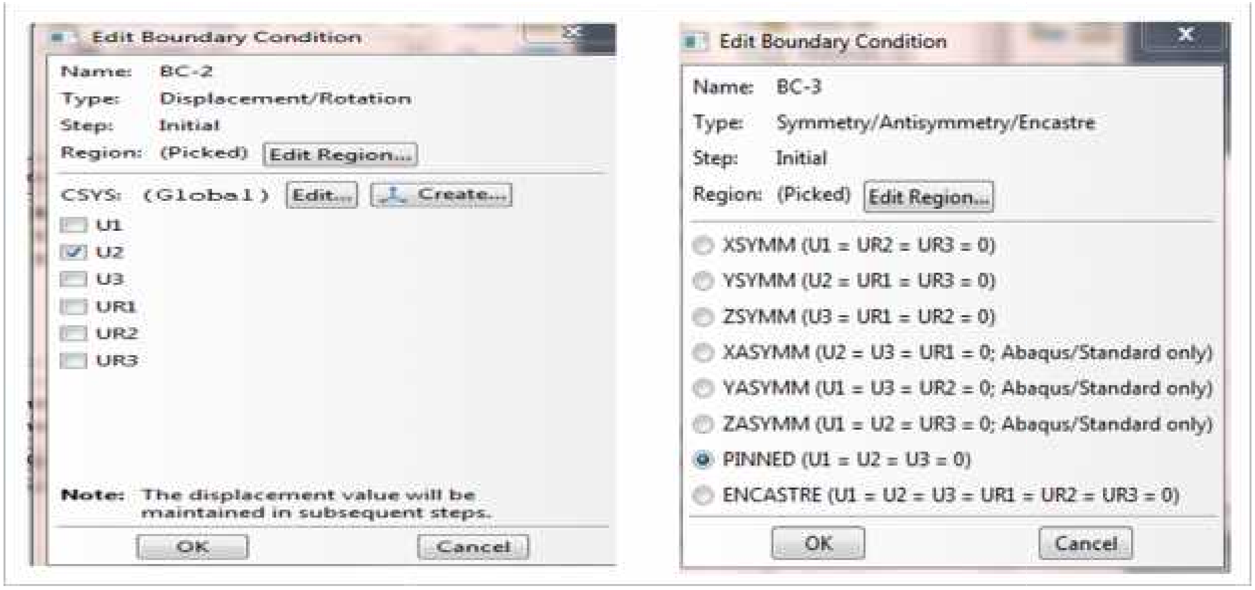


Figure 4.13: Applied Load

4.8. Appling boundary conditions

Boundary conditions are applied on both sides of the full length (top) leave having eyes. In fig 4.14 below first eye was fixed in x, z-directions and free to move in y-direction and second eye was fixed in x, y, z-directions.



Name: BC-2
Type: Displacement/Rotation
Step: Initial
Region: (Picked)
CSYS: (Global)
☐ U1
☑ U2
☐ U3
☐ UR1
☐ UR2
☐ UR3

Note: The displacement value will be maintained in subsequent steps.

Name: BC-3
Type: Symmetry/Antisymmetry/Encastre
Step: Initial
Region: (Picked)
○ XSYMM (U1 = UR2 = UR3 = 0)
○ YSYMM (U2 = UR1 = UR3 = 0)
○ ZSYMM (U3 = UR1 = UR2 = 0)
○ XASYMM (U2 = U3 = UR1 = 0; Abaqus/Standard only)
○ YASYMM (U1 = U3 = UR2 = 0; Abaqus/Standard only)
○ ZASYMM (U1 = U2 = UR3 = 0; Abaqus/Standard only)
● PINNED (U1 = U2 = U3 = 0)
○ ENCASTRE (U1 = U2 = U3 = UR1 = UR2 = UR3 = 0)

Figure 4.14: Boundary Conditions on Left eye (L) and right eye (R)

Theoretical and finite element analysis results for steel as well composite made leaf spring are calculated and graphically presented on the graph.

5.1. Effect of orientation of plies on stress and deflection

In the composite layup 30 plies are inserted for each leaf and following are cases are studied to see the effect of orientation. In the first case all the 30 plies are given 0 degree orientation, in second all the plies are given 90 degree orientation and in the third case all the plies are given 0,45.-45 degree symmetric orientation. Stresses and deflection obtained for the three cases are shown below in the table.

Table 5.1: Different Orientation of Plies

Case	Ply orientation	Glass/epoxy (stress)	Glass/epoxy (deflection)	Carbon/epoxy (stress)	Carbon/epoxy (deflection)
1	0	159.5	116.7	555.4	98
2	90	143.6	189.4	142.8	122.8
3	[0,45,-45]	204.9	140.9	659.8	107.3

From the table we can see that deflection is minimum for both carbon/epoxy and glass/epoxy in the first case. Stress is minimum for both carbon/epoxy and glass/epoxy in the second case but in the second case deflection is more which tend to decrease the stiffness. So case1 is better of all the cases keeping in view stress and stiffness. So for comparison with steel leaf spring first case is taken that is all the plies are given zero degree orientation.

5.2. Theoretical results

Load (P) =17500N Thickness (t) =12mm

Width (b) =70mm Length (centre to eye) =725mm

Number of full length leaves (n_f) = 2

Number of full length leaves (n_g) = 7

Maximum stress calculated

$$\sigma = \frac{6\,P\,L}{n\,b\,t^2}$$

$$\sigma = \frac{6\ \times 17500 \times\ 725}{9 \times\ 70 \times\ 12^2}$$

$$\sigma = 839.12\ N/mm^2$$

Maximum deflection calculated

$$\delta = \frac{12\,P\,L^3}{E\,b\,t^3\ (\,3n_f + 2n_g\,)}$$

$$\delta = \frac{12 \times 17500 \times 725^3}{210\ \times 10^3 \times 70 \times 12^3\ (3 \times 2 + 2 \times 7)}$$

$$\delta = 157.52\ mm$$

5.3. Finite elemnt analysis results

Finite element analysis results for stress and deflection were plotted as contour plots for leaf springs made of steel, glass/epoxy, carbon/epoxy as shown below.

5.3.1. Stresses and Deflections in Steel Leaf Spring

In the contour plots below, maximum stress and deflection for the carbon/epoxy leaf spring comes out to be 911.7 N/mm^2 and 152.2 mm respectively. Maximum stress concentration was seen in the top full length leaf near the eye end. Maximum deflection was obtained in the center and it is decreasing as we move from center to the end of leaves.

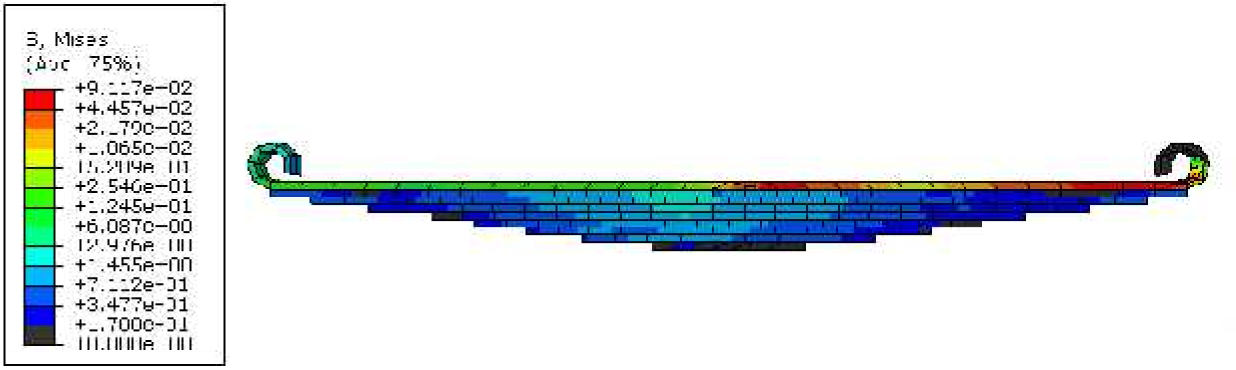


Figure 5.1: Stress contour in Steel Leaf Spring

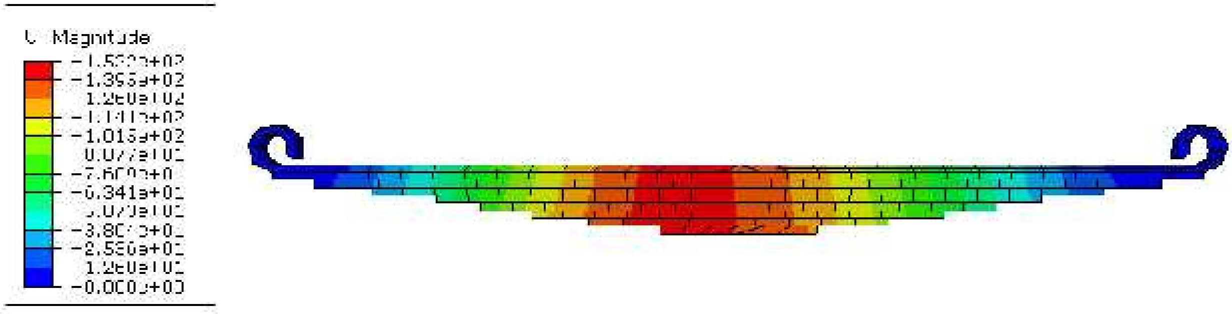


Figure 5.2: Deflection contour in Steel Leaf Spring

5.3.2. Stresses and Deflections in glass fiber/epoxy composite leaf spring

In the contour plots below, maximum stress and deflection for the carbon/epoxy leaf spring comes out to be 159.5 N/ mm^2 and 116.7 mm respectively. Maximum stress concentration wass in the top full length leave near the eye end. Maximum deflection was obtained in the center and it is decreasing as we move from center to the end of leaves.

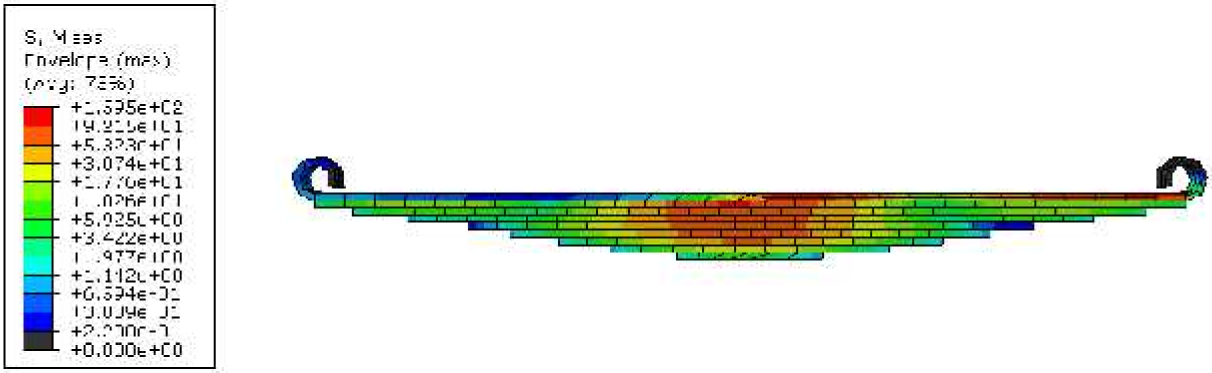


Figure 5.3: Stress contour in glass fiber/epoxy composite leaf spring

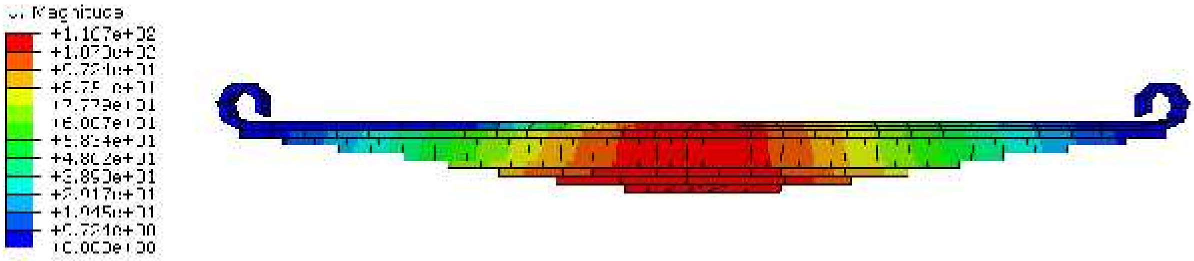


Figure 5.4: Deflection contour in glass fiber/epoxy composite leaf spring

5.3.3. Stresses and Deflections in Carbon fiber/Epoxy composite Leaf Spring

In the contour plots below, maximum stress and deflection for the carbon/epoxy leaf spring comes out to be 555.4 N/ mm^2 and 98 mm respectively. Maximum stress concentration was in the top full length maximum leaf stress near the eye end. Maximum deflection was obtained in the center and it is decreasing as we move from center to the end of leaves.

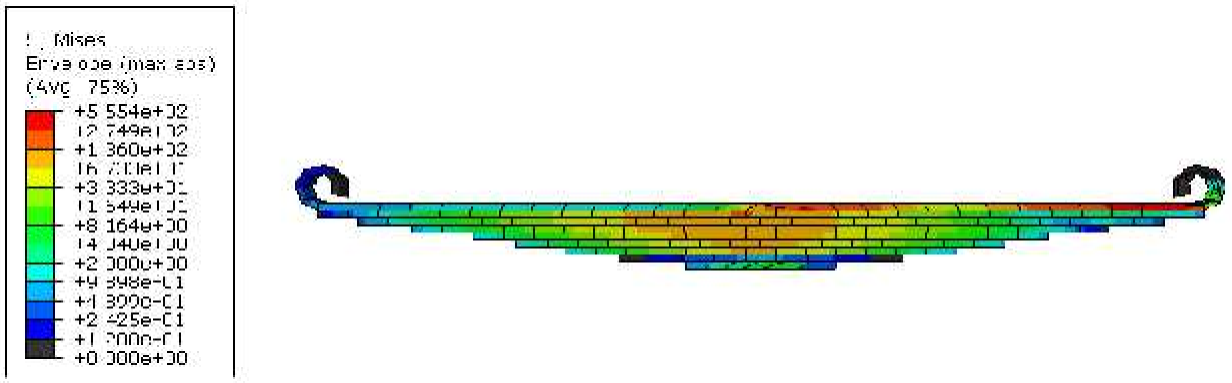


Figure 5.5: Stress contour in carbon fiber/epoxy composite leaf spring

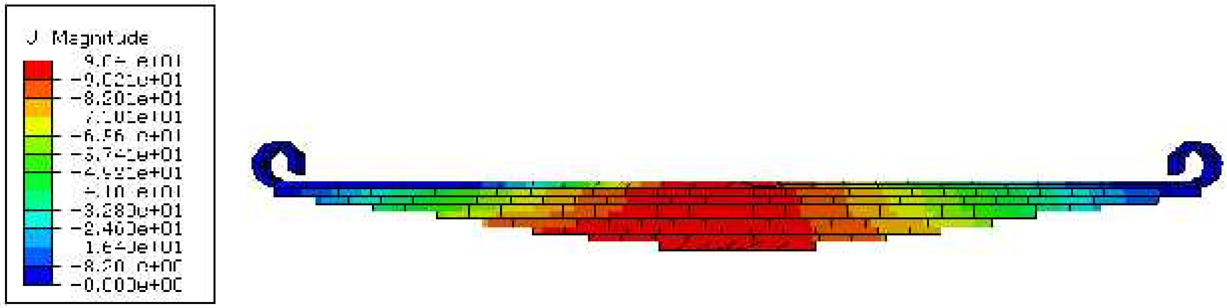


Figure 5.6: Deflection contour in carbon fiber/epoxy compoosite leaf spring

6.1 Comparison of result

Comparison of FEA and theoretical result is done in table 6.1 and table 6.2 and % deviation in stresses and deflection is obtained and results are shown on graph.

Table 6.1: Comparison of results (steel)

Results	Theoretical results	Experimental results(steel)[17]	FEA results (steel)
Maximum stress (kgf/mm^2)	839	997.64	911.7
Maximum deflection(mm)	157.52	157.3	152.2
% variation from FEA results of steel in stress	8.6%	9.4%	-
% variation from FEA results of steel in deflection	3%	3%	-

Table 6.1 shows the theoretical, experimental and FEA results of steel leaf spring. The deviation of FEA results from experimental (taken from research paper) and theoretical results is below 10% in case stress and 3% in case of deflection. As FEA analysis softwares give approximate solution and deviation of FEA results from experimental and theoretical results is below 10%, so finite element analysis of stress and deflection are correct.

In figure 6.1 and 6.2 graphs were plotted for maximum deflection and stress by changing the load. From graph we can see that variation of FEA from theoretical results in stress and deflection is quite less. It is below 10% in case stress and 3% in case of deflection.

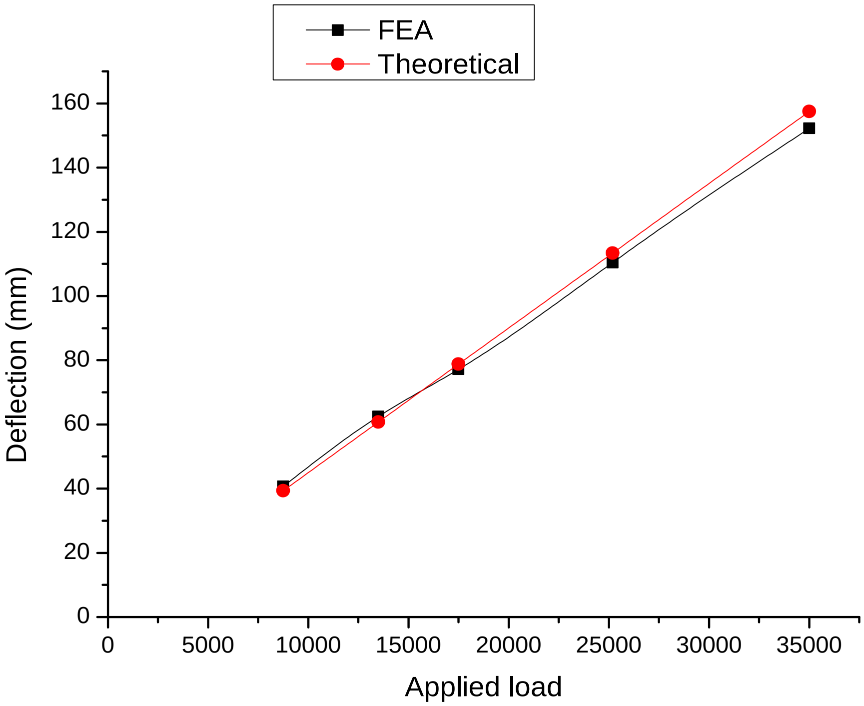


Figure 6.1: Comparison of Theoretical vs. FEA of steel (Deflection)

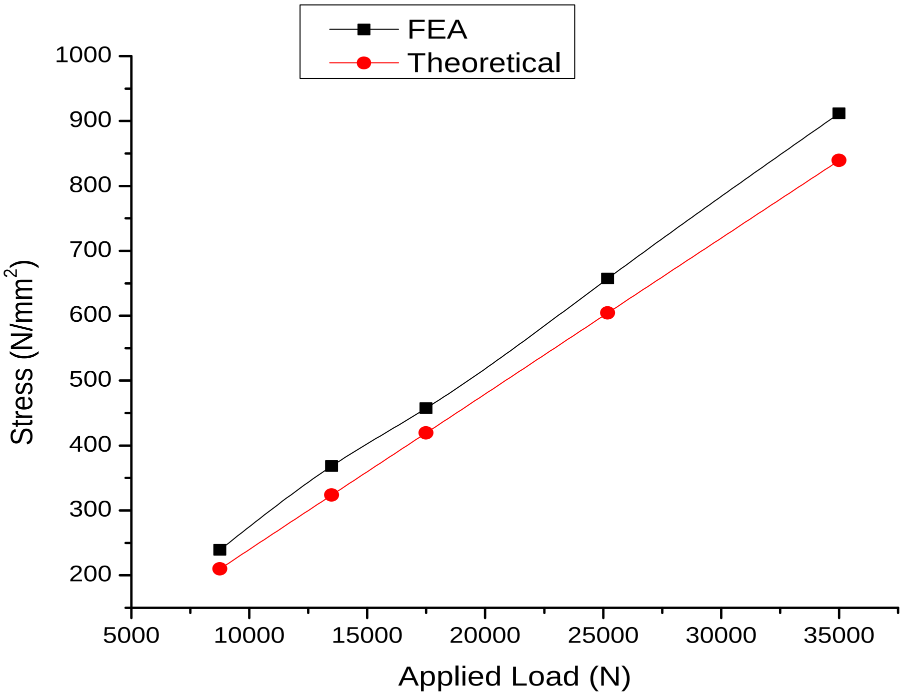


Figure 6.2: Comparison of Theoretical vs. FEA of steel (Stress)

Table 6.2: Comparison of FEA results of steel and composite material

FEA Results	Steel	Carbon epoxy	Glass epoxy
Maximum stress (kgf/mm^2)	911.7	555.4	159.5
Maximum deflection(mm)	152.2	98	116.7
% variation from FEA results of steel in stress	-	39.08%	82.5%
% variation from FEA results of steel in deflection	-	35.6%	23.32%

From the above table 6.2 we can see that the stresses and deflection produced in the leaf spring made of composite materials (glass/epoxy) and (carbon/epoxy) are quite less than the stresses produced in the leaf spring made of steel. The maximum stress produced in the all the three materials is less the ultimate tensile and compressive strength of the material, so the design is safe. Maximum deflection in case of steel is more than glass/epoxy and carbon/epoxy and it is minimum in carbon/epoxy. So from the above results we conclude that in comparison to steel leaf spring there was reduction in stresses , deflection of leaf spring made of composite carbon/epoxy and glass/epoxy.

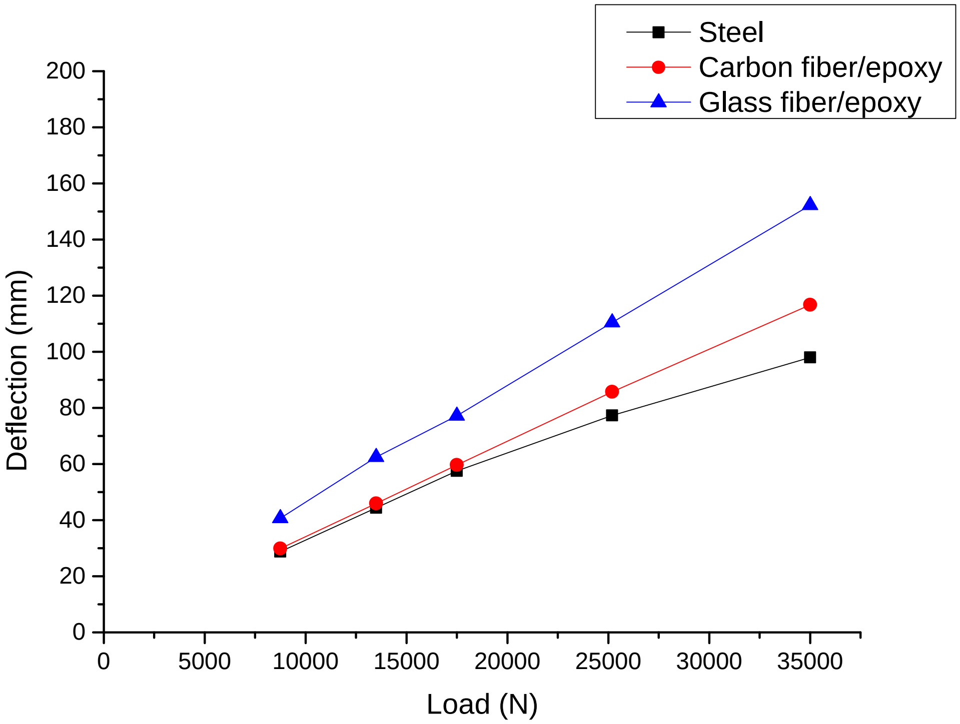


Figure 6.3: FEA results of steel, carbon fiber/epoxy, glass fiber/epoxy (Deflection)

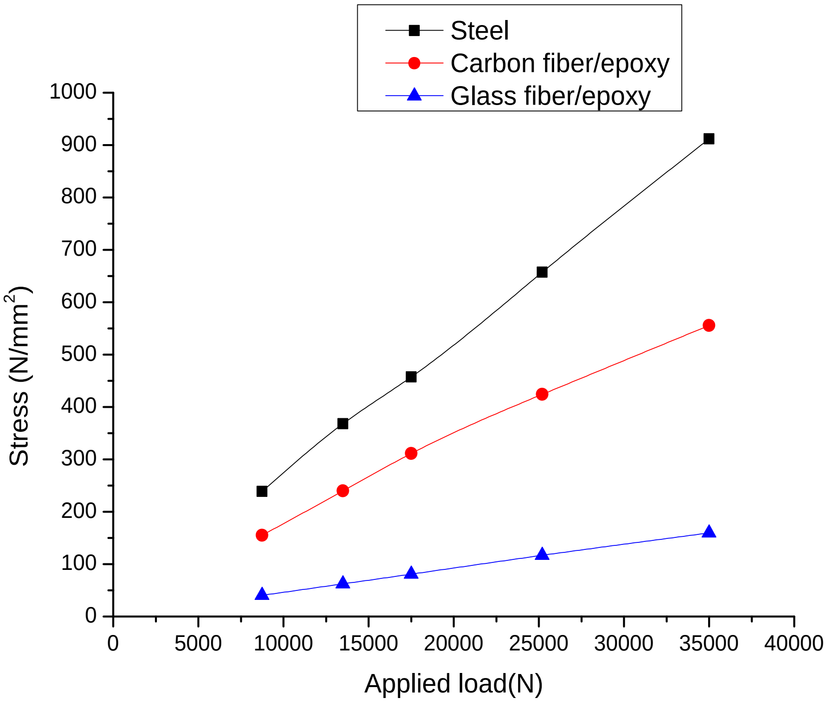


Figure 6.4: FEA results of steel, carbon fiber/epoxy, glass fiber/epoxy (Stress)

In figure 6.3 and 6.4 graphs were plotted for maximum deflection and stress by changing the load. From graph it is seen that stress and deflection produced in the all the three materials is increasing with increase in the load. Maximum deflection in case of steel is more than glass/epoxy and carbon/epoxy and it is minimum in carbon/epoxy. Stress produced in composite leaf spring is quite less than steel. So from the above results it is concluded that in comparison to steel leaf spring there is 50-80% reduction in stresses 20-40% reduction in deflection of leaf spring made of composite carbon/epoxy and glass/epoxy.

A comparative study has been made between composite leaf spring and steel leaf spring with respect to stress and deflection. By employing a composite leaf spring for the same load carrying capacity, there is50-80% reduction in stresses 20-40% reduction in deflection and reduction in weight which results in more fuel efficiency and improved riding qualities. So composite is a good replacement for steel for multileaf springs.

In future lot of work needed to be done :

- The FEA results can be compared with the results obtained from the mathematical models which consider micromechanics of composite leaves.
- The composite materials have more elastic strain energy storage capacity and high strength to weight ratio as compared with those of steel the work can be extended to replace multileaf steel spring with monoleaf spring made of composite.
- Replacing the each leave of multi leaf spring made of steel with different composite material

Appendix

Firstly part is modeled and assembled in SOLID WORKS 2012 and then it is imported in

ABAQUS 6.10

Part > file > import geometry .

Property > create material > mechanical > elasticitcity > elastic > type > engineering constants > create composite layup > composite layup manager > plies > assign material > thickness > stacking direction > rotation angle > rotation axis > layup orientation > coordinate system > region.

Assembly > create instance > instance type.

Step > create step > Static genral.

Interaction > create interaction > surface to surface contact > master surface >slave surface.

Load > create load > mechanical > concentrated force

Boundry condition > create boundry condition > mechanical > displacement rotation.

Meshing > seed part instance > mesh > element type .

Job > create job > write input >data check > submit > results > visualization.

Web References

[1] Leaf spring assembled at rear axle of automotive. Retrieved Nov 15, 2013, from http://en.wikipedia.org/wiki/Leaf_spring#mediaviewer/File:Leafs1.jpg

[2] Nipping in Leaf Spring. Retrieved Dec 13, 2013, from http://nptel.ac.in/courses/112105125/pdf/mod7les3.pdf

[3] Cantilever approach. Retrieved Feb 10, 2014, from http://nptel.ac.in/courses/IIT-MADRAS/Machine_Design_II/pdf/4_5.pdf

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