DESIGN OF COMPOSITE-BASED LEAF SPRING SYSTEMS FOR AUTOMOTIVE SECTOR

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ABSTRACT

DESIGN OF COMPOSITE-BASED LEAF SPRING SYSTEMS FOR AUTOMOTIVE SECTOR

The applications of fiber reinforced polymeric composites in several engineering fields such as automotive, aviation, defense industry and marine are observed vastly nowadays. Especially in the automotive industry, the necessity of the reduction of fuel consumption and CO_2 emission has entailed the utilization of the composite materials to provide weight reduction without sacrificing any material strength.

Conventional steel leaf springs are components significantly affecting the weight of the vehicle as well as providing ride comfort and vehicle stability. Hence, fiber reinforced polymeric composites having many outstanding properties such as low density, high strength, corrosion resistance, high fatigue life, high wear resistance, are convenient materials for these types of applications.

In this thesis, three different composite-based mono leaf springs were designed and analyzed. It was inferred from the analyses that 0° unidirectional glass fiber system hasn't generated the intended spring rate accurately. Consequently, alternating configurations of the glass and carbon hybrid systems were studied. It was deduced from the studies that material configuration of $[0°_{6G}/0°_{2C}/0°_{22G}]_S$ was generated the intended spring rate.

Three different composite-based mono leaf springs including indicated material configurations were fabricated within the thesis study. Manufactured prototypes were also tested by using leaf spring test rig for determining the behavior of the prototypes experimentally. The obtained results were compared with FEA and it has been observed that the results are in compliance.

ÖZET

OTOMOTİV SEKTÖRÜNE YÖNELİK KOMPOZİT ESASLI YAPRAK YAY SİSTEMLERİNİN TASARIMI

Fiber takviyeli polimerik kompozitlerin otomotiv, havacılık, savunma sanayi ve denizcilik gibi çeşitli mühendislik alanlarındaki uygulamalarının son günlerde çok yüksek miktarlara ulaştığını görmekteyiz. Özellikle otomotiv sektöründe, yakıt tüketiminin ve CO_2 salımının azaltılması gerekliliği, malzeme dayanımından ödün vermeden ağırlık azaltımı sağlayabilecek olan kompozit malzemelerin kullanımını zorunlu hale getirmiştir.

Geleneksel çelik yaprak yaylar, sürüş konforu ve araç stabilitesi sağlamasının yanında, aracın ağırlığını da önemli ölçüde etkileyen elemanlardır. Bu nedenle, düşük yoğunluk, yüksek dayanım, korozyon direnci, yüksek yorulma ömrü, yüksek aşınma dayanımı gibi birçok üstün özelliklere sahip fiber takviyeli polimerik kompozitler bu tip uygulamalar için elverişli malzemelerdir.

Gerçekleştirilen bu tezde, 3 farklı kompozit esaslı yaprak yay tasarlanmış ve analiz edilmiştir. Analizler neticesinde 0° tek eksenli cam elyaf sistemin istenilen yay davranışını tam olarak sağlayamadığı tespit edilmiştir. Bunun sonucunda, cam ve karbon elyaf karma sistemin alternatif konfigürasyonları üzerinde çalışılmıştır. Çalışmalar neticesinde, $[0°_{6G}/0°_{2C}/0°_{22G}]_S$ malzeme konfigürasyonunun istenilen yay davranışını sağladığı tespit edilmiştir.

Tez kapsamında belirlenen malzeme konfigürasyonlarına sahip 3 farklı kompozit yaprak yay üretimi gerçekleştirilmiştir. Üretilen prototipler yaprak yay davranışını deneysel olarak belirlemek için yaprak yay test düzeneği kullanılarak test edilmiştir. Elde edilen sonuçlar sonlu eleman analiz sonuçları ile karşılaştırılmış ve sonuçların birbirleri ile uygunluk gösterdiği belirlenmiştir.

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CHAPTER 1

INTRODUCTION

Fiber reinforced-polymer composites have been utilized for use as succession for metallic materials in many weight-critical components in aerospace, automotive and other engineering fields owing to their low density, better strength to weight ratio and modulus to weight ratio. In addition to aforementioned properties, many fiber reinforced composites present excellent fatigue strength and higher corrosion resistance (Shokrieh and Rezaei 2003).

Exterior body components, chassis components and engine components are main application areas of the fiber reinforced composites in automotive industry (Mallick 2007). Weight reduction is the main purpose of selecting fiber reinforced composites instead of metals in these applications. Reducing weight of vehicles has become an important issue in recent years in order to meet the needs of natural resource conservation and energy economy for the automobile industry (Talib et al. 2010). This can be achieved by the advanced materials, shape optimization and improved fabrication process.

Leaf spring systems, which affect the weight of the vehicle in addition to ride comfort and the stability, are important parts of the vehicle. Therefore, composite materials, which have many superior properties over metals such as low density, high strength, corrosion resistance, high fatigue life, high wear resistance, are convenient materials for these type of applications (Shankar and Vijayarangan 2006).

Springs demonstrate noteworthy deformation when loaded and their flexibility allows them to absorb and store mechanical energy. This is their main design target as a machine component. Hence, the material and the shape of the springs become crucial design parameters (Mahdi et al. 2006). Leaf spring is widely utilized as automotive suspension in the industry and they prevent the harmful effects of the good shocks on vehicle components, secure the vehicle stability and provide ride comfort (Deshmukh and Jaju 2011). The materials having maximum strength and minimum modulus both in the longitudinal direction give us higher specific strain energy and this again makes the

composite materials very effective candidate for the leaf spring applications (Al-Qureshi 2001).

Several kinds of composite leaf springs can be designed due to the variety of vehicles which have leaf springs and apply various kinds of loading on them. In these springs, bending affects the shape of the springs, such as; leaf springs are designed thick in the middle where the bending is maximum, and thin at the ends (Shokrieh and Rezaei 2003). Suspension components should be placed within certain geometry owing to the vehicle's existing structure. Weight minimization is an important parameter so as to use materials efficiently and spring should be tapered from center towards the ends where the bending moment is minimum there (Sancaktar and Gratton 1999). However, replacement of isotropic steel alloys with anisotropic fiber reinforced plastic material brings along design and manufacturing problems.

The aim of this study is to obtain optimum composite leaf spring structures and also to fabricate the composite leaf spring prototypes. For this purpose, a relationship between material selection, composite structure design, material properties and mechanical behavior of the leaf spring was obtained. Composite-based mono leaf spring has been designed and finite element analysis has been performed under given loading conditions. Validation of the finite element model has been presented with the comparison of the experimental and numerical results. Thus, quasi-static analysis of the created leaf spring model has been investigated by the finite element program ABAQUS.

1.1. Theme of This Study

This study is part of the Design and Manufacturing Techniques Improvement of the Composite-based Leaf Spring Systems for Automotive Sector Project. This project was supported by the Ministry of Science, Industry and Technology of Turkey and OlgunCelik San. Tic. A.S. under the SANTEZ Project 01001.STZ.2011-2 and investigated the utilization of the composite-based materials for automotive leaf springs. The aim of this study, within the workspace of the aforementioned project, is the development and finite element analysis of fiber reinforced composite leaf spring systems under given boundary and loading conditions.

Literature review of the work is detailed in Chapter 2. There are several researches about the design, finite element analysis and manufacturing of the composite leaf springs in the literature where finite element analysis results provide favorable relationship between the analytical and experimental results. However, providing the relationship between material selection, lay-up selection, material test results and leaf spring behavior is the lack of literature and there are very limited information about this subject.

Suspension systems of a vehicle and the components of a suspension system are briefly investigated in Chapter 3. Leaf springs and their functions in a vehicle are introduced. History of composite leaf springs, materials widely used, and current manufacturing methods have also been presented in the chapter.

Finite element modeling and analysis performed within this study is given in Chapter 4. Numerical modeling and analysis steps of the composite-based leaf springs are also presented.

Finally, the composite leaf spring models created and analyzed are presented in Chapter 5. Validation of the finite element model in ABAQUS is also investigated and detailed. Results under given loading conditions are presented and compared with the experimental results.

CHAPTER 2

LITERATURE REVIEW

2.1. Introduction

Composite material means that two or more different materials combined on a macroscopic scale to obtain serviceable third material which usually demonstrates the best properties of the constituents (Jones 1999). Therefore, many researches have been presented by many scholars to get the best material combination on composite-based leaf spring applications. This chapter details the previous works on the applications, designs, finite element modeling and analysis, and manufacturing of composite leaf springs.

2.2. Leaf Spring Applications of Composite Materials

Comprehensive studies have been done on the application of fiber reinforced composites as suspension system in automotive so far. Sufficiency of the composite materials for the structural applications has improved the integration of the composite parts instead of metallic parts.

Fiber reinforced polymer leaf spring was designed by C.J. Morris so as to perform the function of rear suspension which consists of steel lower arms and coil springs. The three-door Ford Escort model was chosen to obtain low spring rate. Constant cross section design was chosen as this type design was proper for the selected fabrication technique and fibers could be fully aligned along the spring without interrupting. Filament winding-compression molding process was selected as manufacturing technique and glass fiber was selected as reinforcement material since the glass fiber is cost effective material. Thus, prototype fabrication was carried out and the vehicle attachment of the spring model performed by means of the steel end fittings. Afterwards, the rough road durability test, which is prominent test method to obtain whichever chassis component will fail firstly, was performed. He concluded from the test results that the spring didn’t demonstrated any damage with the favorable fittings.

Besides, vibration, noise, harshness parameters were determined as well as the durability test and these measurements gave close results as compared to the results in regards to the standard Escort Measurements'. As a conclusion, he demonstrated that the vehicle weight was reduced roughly 3.2 kg and durability of the system through the fiber reinforced polymer mono leaf rear suspension system was assured (Morris 1986).

Composite leaf springs can be designed as mono leaf or multi leaf. Mono leaf composite leaf springs are given preference to the multi leaf springs as they provide fabrication easiness and interleaf friction cannot play a role in damage. On the other hand, multi leaf springs were also investigated by many researchers.

The glass fiber reinforced polyester double-leaf spring was designed for rail freight vehicles to replace existing multi leaf steel springs on a wagon using same connecting components (Hou et al. 2005). The double-leaf design was chosen in their study so as to damage top leaf firstly and then bottom leaf can resist pre-setted load. They concluded that the composite double-leaf spring had similar strength properties to the existing steel spring. They utilized the finite element analysis to guess the stiffness, strain and spring rate of the composite-based leaf spring. Results showed that the numerical results were in agreement with the experimental results. Finally, it followed from their static test results that the double-leaf spring design could carry approximately 150 kN.

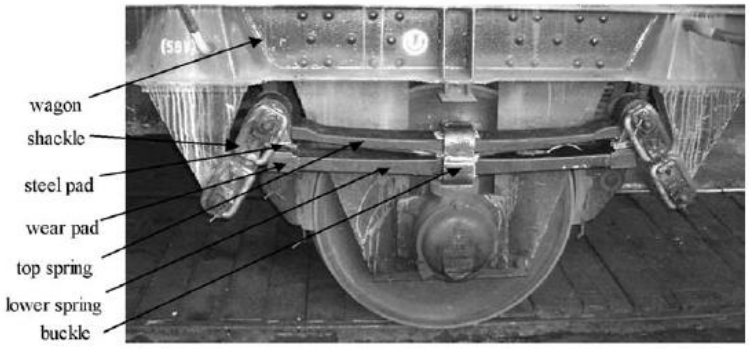


Figure 2.1. Wagon on composite double-leaf spring
(Source: Hou et al. 2005)

Many structural components of the vehicles are subjected to cyclic loading which significantly affects the life of the structure. So, it is important to indicate the number of cycles to fail. A leaf spring is one of them which is subjected various kinds

of loads such as vertical loads, transverse loads, torsion, cyclic loading and so forth. Hence, obtaining design stresses much below the strength properties of the material and achieving admissible fatigue life is important for the researchers.

Design analysis of a single E-glass/epoxy leaf spring was carried out analytically for given light weight vehicle conditions by the researcher (Gebremeskel 2012). Unidirectional E-glass fibers were selected as reinforcing material due to their high strength to weight ratio and high specific strain energy capacity. The number of cycles to fail the spring was calculated analytically and the result demonstrated that the fatigue life of the designed leaf spring was acceptable with regard to the design stresses and strength properties of the material. Finite element analysis simulation of the designed leaf spring was performed using a computer program Abaqus/ CAE 6.10 considering static loading only. Maximum stress failure criterion was controlled by the finite element analysis results. It was proved that a single E-glass/epoxy leaf spring satisfies the weight reduction and strength requirements. In addition, roughly 221000 cycles that fulfills the fatigue life expectancies of the leaf spring for light weight vehicles was achieved. Its prototype was also fabricated using hand lay-up method.

Figure 2.2. Prototype of E-glass/epoxy composite leaf spring
(Source: Gebremeskel 2012)

2.3. Design and Material Selection of Composite-based Leaf Springs

Several kinds of parameters should be considered in the leaf spring design. Flexural stiffness is one of them and should be increased from ends to centre of the spring as bending plays a crucial role in the middle of the spring due to the vertical loading conditions. It follows from this idea that different types of design can be considered such as constant cross section, constant width varying thickness and constant thickness with varying width. The constant cross section design assures some

advantages from the fabrication easiness and fiber alignment point of view (Rajendran and Vijayarangan 2001).

Behavior of a vehicle is markedly affected in terms of the ride comfort and vehicle stability by the suspension system in the vehicle. Leaf springs sustain different kinds of loading cycles that cause to fatigue failure. Reducing weight which is not supported by the suspension system in the vehicle gives rise to the reduction of fatigue stress. Weight reduction in the leaf spring brings about substantial progression in the vehicle cost and ride comfort if it is considered that the leaf spring comprises of an important part of the unsprung weight. Design optimization of a mono leaf composite-based leaf spring was presented using an artificial genetics approach (Rajendran and Vijayarangan 2001). The optimum dimensions which present minimum weight with favorable stiffness and strength properties was obtained by applying genetic algorithms (GA). Minimization of the weight of the spring was selected as the objective function in their study. Centre thickness and width were considered as the design variables since the constant cross section design was selected for the spring which had unequal end thickness and end width. Bending stress and vertical deflection were considered as design constraints and safety factor was taken as 2.5 that is adequate for the static and fatigue behavior of the spring. Computer program using C language was made to obtain proper design both steel and composite leaf springs efficiently. As a conclusion, variation of the thickness and width for steel and composite-based design was obtained and it was inferred from the variations of the weight of springs that % 65 weight reduction was accommodated by replacing steel spring with a composite one and that the weight optimization of the composite leaf spring gave approximately %23.4 weight savings. It should not be forgotten that a little weight reduction can also affect the passenger ride comfort and provide fuel efficiency.

Material selection is one of the most important parameter in the leaf spring design and affects the strain energy capacity of the leaf spring. Considering different materials that can be used as a leaf spring material, glass fiber presents good combination in terms of the cost and material properties. There are some disadvantages of carbon fibers such as low impact strength, high cost and low galvanic corrosion resistance though carbon fibers have better strain energy capacity. Thereof, glass fiber reinforced composite is selected as leaf spring material in general.

Joints design is another important study for researchers studying on composite leaf springs. Leaf springs can perform their functions only with appropriate joints.

Various kinds of joints can be considered to fix the spring to the axle and the body. Steel eye is one of them and this joint design provides manufacturing easiness and low cost. However, some regions including stress concentration can occur during the attachment process like drilling. Composite eye is another design and there is no region including stress concentration in this type. Fibers to be used in the spring body go around the eye so that the spring and eye can be fabricated simultaneously. Manufacturing complexity and high cost are demerits of this type joints. Conical or concave steel eyes can be considered as a joint type. In these types, composite based springs should have conical or concave width profile in order to mount the joints readily. Rubber pads should be utilized in these joint types to prevent friction between the steel eye and composite-based spring. The region of stress concentration does not exist in this type. On the other hand, the total cost of manufacturing is a problem. As a result, steel eye can be considered as a joint in terms of the fabrication easiness and low cost. However, this joint type should be strengthened as the material will be drilled. Therefore, some additional plies with different rotation angles can be laid at the upper and lower surface of the spring ends to satisfy the strength requirements (Shokrieh and Rezaei 2003).

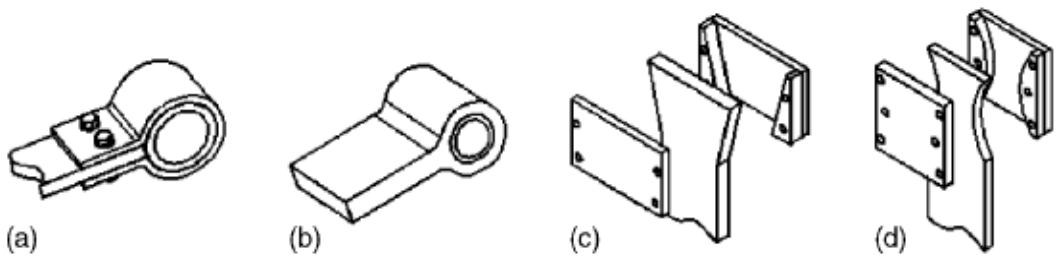


Figure 2.3. Different joint types to attached the composite leaf spring to the vehicle: (a) Steel eye, (b) Composite eye, (c) Conical profile, (d) Concave profile (Source: Shokrieh and Rezaei 2003)

A comparative study between a laminated composite mono leaf spring and an existing steel leaf spring used in a passenger car was made by the researchers (Raghavedra et al. 2012). Specifications of an existing mono leaf steel spring were taken for modeling and analysis. They modeled uniform cross section springs of three different composite materials namely, E-glass/epoxy, S-glass/epoxy and Carbon/epoxy.

Static analysis of 3-D model of laminated composite leaf spring (LCLS) was done using ANSYS 10.0 and analysis results were compared with the existing mono leaf steel spring. In conclusion, they deduced that carbon/epoxy laminated composite mono leaf spring had outstanding mechanical properties in comparison to the other composite materials in point.

Hybridization is an outstanding method especially in automotive industry to improve performance and decrease the weight. Hence, the incorporation of carbon and glass fibers increase the spring constant and improve the rigidity and fatigue performance of the composite (Al-Qureshi 2001).

F.D.Meatto and E.D.Pilpel described a hybrid mono leaf spring for light truck applications that arose from an existing steel main leaf in concurrence with an E-glass/epoxy composite cladding attached to top and bottom faces of the main leaf. In their study, they conducted various kinds of testing such as flexural testing, fatigue testing, creep testing, impingement testing and the testing of resistance against automotive fluids in order to specify the durability of the hybrid leaf spring. They concluded from the results that the brake fluid affected the coating more negatively and thermoset protective coating was more powerful method to protect the spring against the impingement (Meatto and Pilpel 1999).

2.4. Finite Element Modeling and Analysis

Composite leaf springs are tested by leaf spring test rig. Thus experimental results are obtained from there. Finite Element Analysis is a convnient method for obtaining stress, strain results of the leaf springs. Researchers can compare FEA results with the experimental results to validate their models. Consequently, it is important to obtain close results between them.

Constant thickness constant width semi-elliptical and cantilever E-glass/epoxy composite leaf springs were modeled by the researcher (Narayana 2012). Pro/E was used for the modeling and ANSYS software for the analysis. Displacement and stress components that were obtained from the FEA were compared with the steel leaf spring’s. Eigenvalues of the composite leaf spring system was indicated to explore the vehicle comfort. It was observed from the results that the stress results in the spring

were proper in terms of the strength limits and that mode shape two maintained suitable ride comfort for the passengers.

Theoretical calculations are significant parts of the leaf spring design and analysis. It is important to compare the FEA results with the analytical solutions as the numerical solutions give approximate results. V.Pozhilarasu and T.P.Pillai investigated the spring rate and bending stress comparisons of the conventional steel and multi leaf E-glass/epoxy composite leaf spring. ANSYS 11.0 was used for the analysis. Analytical calculations and FEA results were compared from the deflection and bending stress point of view. Results demonstrated that the multi leaf composite leaf spring could be utilized with high mechanical performance and weight saving (Pozhilarasu and Pillai 2012).

Finite element selection is another important analysis parameter and should be studied delicately. Element selection may depend on the shape, type and thickness of the composite structure which will be analyzed. Ka and Zhigao described the finite element analysis of the multi leaf glass fibre reinforced leaf spring. Mathematical model and FEA of the spring were done using ANSYS software. Solid element was chosen by them because of the orthotropic properties of the composite materials. They used three dimensional contact elements to define interleaf contact between the leaf faces in their study. Constraints and loading conditions were applied to model taking into account the vehicle dynamics and test methods. FEA results showed that the stress results were lower than the steel spring when the single spring was selected as an example (Ka and Zhigao 2011).

There has been increasing interest in the optimization of the composite-based materials in recent years since the applications of the laminated composite materials have become widespread in all engineering fields. The optimization can be performed by a computer algorithm or finite element method. T.Ekbote, K.S.Sadashivappa, D.Abdul Budan studied the geometry optimization of E-glass/epoxy mono leaf composite leaf spring using ANSYS software. Thickness and width at the center and at the ends of the spring were selected as design variables. Tsai-Wu failure criterion and deflection were selected as design constraints. Three dimensional eight-noded brick elements were selected with proper aspect ratio for the finite element model of the spring. As a result, they concluded that 42 mm thickness and 32 mm width at the center, 16 mm thickness and 84 mm width at the end gave adequate results for the vertical load of 1925 N in terms of the analytical results. They inferred from the results that the

geometry optimization by finite element analysis could be effective for the prelude of the composite leaf spring design and analysis (Ekbote, Sadashivappa, and Abdul Budan 2012).

2.5. Manufacturing of Composite-Based Leaf Springs

Fabrication process of composite leaf springs should be determined carefully as obtaining efficient and economical manufacturing technique is slightly problem for composite materials. Hand lay-up, filament winding, RTM, pre-preg or vacuum infusion methods can be used for the manufacturing of composite leaf springs.

Using pre-preg technology presents higher operation speed. RTM that is another process provides cost effectiveness. Filament winding technique can be considered for constant spring design. This technique can also be used for high volume production and curing process can be operated at higher temperature and under higher pressure in this technique (Al-Qureshi 2001).

Jadhao and Dalu presented the performance comparison between the existing steel leaf spring and mono leaf composite leaf spring. They tested the springs experimentally in order to obtain flexural properties of the springs. Hand lay-up technique that provides fabrication simplicity was used in their study. Mould was manufactured from plywood according to required dimension. Hand lay-up process was applied up through the required thickness is achieved. After obtaining the prepared prototype, sample was tested. Finally, they presented the comparison of the experimental results with the FEA results (Jadhao and Dalu 2011). It follows from the results that the deflection and stress results for the composite leaf spring are in good agreement with the experimental results.

Fabrication of composite parts requires great efficiency in automotive industry owing to the necessity of duplicate production of automotive parts. For this reason, new processing techniques and chemistry have come in an increasing demand for the manufacturers. Continuous fiber reinforced epoxy systems have been chosen by the sector due to their strength performance and economical cost. However, their time consuming reaction process is great problem when considered mass production of the automotive parts. Therefore, high performance epoxy systems were developed which satisfy the faster processing demand of the industry. Moreover, some disadvantages

took place based upon the fast curing that reduces strength properties and surface quality (Reichwein et al. 2010).

Epoxy composite processing can be made up by several methods such as hand lay-up, RTM or pre-preg technology. Developing a pre-preg technology for the manufacturing of composite leaf springs provides splendid performance and cost compared to the other methods. For this reason, researchers established a manufacturing process using pre-preg technology in their fabrication process (Reichwein et al. 2010).

CHAPTER 3

BACKGROUND

Composite material signifies the combination of two or more separate constituents at a macroscopic level to meet the performance demands. Composite materials can be used in many cases effectively to reduce especially mass without decreasing the stiffness of the system. Therefore, the cases where the reduction of weight is important such as aircraft or automotive applications, their high strength to weight ratio makes them more useful. Composites provide other significant advantages over the conventional metallic materials such as high strength, stiffness, fatigue life, impact resistance and corrosion resistance and so forth (Kaw 2006).

Reinforcement type generally plays an effective role in composite material classifications. Fibrous and particulate composites are two main classes of composites. Either long or chopped fibers compose the fibrous composites and particulate composites consist of particles embedded in a matrix (Staab 1999). Low performance composites demonstrate some stiffening though they do not provide good strength properties. Whereas, continuous fiber reinforced composites provide required mechanical properties in terms of the strength and stiffness. In addition, changing arrangements of continuous fibers in a structure provides design flexibility to meet the desired requirements (Kollár and Springer 2003).

3.1. Introduction to Suspension Systems

Vehicle dynamics, which also includes many other sciences, is one of the most important studies of the modern mechanics. Safety and ride comfort are main focus of the vehicle dynamics. Therefore all of constituent parts of a vehicle such as vehicle, driver and environment should be carefully investigated as a whole. In this study, only ground vehicles like light weight vehicles, trucks, railway vehicles are taken into consideration and their dynamics are briefly investigated.

There are various kinds of suspension systems, which are used to carry the weight of car, control the direction stability of vehicle, prevent the effects of road

shocks, and sustain the accurate wheel alignment and balancing, in the automotive industry. Cost, weight, space, kinematical properties are important concern for the selection of suspension systems. Vehicle suspension systems generally consist of control arms, links, leaf springs, anti-roll bar, buffer, bushings and tires. Tires in the vehicle fulfill a task as air spring and are important to support the vehicle and its weight (Rill 2006).

Springs are vital components of a vehicle suspension because of their properties of energy absorbing. In addition, their function of supporting the weight of vehicle also makes them critical for the vehicle suspension systems.

Coil springs, torsion bars, leaf springs and air springs are used in the suspension systems of ground vehicles in general. Energy absorbing properties of the first three by compressing under loading play a determinative role in the vehicle ride height (Rill 2006; Soner et al. 2011). We can deduce from this determination that designing these components considerably influences vehicle aerodynamics and comfort.

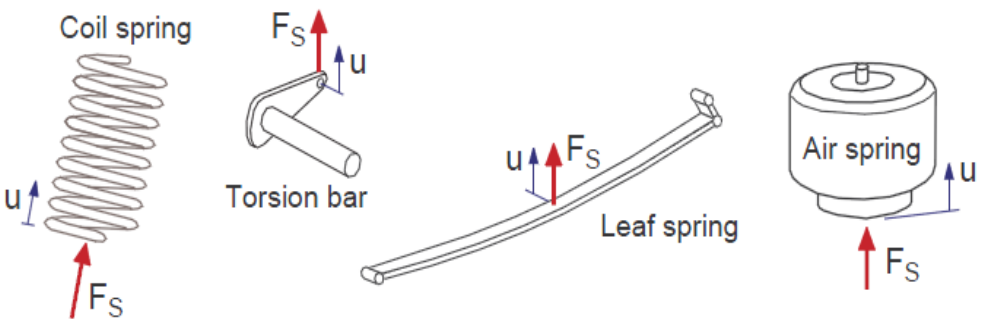


Figure 3.1. Springs in a vehicle suspensions
(Source: Rill 2006)

Anti-roll bar, which is one of the force elements in the vehicle suspension systems, is utilized to prevent the increase of the angle of roll and increase the vehicle stability (Rill 2006; Bayrakceken, Tasgetiren, and Aslantas 2006). This stabilizer component is placed between the two wheels of the vehicle by lower control arms and bearing to chassis. In conditions that suspensions at both wheels travel in the opposite directions especially during cornering, it generates a force to stabilize this situation. Applied loads in opposite direction bring about a vertical displacement in the bar. Thus, the stiffness becomes a significant consideration in the design.

3.2. Leaf Springs

Suspension systems include lots of components and leaf springs form a significant part of them, and widely used in sport cars, light weight vehicles and railroad vehicles. Therefore, it is important to design a leaf spring accurately in order to provide reliable suspension. Experimental tests done on a conventional tandem leaf spring have demonstrated that leaf springs show nonlinear behavior owing to the loading conditions (Omar et al. 2004). From this consequence, it follows that the leaf spring design and assembly should be considered more rigorously.

Leaf springs provide isolation between the body and the chassis by way of energy absorption, which takes place due to the road conditions, and then release this strain energy to provide the stability. Hence, leaf springs play a vital role to provide occupant comfort and vehicle stability.

Leaf spring classification commonly depends on design and spring rate of the spring. According to design classification, leaf springs can be fully elliptic, three quarter elliptic, half or semi elliptic, quarter elliptic or transverse semi elliptic configurations. The most common type for the vehicle rear suspension is half or semi elliptic design and largely used as light weight vehicle suspension (Omar et al. 2004).

There are three main types of metallic leaf springs and these are conventional, multi-parabolic and parabolic leaf springs (Soner et al. 2011). Parabolic leaf springs are used commonly due to their advantages of low weight, low cost and high fatigue strength. Moreover, there are also several types of parabolic leaf springs such as parabolic, multi-parabolic and z-leaf spring (Kanbolat et al. 2011).

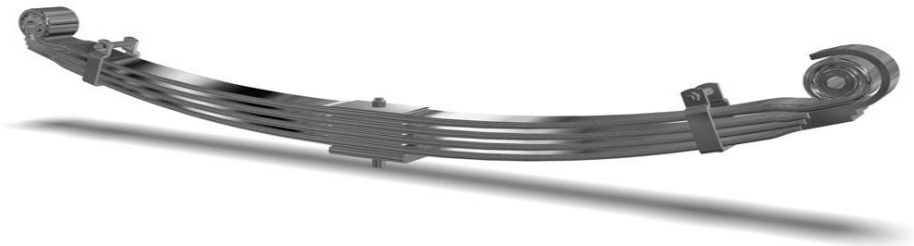


Figure 3.2. Photograph of a Multi-leaf Parabolic Leaf Spring
(Source: “Products” OlgunCelik, OlgunCelik Inc.)

Leaf springs are subjected to various kinds of loads such as vertical load, lateral load, torsion or combination of these loads. In addition to vertical loads, torsional moments, which come from the braking and are just as dominant as vertical loads, also influence a leaf spring. To prevent any failure and to design a leaf spring safely, all of loading conditions should be investigated in a detailed manner. Spring ends, spring eyes and assembly tools are also significant parameters, which influence the manufacturing process, performance and cost, in the leaf spring design. In consequence, these subjects should also be studied carefully.

3.3. Composite-based Leaf Springs

The recent agreements in regard to the reduction of CO_2 emission in vehicles lead to changes in the engineering of automotive. In addition, fuel consumption is also significant consideration for the industry. Thus, weight reduction has become a requirement in terms of the research doers and producers.

There are many components and parts in a vehicle to reduce weight. A leaf spring, which corresponds to the important part of the unsprung weight, is one of them. Conventional leaf springs are heavy weight suspension components because of their material. Many conventional leaf springs are steel-based materials that have lower strength to weight ratio. Hence, using new advanced materials has become a necessity. Composite materials are appropriate candidates for these applications owing to their merits of especially high strength to weight ratio and corrosion resistance.

Fatigue strength, which is crucial for many structural components, is also important for the classical leaf springs and lots of tests should be performed on the different design alternatives that may contain different leaf layers. This design procedure for the multi-leaf steel springs takes a long time and the cost causes trouble from the manufacturing point of view (Soner et al. 2011; Soner et al. 2012). For this reason, this design and test procedure has necessitated the design of mono leaf springs arise from an advanced material.

History of composite-based leaf spring goes back to 1963 when first investigations on the usage of advanced materials in the structural vehicle components were made. In those years, researches weren’t maintained by the doers due to the scarcity in the market demands. However, in the following years, composite leaf spring

studies have proceeded by means of the automotive industry's increasing interest in the weight reduction and energy economy. Thus, a new material Liteflex, which consists of the combination of epoxy resin and unidirectional glass fiber, was found by Delphi in 1981. The replacement of the steel spring with a composite one provided important weight reduction. Thereby, usage of composite leaf springs, however front or rear, has advanced in many applications such as trucks and passenger cars (Richard 2003).

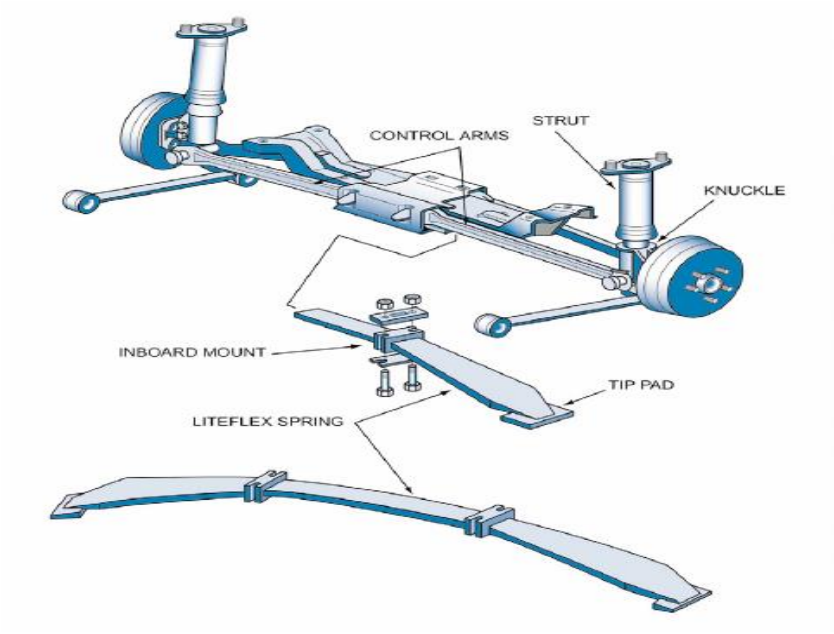


Figure 3.3. Construction and assembly of rear transverse leaf spring
(Source: Richard 2003)

3.4. Composite Leaf Spring Materials

Several mechanical properties can be obtained with different material combinations in a composite-based leaf spring. Hence, it is important to select better material combination which provides desired requirements under given boundary and loading conditions.

There are lots of parameters in material selection of composite leaf springs. To provide strength requirements with weight reduction has been priority of the researchers. Proper lay-up that presents high performance according to loading conditions should be selected. Moreover, material cost is another significant consideration for the automotive industry and it should not be forgotten that

optimization among these parameters is necessity to obtain best material selection.

Constituent materials of the composite-based leaf springs are investigated individually in the following section in detail.

3.4.1. Matrix Materials

Although matrix plays a partial role in the load carrying capacity of the composites, it provides protection against unfavorable environmental effects, keeps the fibers together and transfers the load to the fibers. In addition, selection of a matrix material influences the shear properties and manufacturing process of composites. For example, curing time, curing temperature and viscosity properties of epoxy polymers plays an important role in the aerospace and automotive applications that time and process quality are crucial consideration in terms of producers (Mallick 2007).

There are several types of matrix materials and their mechanical properties are significant consideration from the material selection point of view. However, thermoset polymers, which provide processing easiness owing to their low viscosity, such as epoxies and polyesters are used as matrix material in general. Resins provide good wetting between the fibers and matrix, and this affects the mechanical performance of the composite. Moreover, thermal stability and chemical resistance of thermoset polymers may be put forward as the selection reason (Mallick 2007).

Epoxy resin is one of the thermoset polymers used in advanced polymer composites. The property of low molecular weight makes them useful for many applications. Their viscosity, impact and degradation properties can also be improved through the hardener and filler usage. Among other advantages of using epoxies are their high strength, low viscosity, low shrink rates and processing easiness (Kaw 2006).

3.4.2. Reinforcement Materials

Common fibers used in polymeric composites are glass, carbon, graphite and kevlar. Glass fibers are commonly used due to their advantages such as high strength, low cost and high resistance against chemical factors. On the other hand, having lower modulus and fatigue strength as well as high gravity brings some problems especially in

the structural applications.

The main types of glass for composites are E-glass, C-glass and S-glass. E-glass, which provides good strength, stiffness and electrical properties, is used most commonly. C-glass is utilized for chemical environments as it has superior resistance against corrosive environments. And finally, S-glass is used in the structural applications owing to its higher strength and modulus properties (Hull and Clyne 1996).

3.5. Manufacturing Methods of Composite Leaf Springs

There are many manufacturing techniques used in the fabrication of composite leaf springs. Some of them have been mentioned in the literature review. Furthermore, these methods are investigated in the following subtitles at large.

3.5.1. Hand Lay-up

This method is generally used for prototype production in the preliminary applications. Firstly the mold of composite structure is designed with regard to the final shape of the part. Gel coat can be applied to the mold surface to obtain high quality surface. Individual fibers or woven fabrics are positioned into the open mold surface and then resin is applied over and into the positioned plies. After, roller can be used to remove the trapped air and this process is repeated through the desired thickness is obtained. Finally, it is cured by itself or autoclave else press can be used (Staab 1999).

3.5.2. Filament Winding

Filament winding techniques are widely used in many engineering applications such as automotive drive shafts and leaf springs, pressure vessels, pipelines, oxygen tanks and so on. In this process, fiber material dipped into the resin bath which contains catalyst, hardener, and other necessary constituents. After this impregnating process, wiping machine is used to remove redundancy resin from the rovings and to prevent inequality of coating thickness among the rovings. This wiping device also provides check of fiber tension in the rovings. Then, the impregnated resin is wound around a

mandrel that is generally circular shape. The winding speed is controlled so as to obtain required winding angle and slower speeds should be performed to obtain delicate winding process. Finally, after obtaining the desired thickness, part is cured on the mandrel in common and then mandrel is extracted from the final cured part (Mallick 2007). To provide automation easiness, and cost effectiveness by means of lower labor cost and material cost, makes this process useful for the leaf spring fabrication.

3.5.3. Resin Transfer Molding

Resin transfer molding has been used especially in many automotive applications such as body panels, leaf springs, hoods, fenders and so forth up until now. In a resin transfer molding process, reinforcements are located into the mold surface up to the desired thickness is obtained and mold is closed. Then, liquid catalyzed resin is applied at positive pressure and air is removed from the vents. After the part is cured, composite part is extracted from the mold. To extract the part from the mold easily, mold releasing agent can be applied to the mold prior to the injection molding. This process also provides many capabilities to improve properties, decrease the cost and accelerate the production. Vacuum-assisted injection molding is one of them and generally used to compress the reinforcements, clamp the mold and provide lower internal pressure which supports the decrease in the part defects (Miracle and Donaldson 2001).

3.5.4. Vacuum Infusion

Vacuum infusion process is one of the resin injection techniques and applicable for many engineering products because of its advantages such as providing higher volume fraction, higher mechanical properties and lower cost. In this technique, dry reinforcement is impregnated by resin under vacuum. After curing, the vacuum bag is opened and the part is extracted. This process can be used for lots of geometries however sharp edges and thickness variation can give rise to some problems and parts have those properties are not feasible in this technique (Miracle and Donaldson 2001).

To provide high fiber fraction, low void content and cost has increased the applications of this technique particularly in the automotive sector.

In addition to the aforementioned methods, some processes can be used simultaneously to improve the manufacturing quality. For instance, vacuum-assisted resin injection method is one of them. This technique is generally utilized to aid the resin distribution in a closed mold.

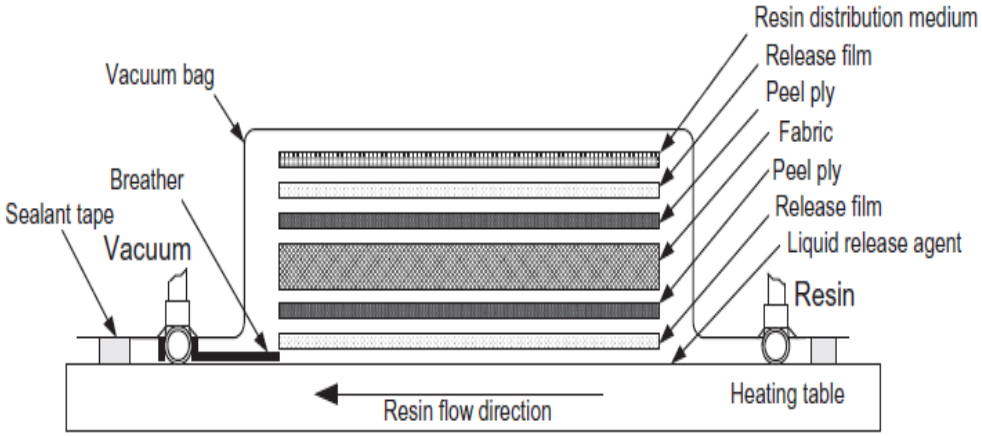


Figure 3.4. Vacuum-assisted injection molding
(Source: Atas et al. 2011)

CHAPTER 4

MODELING AND FINITE ELEMENT ANALYSIS OF COMPOSITE LEAF SPRINGS

Analysis of composite laminates necessitates the usage of computers for engineering applications due to their complex structure and loading conditions even though design analysis can be performed readily for a plate or a beam that can be defined as a simple structure. Therefore, finite element analysis that is a practical and convenient method, should be utilized to perform design analysis of composite laminates for the structures having complex boundaries or loading conditions (Mallick 2007). There are many commercial software that use finite element procedure for analysis.

Numerical modeling and finite element analysis of a composite based mono leaf spring is investigated in this chapter. Finite element method is shortly described, macromechanical behavior of composite structures is explained briefly and the numerical modeling procedure of a composite leaf spring is introduced in detail.

4.1. Introduction to Finite Element Method

Analytical solution of a process or a problem is not always available, or too cumbersome. However, solution of a problem or behavior of a structure can be obtained more easily by numerical methods using a computer (Reddy 1993). Finite element method (FEM) is one of the numerical methods used for the estimation of the solution of a structure or a problem. Solution does not give exact results for the lots of problems not having exact formulation due to their complex boundaries and loading conditions.

Basics of finite element method involve three main steps. These are discretization of a structure to pieces known as finite elements, specifying approximation functions which describe the behavior of each element and obtaining algebraic relations as a result of reconnecting process of the elements. These algebraic equations may be high in number, therefore software usage is required to handle them. (Cook 1994).

Aforementioned steps in finite element modeling are practically the same for all materials. However, design and analysis of composite materials is more troublesome and complex than that of isotropic materials owing to their orthotropic material properties. Their layered structure and lay up configurations are another important concern from the analysis point of view. In addition, their failure criteria are more sophisticated than that of conventional materials, and damage and failure should be studied carefully in their design and modeling with regards to the finite element modeling and analysis (Sezgin 2008).

4.1.1. Finite Elements

Finite elements, which can be several geometric shapes, are subdomains of the actual structure. They are created through discretization of the structure and their characteristic behavior is used to obtain the solution of the structure after the assembling procedure of whole elements.

There are lots of elements can be used for different problems in Abaqus. Each element is unique and has an individual name. This comprehensive element opportunity makes this program useful especially composite modeling requiring more attention.

Finite elements can be characterized by their family, degrees of freedom, number of nodes, formulation or integration features. Element geometry indicates the family of an element and continuum elements, shell elements, beam elements, rigid elements and truss elements are elements that widely used for stress analysis. Each element has different degrees of freedom such as displacements, rotations or temperatures that are calculated during the analysis only at the nodes which mostly indicate the interpolation order. Elements can be divided into three groups according to interpolation order. These are first order elements, second order elements and modified second order elements. Major distinction between those elements is the positions of nodes. For instance, elements, whose nodes locate only at their corners, use linear interpolation; however, elements having nodes at midpoints in addition to nodes at the corners use quadratic interpolation (Abaqus 2012).

4.1.1.1. Element Formulation

Usually Lagrangian or Eulerian formulation is used as function to describe element's behavior in finite element method. Lagrangian formulation is commonly used in solid mechanics problem. In this method, material remains stable in the element boundaries during the analysis. Other formulation Eulerian is mainly used in fluid mechanics problem and material flows while elements are stable in the defined space. Elements, which were used in this study, use Lagrangian formulation since determining the composite leaf spring behavior is a quasi-static problem and subject of solid mechanics.

4.1.1.2. Element Integration

Integration points that Abaqus calculates the material response by way of the numerical methods such as Gaussian are important parameter in analysis as they influence the accuracy and the total time of the solution. Fully integrated or reduced integrated elements are available in Abaqus yet problem should be considered carefully to select proper element type in terms of the accuracy of the problem. Fully integrated elements that have integration points completely use these required Gauss points to integrate the polynomial terms. Second-order elements have totally 9 integration points meanwhile first-order elements have 4 points (Abaqus 2012). Nevertheless, usage of the fully integrated linear elements makes a significant problem, which often called as shear locking, in bending conditions. Shear locking makes elements too stiffer to bending loads. Therefore, these elements shouldn't be used for bending conditions to obtain accurate result. On the other hand, using linear reduced integration elements causes another important problem called as hourglassing because they have single integration point at the element's centroid and this makes an element too flexible to bending loads. Hence, problems in which contain bending loads at least four reduced integrated linear elements should be used to provide this problem and obtain more accurate results (Abaqus 2012).

4.2. Classical Lamination Theory

Mechanics and design process of composite structures are significant subjects in composite modeling to utilize from the composite materials effectively. Mechanics of composite materials can be divided into two groups as micromechanics and macromechanics. The micromechanics investigate the influence of the fiber and matrix constituents, and their combinations on the structure behavior. However, inadequacy of this approach in the prediction of the advanced laminate properties lead many approaches, which are used to determine mechanics of composite materials, to use macromechanics. In these methods, which can accurately predict the laminate properties, stress-strain relationships, inelastic behavior, interlaminar stresses are generally addressed (Miracle and Donaldson 2001). The theory makes it possible to proceed from a lamina to the laminate to determine the laminate properties (Jones 1999). A typical nomenclature of a laminate is shown in Figure 4.1.

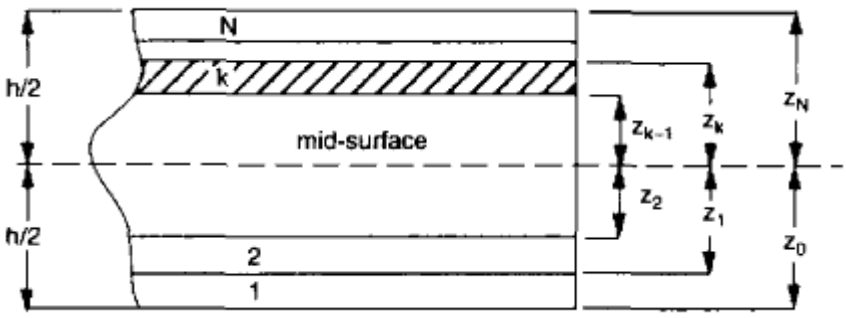


Figure 4.1. Laminate stacking sequence nomenclature
(Source: Staab 1999)

Full determination of stresses, strains and other outputs is only possible by using of the numerical analysis though the lamination theory is widely used method to predict the behavior of the composite laminates. Orthotropic material properties of composite materials and the sophisticated geometries necessitate the usage of computer programs to analyze all levels of the laminate. The numerical analyses provide great ease in the analyses in terms of time and cost. On the other hand, numerical results should be validated by the experimental or analytical results to understand the accuracy of the numerical model and obtain correct results (Miracle and Donaldson 2001).

4.3. Numerical Modeling and Analysis of Composite Leaf Springs

A composite mono leaf spring was modeled and analyzed by using Abaqus 6.12-1 finite element computer program. As previously mentioned, modeling and analysis of composite structures is quite difficult since composite materials have orthotropic material properties. For this reason, preprocessing and postprocessing steps in finite element modeling of composite structures should be done more carefully. Material properties and rotation angles for each ply should be defined, appropriate finite elements for analysis should be selected and output requests should be read accurately after the analysis procedure.

There are two main procedures to solve the numerical problems. These are explicit and implicit methods with different characteristics. Explicit method uses the solution of the previous time step to predict the solution at the desired time step. Small time steps are necessary to obtain accurate results in this procedure. Therefore, impact problems, problems with large deformations and failure problems are usually investigated by using this method. Other procedure is implicit method and this method solves the algebraic equations at the next time step by using the solution of the previous time step. Larger time increments can be selected in this procedure and this reduces the cost of analysis that is a significant parameter for the researchers. Abaqus enables users to choose one of them between these two procedures. Abaqus/Standart and Abaqus/Explicit methods are available in Abaqus. Hence, researchers should investigate the problem carefully so as to determine which method is more proper (Abaqus 2012). In this study, Abaqus/Standart implicit finite element procedure was selected as the method since investigating the spring behavior under given boundary and loading conditions is a quasi-static problem and the global response of the structure is considered.

4.3.1. Import CAD and Edit Geometry

Abaqus can read and import several types of file formats in addition to its own design facility. This property of the program enables users to study together with the other engineering computer programs. Sketch, part, assembly or model can be imported into the Abaqus using the proper file formats. However, there are some significant

considerations that should be considered by the users during and after the import process. Abaqus/CAE compares its own precision with the precision of the CAD part. Import process can be carried out successfully if these precisions coincide. Otherwise, differences between these precisions can make the part imprecise or invalid (Abaqus 2012). This situation necessitates some adjustments on the part and these operations can be made during or after the import process.

A solid mono leaf spring model was imported into Abaqus with a .stp file extension. As mentioned before, imported model sometimes requires some repair process though Abaqus/CAE automatically repairs lots of the file formats during the import process. Hence, it is important for program users to import and repair the geometry accurately so as to perform the finite element analysis correctly.

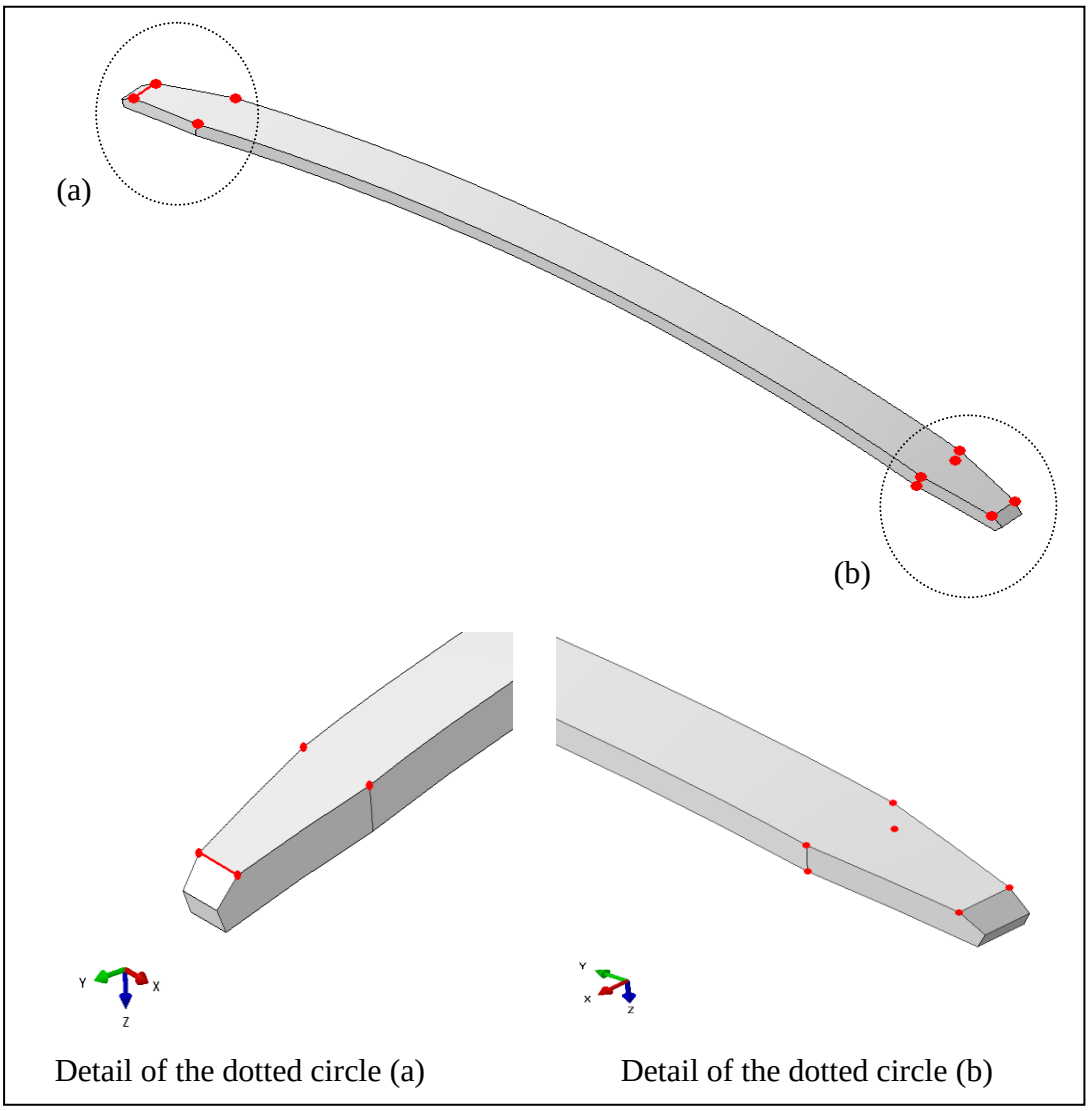
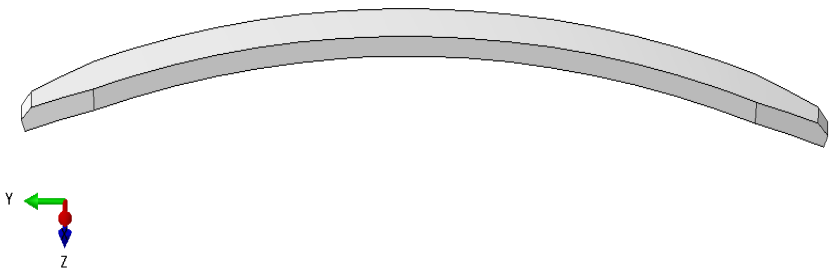


Figure 4.2. Geometry import process

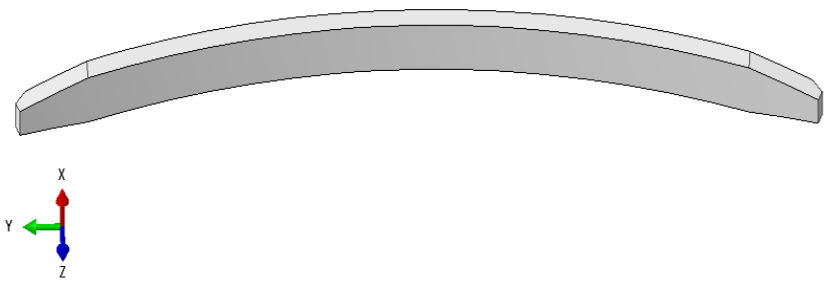
Query toolset is generally used to acquire information about the geometry properties and the model specifications in Abaqus/CAE. In this study, Abaqus demonstrated that the imported part has no invalid entities and there are 11 imprecise entities (1 edge, 10 vertices) in the model when the part was queried. Moreover, the geometry in the part has no free edges, shell faces or wire edges.

There are two methods in Abaqus/CAE to repair the part. In Tighten Gaps method, Abaqus/CAE tries to enhance the precision of the entities in our model. The geometry may not be computed fully though this method is faster than other. In Recompute Geometry method, Abaqus/CAE attempts to match the geometry entirely by changing the adjacent entities. This method is slower and may result in complexity of the part (Abaqus 2012).

Tighten Gaps method was selected as the conversion method. The gaps have been tightened so that the part contains valid geometry and topology. The part obtained after the import and repair process can be seen in different views in Figure 4.3.



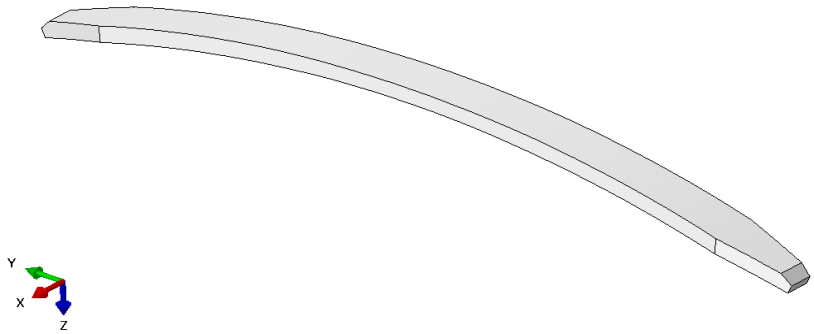
(a)



(b)

Figure 4.3. Repaired solid model views (a) front view (b) bottom view (c) iso view

(cont. on next page)



(c)

Figure 4.3. (Cont.)

After the import process, partition, other important composite modeling process, is performed on the part. Partition process is generally used to obtain smaller regions on the part. These regions may be utilized to define a load condition, change a material property, generate a different mesh, and so on. In addition, partitions provide great convenience in mesh generation. We can mesh unmeshable regions using partition toolset. In our study, partition process was used to indicate the location of the lay-up and the contact regions. The part is partitioned off 30 smaller regions. All of them are used to define the ply regions and three of those are also used to define contact regions contacting with rigid parts.

Creating datum planes on the model in an effort to partition the faces successfully is important in the partition process. There are four datum planes created on the model.

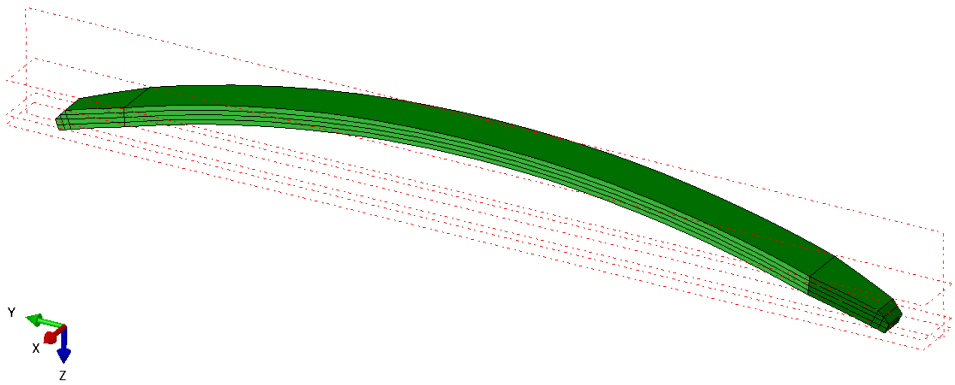


Figure 4.4. Created datum planes on the part

After this stage, face partition and cell partition processes were carried out respectively. 11 faces and 16 cells were partitioned on the part. Sketches, shortest paths between two points and extended faces were utilized to create face partition. Then, these partitioned faces are separated from each other by using extrude/sweep edges toolset.

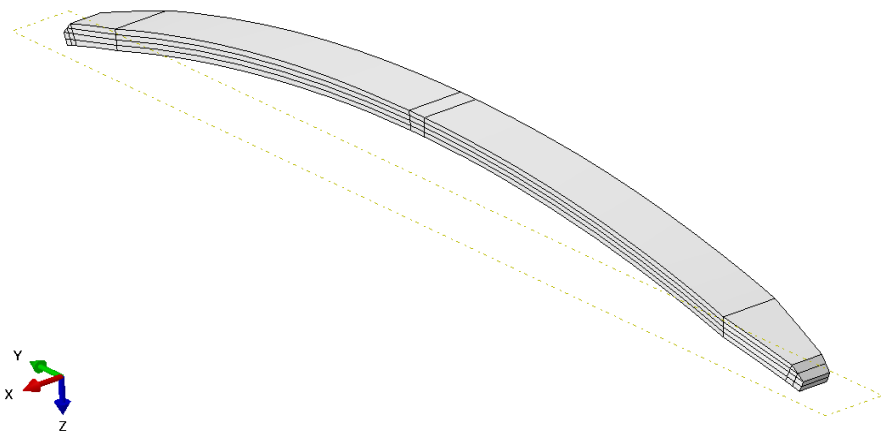


Figure 4.5. Partitioned solid part

Despite the capability of the composite modeling of Abaqus/CAE due to its superior property of composite lay-up creation, creating mesh using hex elements in curved composite parts is a great problem for the program users. For this reason, curved regions on the part should be removed in order to assign hex brick elements and obtain good mesh generation. Therefore, curved regions on the edges of the part were cut off and so, the final shape of the part depicted in Figure 4.6. is obtained.

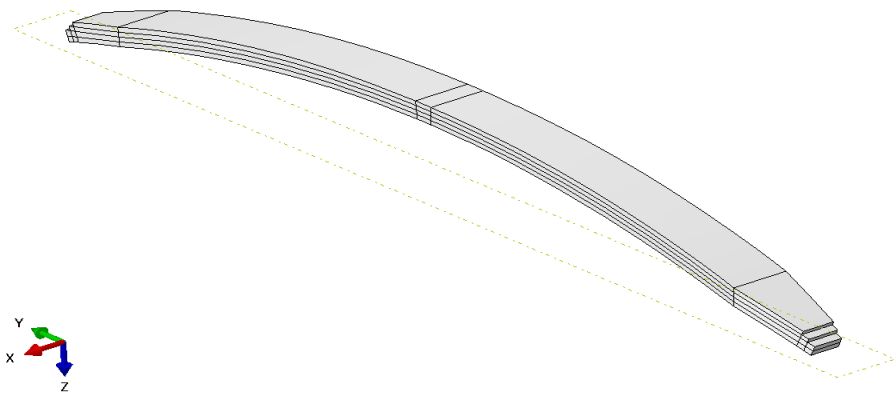


Figure 4.6. Final shape of the part

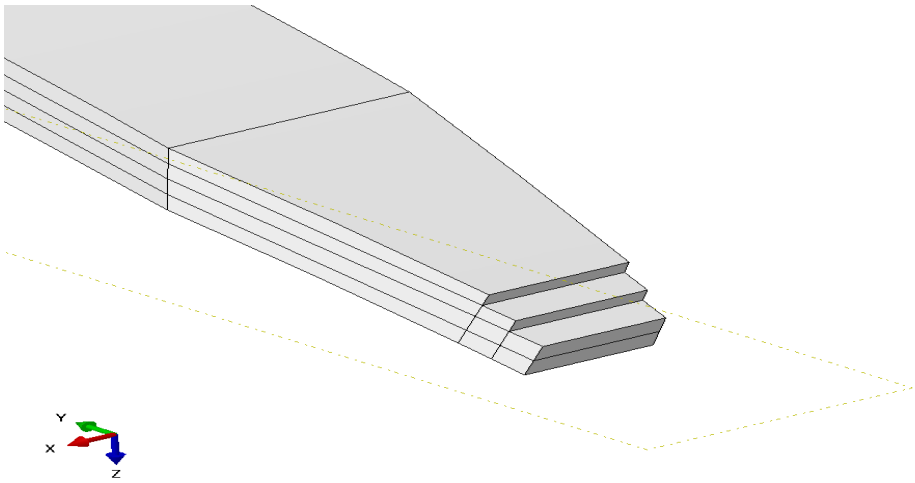


Figure 4.7. Detail of the model edges

4.3.2. Composite Modeling

There are great numbers of techniques in Abaqus for composite modeling. These can be mainly classified into two groups as macro-modeling and micro-modeling. However, mixed modeling, submodeling and discrete reinforcement modeling are available in Abaqus (Nurhaniza et al. 2010). The micro-modeling approach achieved by Composites Modeler (Simulia 2008) provides great opportunity in ply modeling by transferring correct fiber angles and ply thicknesses to the part. Creating composite layup other modeling approach provides a ply table to define ply properties. Name, region, material, thickness, coordinate system, rotation angle and number of integration points of the ply in the layup are entered in this table. In this study, composite layup tool was used as a composite modeler and solid composite layup was selected as the element type. The composite layup interface of Abaqus/CAE used in this study is illustrated in Figure 4.8.

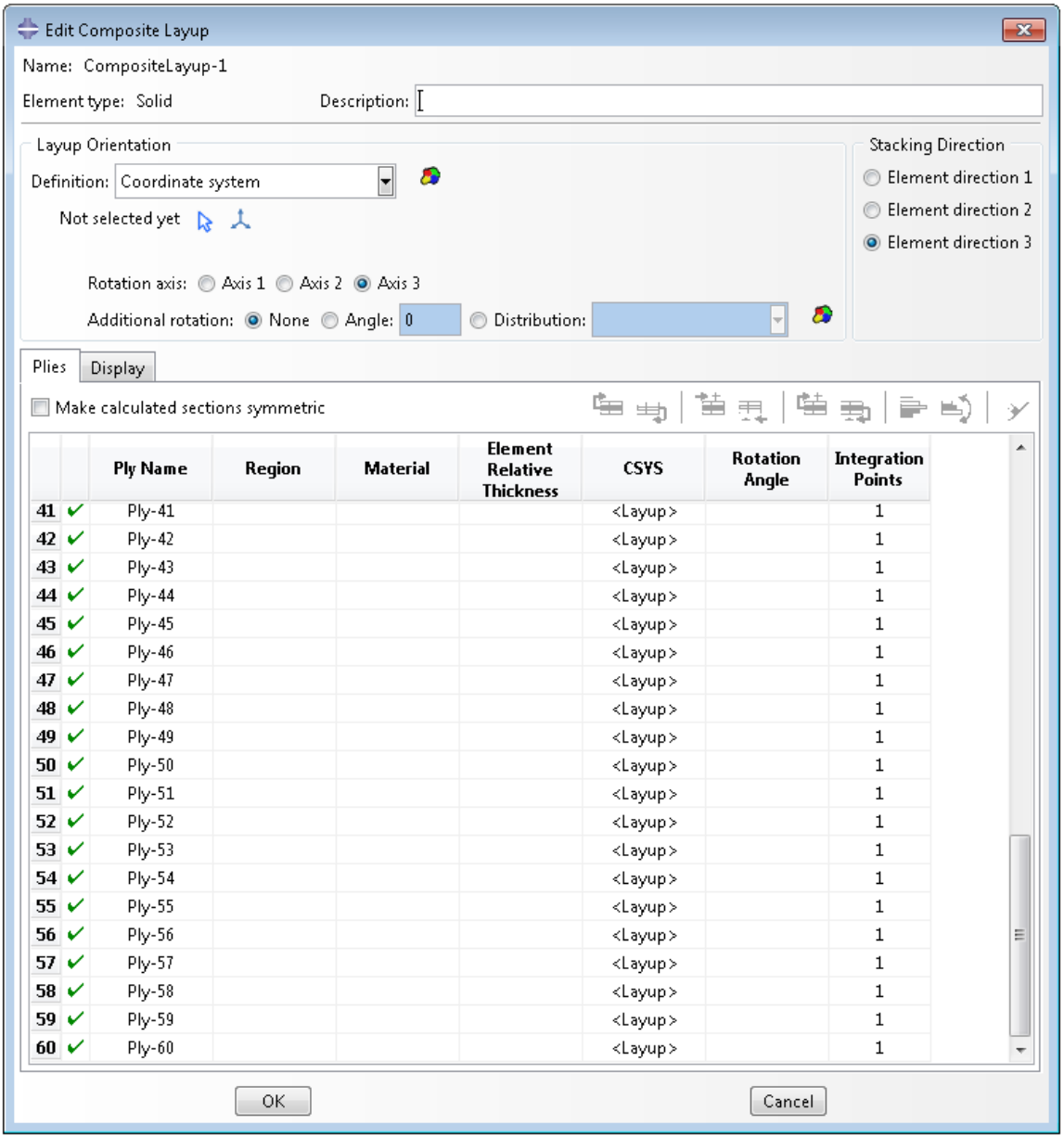


Figure 4.8. Abaqus/CAE composite layup user interface

As can be seen in the figure, Layup Orientation and Stacking Direction of plies are defined firstly. Layup orientation can be defined as the basis orientation of the plies in the given layup and Stacking Direction defines the sequence direction of the plies. As stated previously, composite materials have orthotropic material properties that must be defined more carefully especially in the usage of 3-D continuum elements in the composite modeling (Soteropoulos, Fetfatsidis, and Sherwood 2012). For this reason, discrete layup orientation was used in our model since the geometry of the part has variable topology at the bottom. So, we could define varying orientation which gives us more accurate modeling capability in the layup. These orientations are shown in Figure

4.9. Element Direction 3 that is the thickness direction of the part was selected as the Stacking Direction in the study.

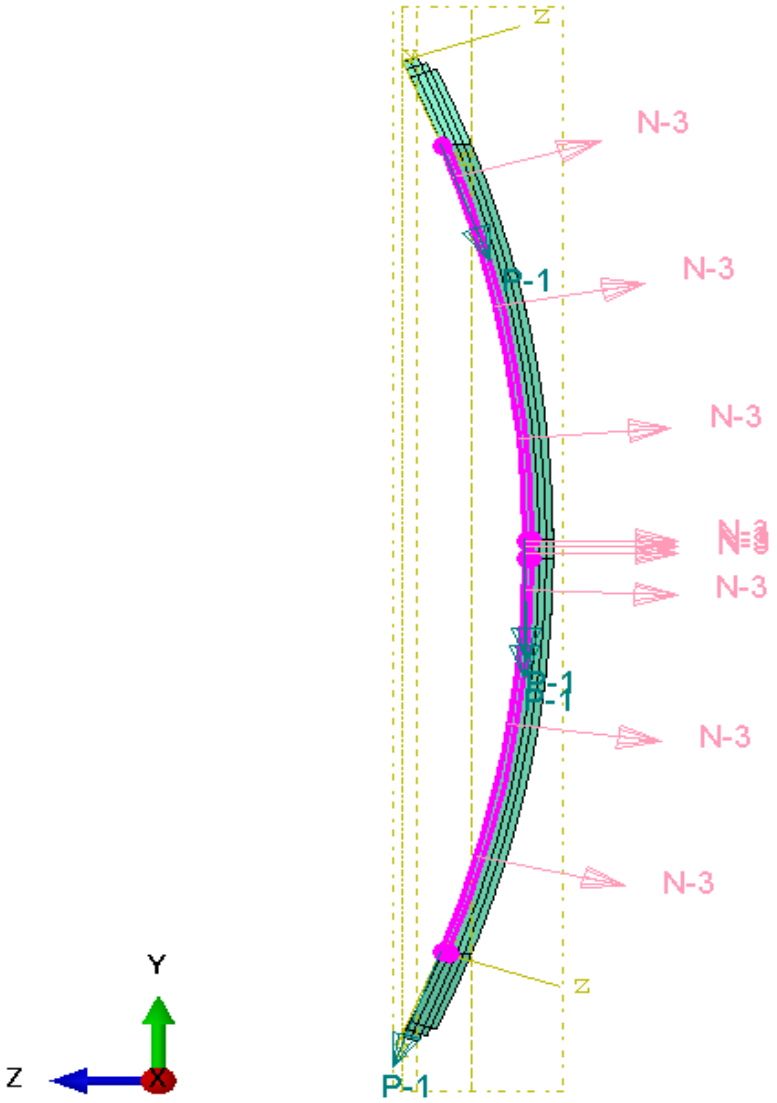


Figure 4.9. Composite mono leaf spring material orientation with discrete coordinate system

The global coordinate system not rotating or varying with the surface curvatures was used at the edges of the part. In this orientation definition, reinforcement and transverse directions of the material was assigned according to existing global coordinate system including defined x-y plane (Soteropoulos, Fetfatsidis, and Sherwood 2012).

After these processes, ply table including initially entered ply number is completed. Ply names are defined firstly and then, the regions of the plies are assigned. In the model, 15 plies are assigned to one layup since there are 4 composite layup in the thickness direction and every ply thickness is assumed as 0.5 mm (Güneş 2013). After then, material, rotation angle and integration points of the ply are entered respectively. Rotation angle is selected as 0° as the fiber-reinforced composites have superior characteristics in the direction of fibers in terms of the strain energy (Shankar and Vijayarangan 2006). As mentioned in the literature survey before, glass fiber-epoxy composites were selected as the optimum materials that are used in the spring production when their cost and strength properties are taken into consideration. Hence, GFRC (glass fiber-reinforced composite) material properties are assigned to the table (Güneş 2013; Samborsky, Mandell, and Agastra 2013; Shankar and Vijayarangan 2006). The material was created before the assignment of the material properties. The density and the engineering constants of the material are entered respectively. Table 4.1 represents the material properties of E-glass / epoxy plies. When all is done, the composite modeling of the part is completed as shown in Figure 4.10.

Table 4.1. Material properties of unidirectional E-glass/epoxy plies

E_1 (MPa)	$E_2 = E_3$ (MPa)	G_{12} (MPa)	G_{13} (MPa)	G_{23} (MPa)	$\nu_{12} = \nu_{13}$	ν_{23}	d (kg/m^3)
37000	9500	3490	3770	3460	0.262	0.35	2600

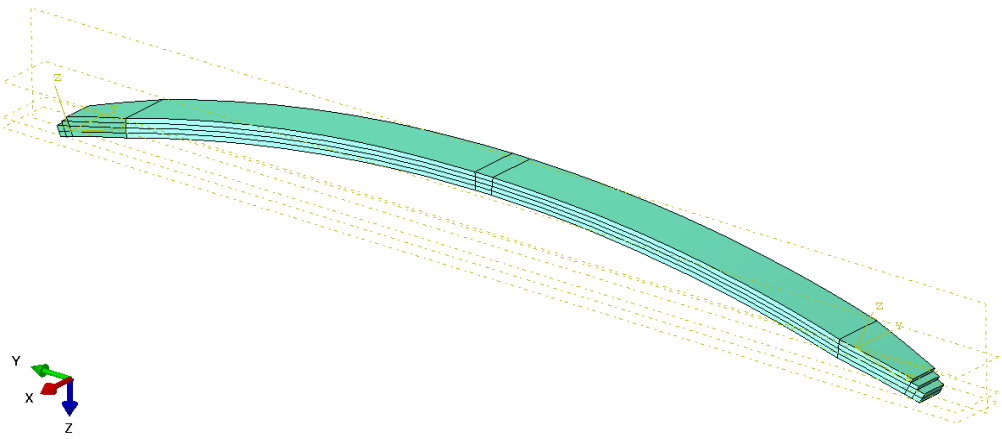


Figure 4.10. Material defined composite mono leaf spring model

4.3.3. Composite Mono Leaf Spring Assembly

Assembly module of Abaqus/CAE is used to create instances of the existing parts, thus generating assembly of the system to be analyzed. Part instances, which may be a dependent or an independent, are created in the first stage. Then, these part instances are positioned to each other relatively using the Abaqus/CAE constraints such as parallel faces, parallel edges, coaxial constraint and so on. An important issue at this point is deciding to create whether a dependent or an independent part instances.

A dependent instance cannot be meshed, only the original part can be meshed and Abaqus implements the applied mesh to all dependent instances of the meshed part in Assembly module. Consuming a few memories due to the fewness of the meshed part may be presented as an advantage of this instance type. Moreover, it is satisfactory for users to mesh the part one time. On the other hand, a dependent geometry cannot be modified and nature of the applied mesh cannot be changed in a dependent type instance. An independent part instance can be meshed contrary to a dependent part instance. Geometry modification can be made and the attribute of the mesh can be changed in this type of instance. Nevertheless, over consumption of the memory resources and necessity of the meshing of each part in one by one steps are drawbacks (Abaqus 2012).

According to assembly procedures, a rigid body has been created firstly in Abaqus/CAE. A rigid cylindrical shell, which has the diameter of 50 mm and the length of 100 mm, has been utilized in the assembled model by taking into consideration the existing supports of the leaf spring test rig. There are two alternatives in Abaqus/CAE to

create a rigid body. These are discrete rigid and analytical rigid parts. These are generally used to create indeformable parts utilized in contact analyses (Airoldi, Bettini, and Sala 2007; Qin, Dentel, and Mesh 2002). Only the shape of the rigid part and facility of the mesh creating play a role in determining which types of part will be used in an analysis.

A rigid body, which is manipulated by a single node known as a reference node, can be defined as an indeformable rigid part. Although a rigid body does not deform during an analysis, the boundary conditions generating rigid body motion can be applied on it. An analytical rigid shell part has been created in this study since the analytical rigid parts are more applicable than the other in the way of time consuming (Abaqus 2012). The analytical rigid surface and the reference node are shown in Figure 4.11.

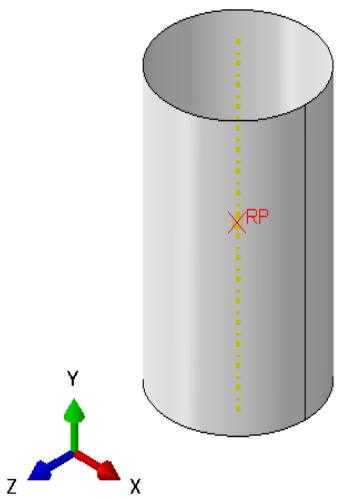


Figure 4.11.The analytical rigid body and the reference node used to define the boundary conditions

Three dependent part instances of the rigid support and a dependent part instance of the composite mono leaf spring model were created in Assembly module. The rigid parts are positioned such that the spacing of 40 mm is left from the ends. The last one is also positioned at the centre point of the upper surface of the composite leaf spring model. All of are positioned in such a way that the cylinder axes are perpendicular to the longitudinal direction of the spring. Figure 4.12 shows the position of the rigid parts and the completed assembly of the system.

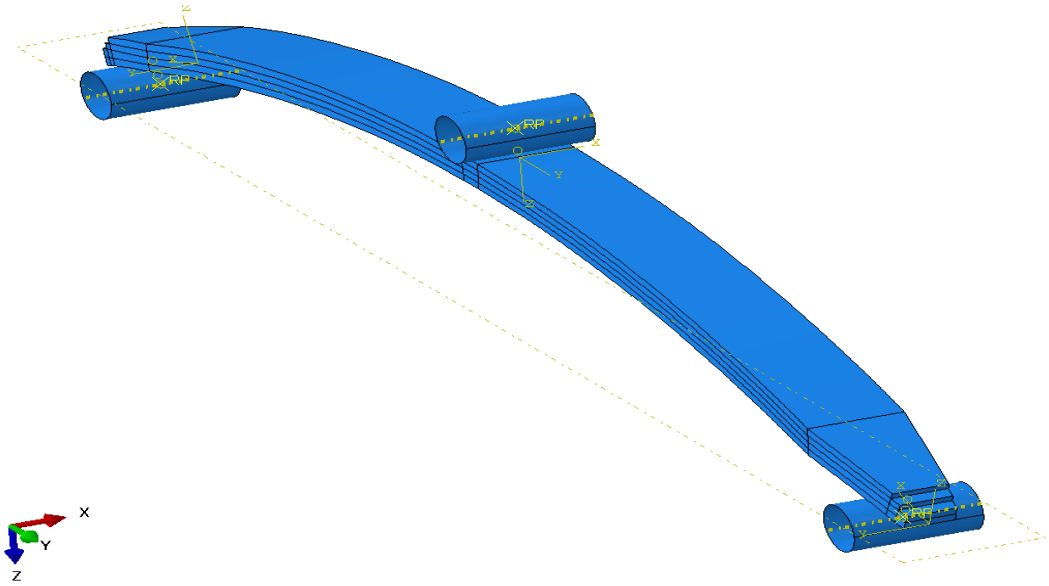


Figure 4.12. Assembly of the composite mono leaf spring model

4.3.4. Mesh and Elements

Abaqus/CAE enables users to create an appropriate mesh in their analyses through the comprehensive toolboxes. There are several unique features of Abaqus/CAE mesh module such as controlling of element shape, meshing technique and mesh quality. In addition, mesh quality can be verified and enhanced by way of the mesh module tools in Abaqus.

In this work, proper element type was selected firstly to create meshes on the composite leaf spring model. C3D8R (An 8-node linear brick, reduced integration, hourglass control) elements were selected firstly as the element type in reference to the proposals of Abaqus documentations and literature studies (Abaqus 2012; Airoldi, Bettini, and Sala 2007; Venkatesan and HelmenDevaraj 2012). Moreover, the analyses were also done using other element types.

C3D8R is a three dimensional, 8-node, reduced integration, hourglass control element. These solid (continuum) elements are generally used in the modeling of solid composites as they can comprise different material properties. This characteristic provides an advantage especially in the hybrid composite modeling including various plies of different materials. The geometry, the node numbering, the node locations and the face numbering of this element are demonstrated in Figure 4.13.

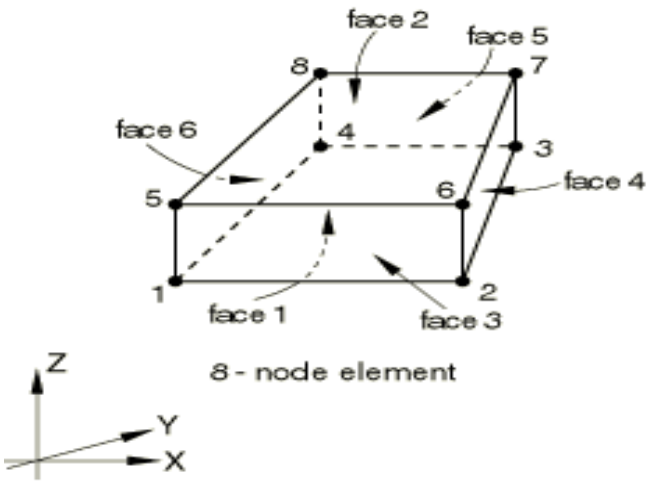


Figure 4.13. C3D8R element geometry, node ordering and face numbering representation (Source: Abaqus 2012)

The aforementioned element has only one integration point at the element centroid. Therefore, the hourglassing can make some difficulties at the point of obtaining accurate results. Hence, the load conditions and the boundary values should be distributed over the many nodes to avoid from the hourglass effect. This element also enables users to create isotropic, engineering constants, lamina, orthotropic or anisotropic material properties in the model. In addition, output requests such as stresses, strains, displacements, reaction forces, reaction moments, contact stresses, contact forces, energy and damage components are available for this element type.

Many problems can be meshed with global seeds in Abaqus/CAE yet local seeds should be utilized in our model to obtain proper mesh generation and mesh density. Using linear reduced integration elements may cause some problems especially in bending problems as mentioned before though these elements provide advantages in terms of time consuming. Structures having bending loads should be studied carefully and minimum four elements should be used in the thickness direction of the structure (Abaqus 2012). Hence, local seeds are assigned as shown in Figure 4.14.

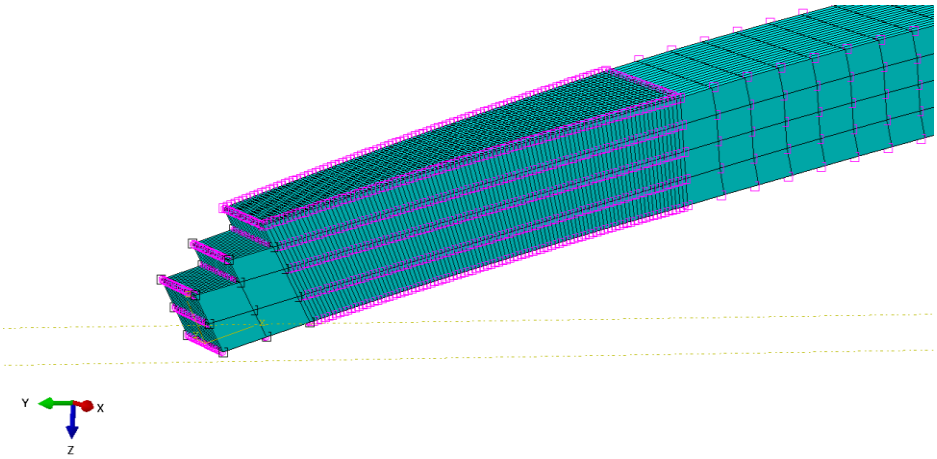


Figure 4.14. Local seeds generation in the model

After assigning the local seeds one by one, the next step is to mesh the part completely using proper mesh algorithm. In this step, non-uniform mesh generation should be assigned some regions having contact, BCs or load conditions. In addition, non-uniform mesh region should be especially assigned the regions expected to have high gradient depending upon the analysis results. A non-uniform mesh region is shown in Figure 4.15. Figure 4.16 also shows the completed mesh in the model. The dark regions in the model demonstrate the non-uniform mesh regions having smaller elements.

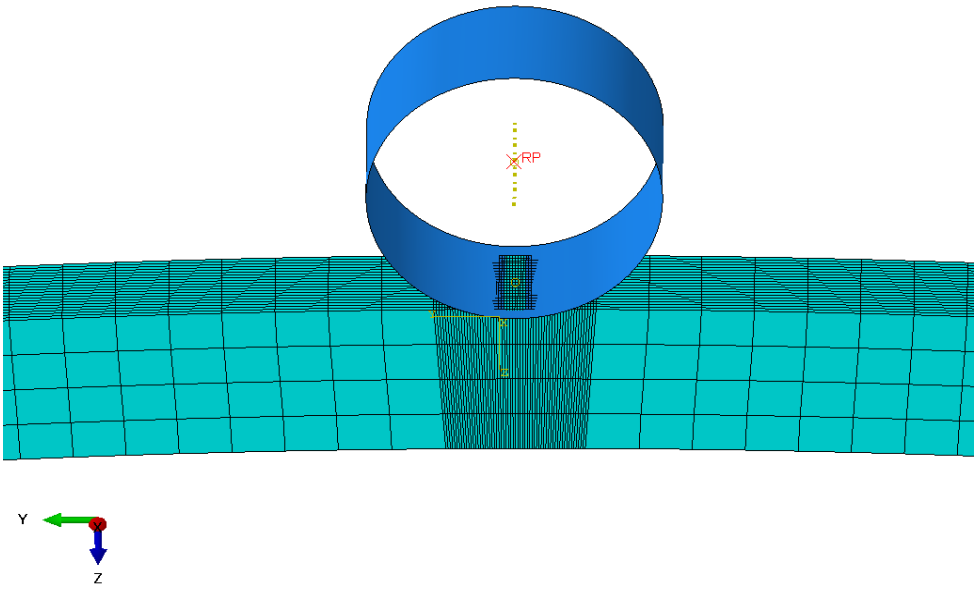


Figure 4.15. Non-uniform mesh in a contact region

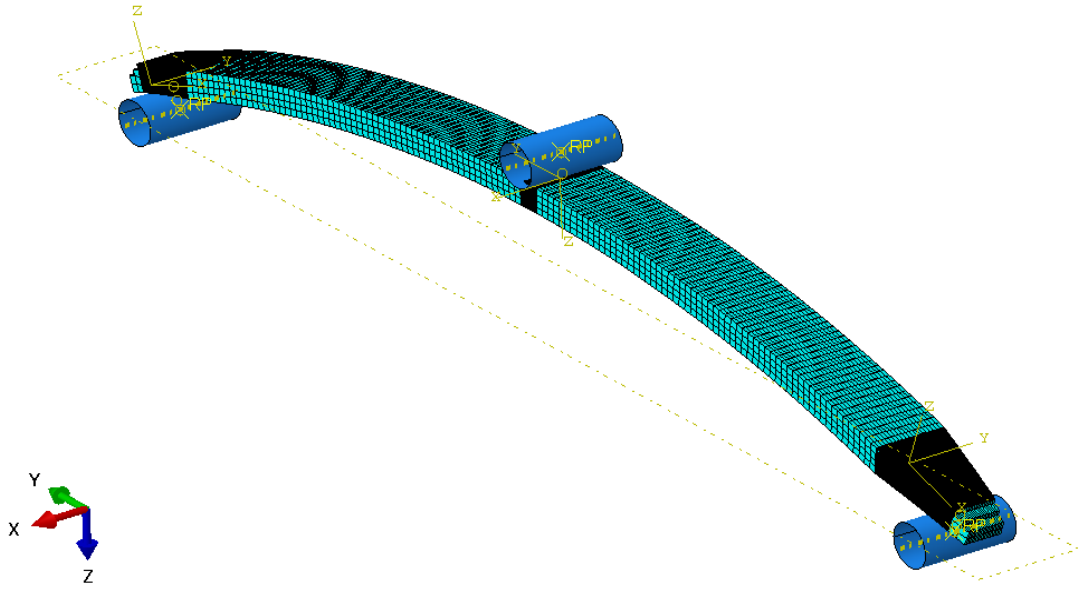


Figure 4.16. Meshed composite leaf spring model

4.3.5. Boundary Conditions and Applied Load

The boundary conditions and the load to be applied were determined by taking into consideration the upper limit value of the mechanic loads that may be took place due to the vehicle weight and the road conditions. As a result, the vertical load is decided as the most dominating and critical mechanic load applied on a leaf spring (Lakshmi and Satyanarayana 2012). The theoretical load-deflection diagram of the system is shown in Figure 4.17. The loading was applied by the upper rigid support using displacement of 135 mm in the z direction, and other displacement and rotation degrees of freedom were restrained in this support. All displacements and rotations of the other two supports, which are on the bottom surface of the model, were also restrained. The rigid body constraint is also created for each support in order that the reference point governs the rigid body.

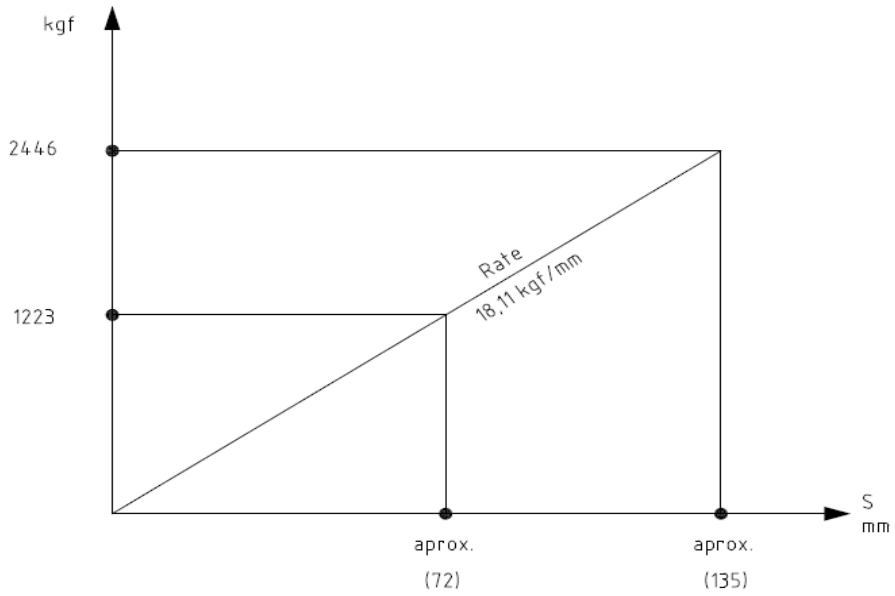


Figure 4.17. Load-deflection diagram for leaf spring
(Source: OlgunCelik 2013)

In Abaqus/CAE, the contact definition, which takes place between the composite model and the rigid supports in the study, plays a crucial role in terms of the accuracy of the analysis. Thereby, the behavior of the contact and the interaction type of the parts should be investigated carefully. However, it may not be possible to create finite element model of the system same with the existing actual system.

In this work, the penalty based algorithm is used to define the interaction properties and surface-to-surface contact is defined between the model and the rigid supports. Abaqus/CAE generates solutions for the contact problems using some formulations like Frictionless, Penalty, Rough or Lagrange Multiplier. The penalty method and the Lagrange multipliers method are primary methods used in the contact problems. The only difference between two methods is the contact stiffness formulation. The Augmented Lagrange method involves a penalty function as well as the classical Lagrange multiplier method. Hence, this method is more expensive than the penalty method. Moreover, the Lagrange method gives more accurate result. However, the penalty method is widely used in finite element analysis owing to its economical advantage and outstanding success in the solution of the frictional contact problems (Ştefancu, Melenciuc, and Budescu 2011). The interaction of two contacting surfaces that use penalty method formulation is demonstrated in Figure 4.18. S_0 represents a

node of slave surface before the loading, and S represents the same node after the application of the load.

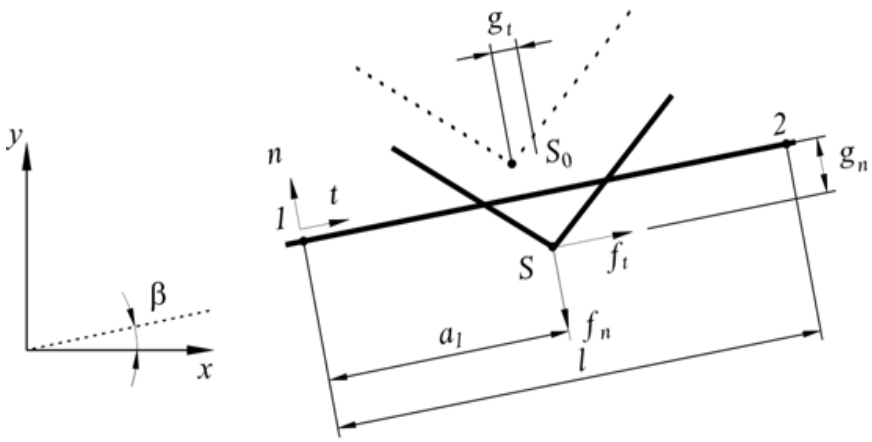


Figure 4.18. The interaction between the contacting surfaces using penalty method (Source: Ştefancu, Melenciuc, and Budescu 2011)

The friction coefficient is assumed as 0.2 in the tangential behavior of the contact (Baere 2005) and the stiffness scale factor, which is one the normal behavior parameter of the contact property, is also entered as 20 to prevent the abnormal penetration of the composite model into the rigid rollers. The abnormal penetration, which affects the analysis results in a negative way, can be seen for the smaller values of the stiffness scale factor in Figure 4.19.

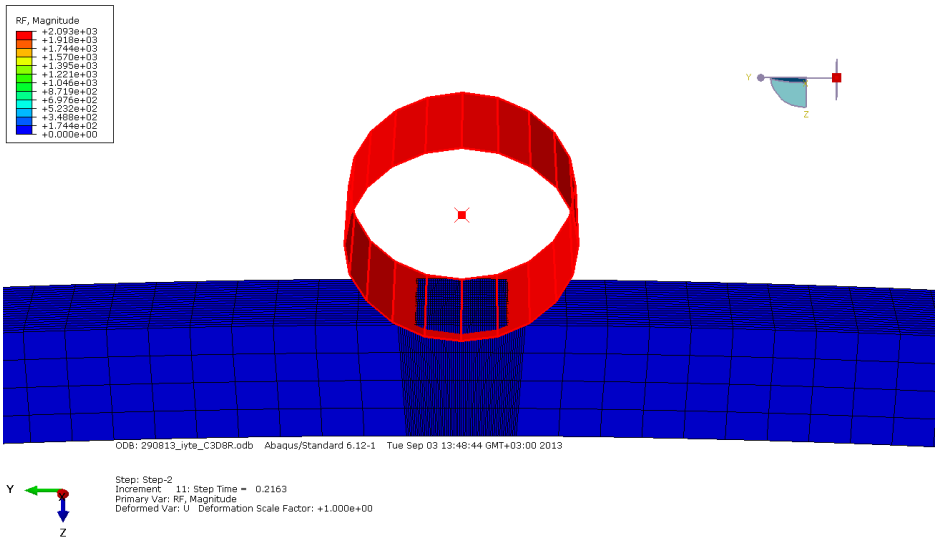


Figure 4.19. The partial penetration of the composite model with smaller stiffness scale factor

In the interaction edit step, the finite sliding formulation and the surface to surface discretization method were also selected (André, Nilsson, and Asp 2010). It is because the sliding may occur in any haphazard form in the finite sliding formulation contrary to the small sliding that allows only relatively small motion of the contacting surfaces (Abaqus 2012) and consequently the model gets ready to run the analysis after all these stages.

CHAPTER 5

RESULTS AND DISCUSSIONS

The validation study, stress analysis and control of the boundary conditions of the designed composite-based leaf springs are given in this chapter. Moreover, the natural frequency analyses of the structures are also presented.

5.1. Validation of the Finite Element Model

An existing composite mono leaf spring was used as a model structure to validate the finite element model of the composite leaf spring created within the thesis study using Abaqus/CAE 6.12-1. Modeling procedures were performed based on the procedures described in detail within the previous chapters. Modeling work was realized by considering the test rig boundary conditions and based on defined loading conditions. Sensitivity of the modeling parameters such as constraints, contact definition, mesh and element type were also controlled respectively by comparing with the experimental test results and eventually the aforementioned procedures with regard to the finite element model of the composite mono leaf spring was obtained. In this section, the comparison of the experimental test results and the numerically-simulated composite mono leaf spring model was presented.

The testing of a composite leaf spring generally consists of two basic steps. In the first step, strain gauges suited for the composite-based materials are attached to the composite leaf spring. In the second stage, the spring was tested on the leaf spring test rig applying vertical load as shown in Figure 5.1.

In this validation study, not only the strain measurements on the spring surfaces but also the spring rate were investigated in detail. In addition, sensitivity of the model to element type, friction coefficient between the rigid bodies and composite model, and loading type were also studied carefully to validate the finite element model.

Figure 5.2 shows the positions of the attached strain gauges. It can be easily seen from the figure that there are 7 strain gauges on the part and two of them are positioned on the compression side, and the other five are on the tension side. General purpose

gauges, which have 120.0±0.15% grid resistance, 2.07±0.5% gage factor and +0.7±0.2 transverse sensitivity, were selected for the tests. It should be mentioned here that the several factors such as test duration, temperature, and purpose of test should also be taken into consideration in determining the proper gauge (Vishay 2003).

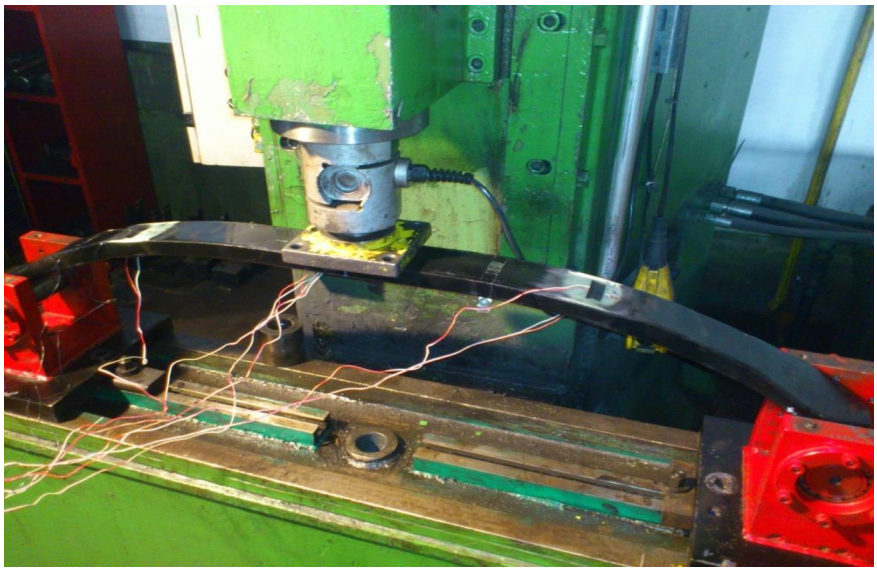


Figure 5.1. Photograph of the experimentally-tested composite model structure in the leaf spring test rig

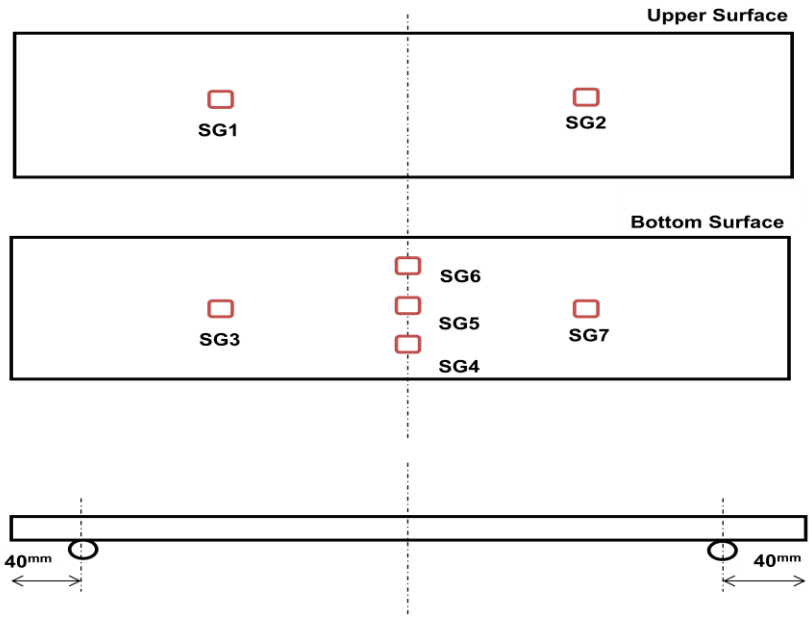


Figure 5.2. Positions of the strain gauges (SG) on the composite part that is subjected to mechanical loading

Figures 5.3 to 5.10 show the comparison of the experimental and predicted spring rate and strain measurements for the leaf spring that was used as a model structure to verify the FEM of the composite-based leaf springs created within the thesis study.

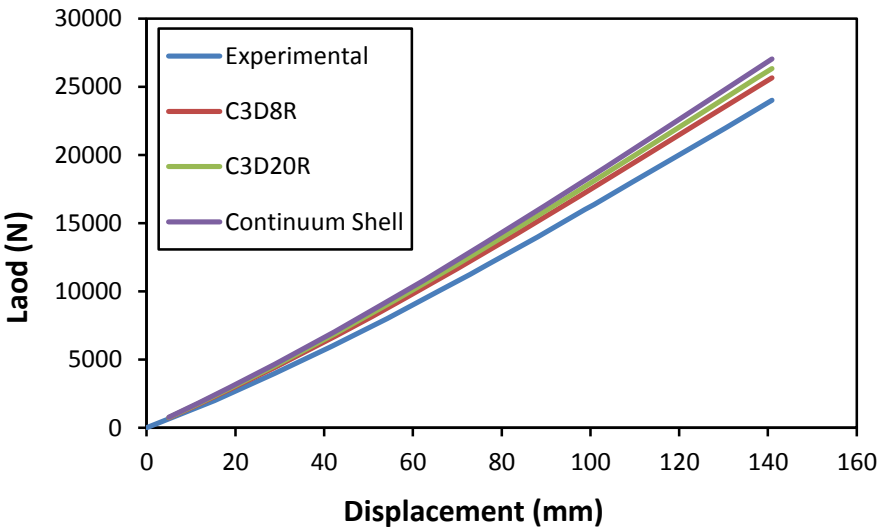


Figure 5.3. The comparison of the experimental and predicted load vs. displacement values of the model structure

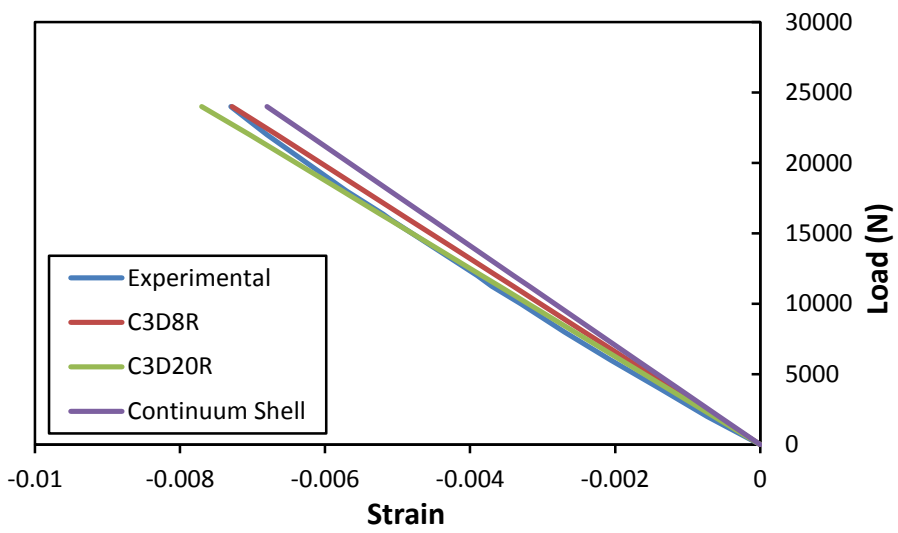


Figure 5.4. The comparison of the experimental and predicted strain values of the SG1 under the loading of 24000 N

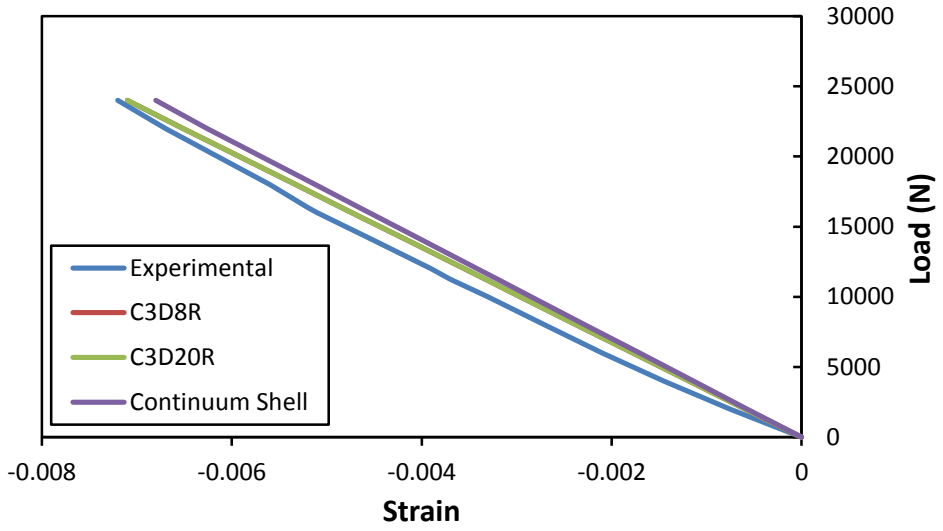


Figure 5.5. The comparison of the experimental and predicted strain values of the SG2 under the loading of 24000 N

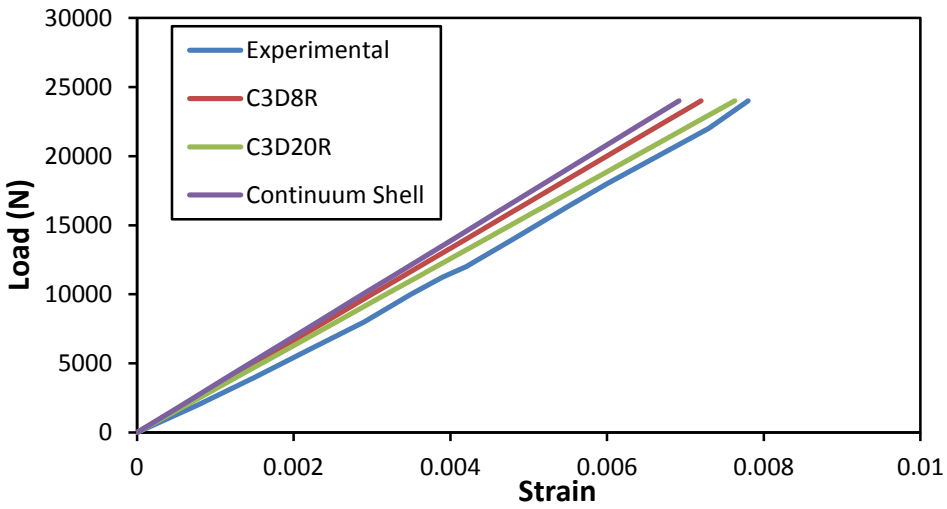


Figure 5.6. The comparison of the experimental and predicted strain values of the SG3 under the loading of 24000 N

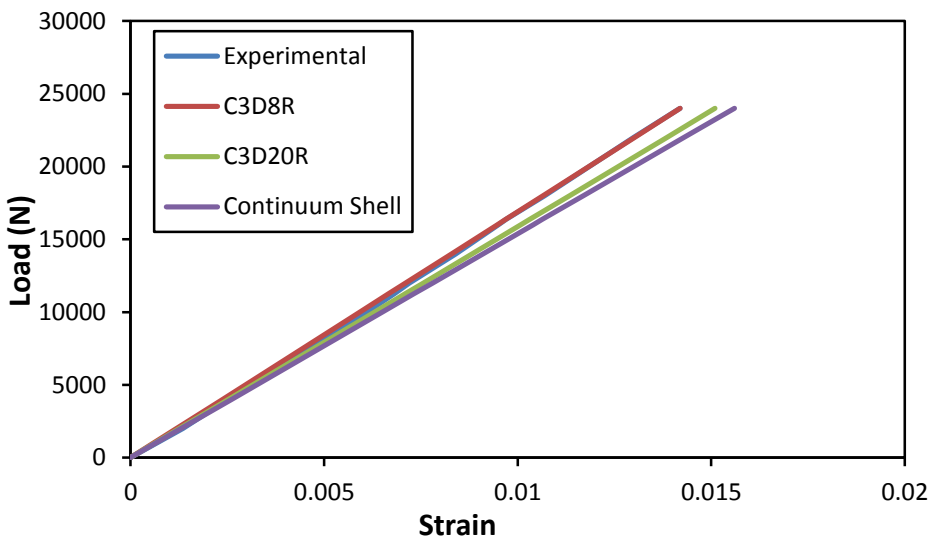


Figure 5.7. The comparison of the experimental and predicted strain values of the SG4 under the loading of 24000 N

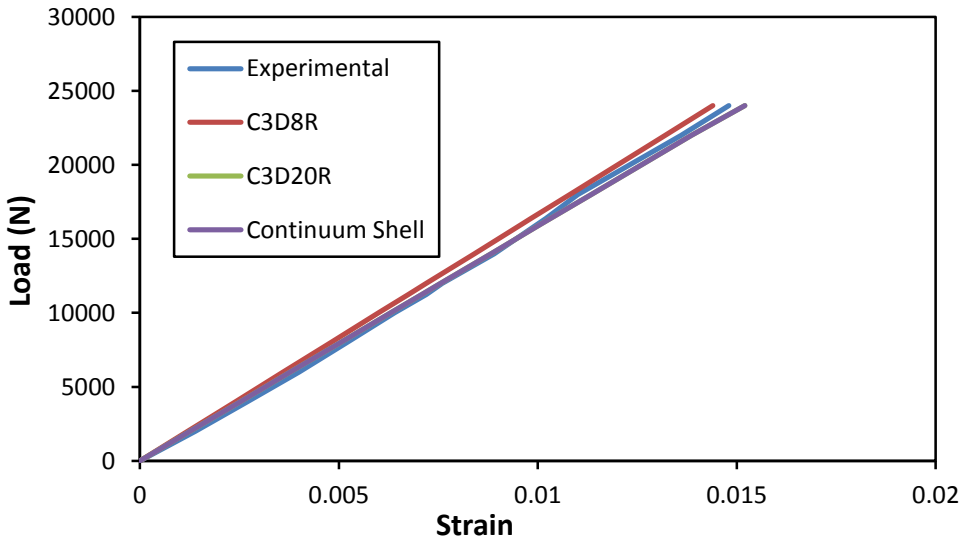


Figure 5.8. The comparison of the experimental and predicted strain values of the SG5 under the loading of 24000 N

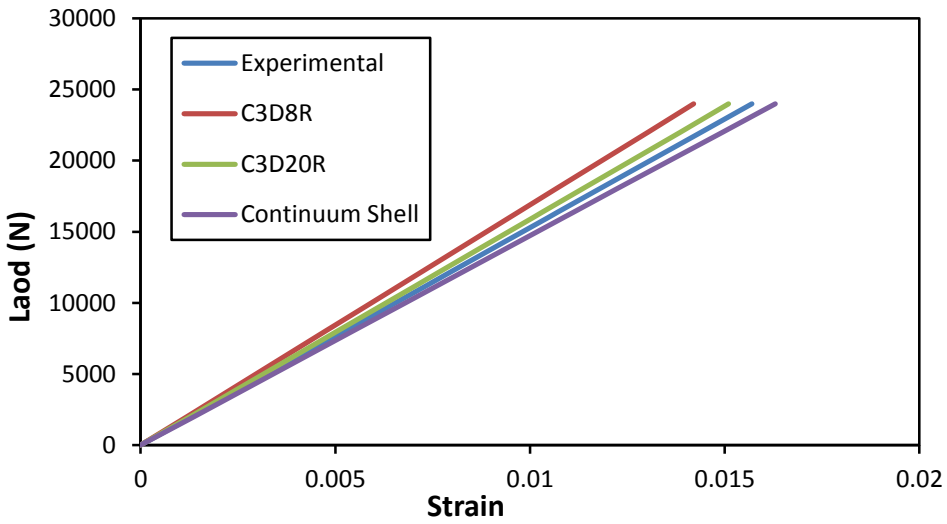


Figure 5.9. The comparison of the experimental and predicted strain values of the SG6 under the loading of 24000 N

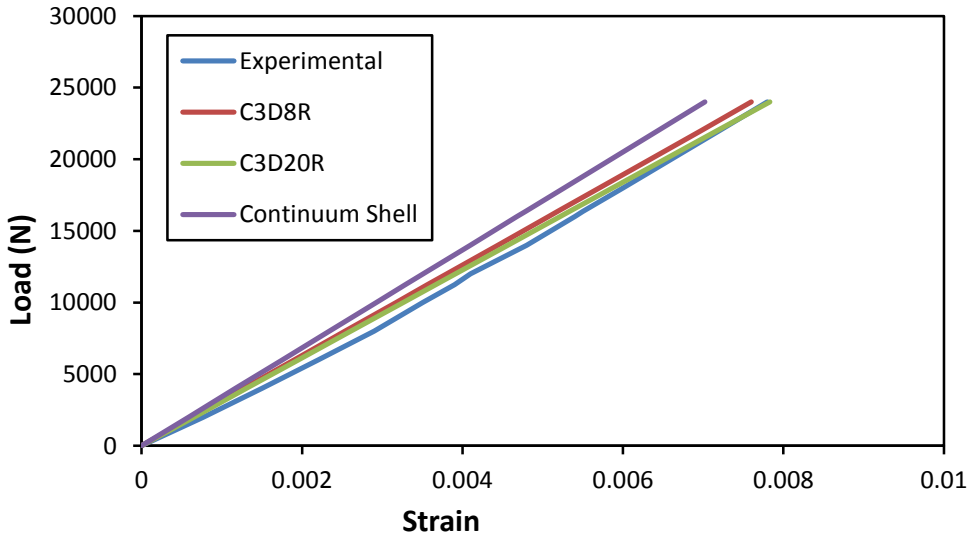


Figure 5.10. The comparison of the experimental and predicted strain values of the SG7 under the loading of 24000 N

It was observed from the validation study that the results obtained with C3D8R and C3D20R element types are good agreement with the experimental test results in terms of the strain measurements. Moreover, these two element types also give appropriate result from the spring rate point of view. Therefore, these two solid, brick element types can be used in the analysis of thick composite-based materials. However, the time is a significant consideration for the researchers and the linear elements are

cheaper than the second order elements since the quadratic elements have more number of nodes and integration points.

It was also observed from the results that the reaction force measured in the device in the experimental test is 24000 N, whereas the finite element model results are 25657.1 N, 26340 N and 27024.7 N with the C3D8R, C3D20R and Continuum Shell element types, respectively. These results indicate that the simulated finite element model anticipated the reaction force resulted in the upper supporter of the part with 6.9% deviation from the experimental results with C3D8R elements. Same comparison between the experimental and numerical results was carried out for the strain values on the selected regions on the model surfaces. As shown in the related figures, these results give us comfort about the usability of the created finite element model. We can see from the figures that the numerical results of the nominal strain values are again in agreement with the experimental results correctly with the 0.27%, 1.41%, 8.33%, 0.1%, 2.78%, 1.41%, 2.63% deviation for the strain gauges with C3D8R elements respectively. Estimated strain results for the C3D20R elements also give the results with the 5.48%, 2.78%, 2.22%, 6.34%, 2.70%, 4.86%, 0.38% deviation from the experimentally-obtained results respectively. Finally, the analysis with Continuum Shell elements produces the results with the 7.35%, 5.88%, 12.72%, 9.86%, 10.14%, 9.03%, 11.11% deviation from the test results. It can be deduced from these results that C3D8R and C3D20R element types are appropriate for the analysis of composite mono leaf spring model. However, it should also be noticed that Continuum Shell elements estimate the strain values between 5% and 13% deviation. As a result, it should be mentioned that the general treatment of the numerical results is in good agreement with the experimental results. The numerical results can be affected by the various kinds of factor such as contact definition, constraints and mesh generation in the model.

5.2. Stress Analysis and Boundary Conditions Control of the Composite Leaf Springs

Within the scope of the thesis study, composite leaf spring behavior was investigated through the 3 dimensional finite element model by using commercial finite element software Abaqus. In this regard, maximum deflection and stress values, which take place on the finite element model having intended boundary and loading

conditions, were determined. Different material configurations were investigated and the optimum configuration in the optimum composite structure was also studied.

5.2.1. Designed Composite-based Leaf Springs

Three different composite-based leaf spring models including diversified material configurations were created for determining the behavior and mechanical properties under required boundary and loading conditions.

Design 1 contains 60 plies of E-glass/epoxy with 0° orientation. The thickness of each ply is assumed as 0.5 mm as mentioned and three integration points are created in the ply in order to obtain more accurate results. This design does not contain any modification in terms of the material configuration and utilized as a reference structure for obtaining optimum configuration in the structure.

Design 2 is created 60 plies of carbon / epoxy with 0° orientation in a similar way. This configuration is assumed to increase the stiffness of the structure owing to the modulus property of carbon fibers in the fiber direction. Table 5.1 exhibits the material properties of the Carbon / Epoxy plies (Isbilir and Ghassemieh 2011).

Design 3 includes glass and carbon / epoxy plies and represents the optimum configuration in the optimum composite structure and this configuration also fulfils the spring rate condition. Created model list is given in Table 5.2.

Table 5.1. Material properties of unidirectional carbon / epoxy plies

E_1 (MPa)	$E_2 = E_3$ (MPa)	G_{12} (MPa)	G_{13} (MPa)	G_{23} (MPa)	$\nu_{12} = \nu_{13}$	ν_{23}	d (kg/m^3)
105000	8200	4500	4500	3000	0.3	0.4	1580

Table 5.2. Configurations of composite-based leaf spring systems created*

Design #	# Plies	Material	Orientation
1	60	Glass	$[0°]_{60}$
2	60	Carbon	$[0°]_{60}$
3	60	Glass and Carbon	$[0°_{6G}/0°_{2C}/0°_{22G}]_S$

*G= glass, C= carbon

5.2.2. Behavior and Mechanical Properties of the Designed Springs

Figure 5.11 exhibits the comparison between the required spring rate and the simulation results of the glass fiber/epoxy composite leaf spring model (Design 1). As seen from the figure, displacement increases linearly as the load increases since we studied in an elastic region and didn't define any damage criteria such as Hashin Damage that Abaqus provides. Based on this figure, it is observed that this configuration provides 169.49 N/mm spring rate however the required theoretical spring rate is 177.74 N/mm. Stress results in the critical regions are also presented through Figure 5.12 to 5.22. These figures are investigated rigorously as follows. From these figures it can be observed that the maximum stress values are taken place in the middle of the structure on both upper and lower surfaces in terms of the normal stresses. It can also be observed from the results that the compressive stresses are more dominating than the tensile stresses on the structure. This can be presented as a result of the loading condition. Moreover, all these maximum stress values are lower than the strength properties of the glass fiber/epoxy ply (Soden, Hinton, and Kaddour 1998; Güneş 2013). In consequence of the normal stress results, it has been understood in a clear way that the glass fiber/epoxy composite leaf spring design is allowable in terms of stress control. On the other hand, this material configuration does not provide the required spring rate condition entirely. Accordingly, the material configuration needed to be changed to increase the system stiffness though the stress results obtained under boundary conditions. As a result of this, Design 2 consisting of 60 plies of carbon/epoxy with 0° orientation was created.

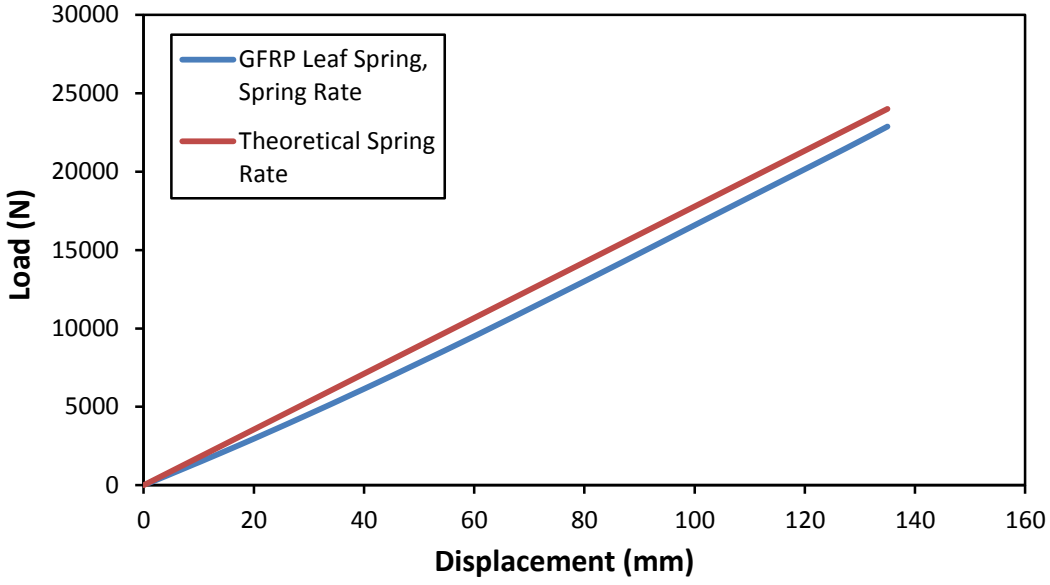


Figure 5.11. The comparison of theoretical and predicted load vs. displacement curves for the glass fiber/epoxy composite leaf spring under flexural loading

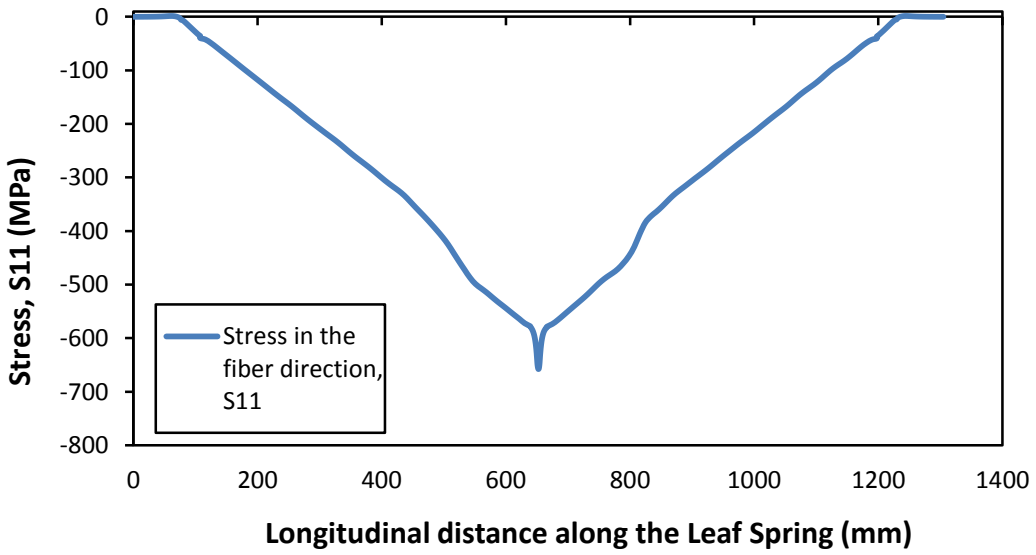


Figure 5.12. S11 stress distribution on the glass fiber/epoxy leaf spring upper surface along the longitudinal length

As shown in Figure 5.12, normal stress values in the fiber direction are negative on the upper surface of the structure and increasing towards to the loading region. In addition, few positive stress values are resulted in the edges up to the support regions.

As revealed in Figure 5.13, stresses in the transverse direction are positive up to the loading region. In that region, compressive stresses are observed as expected and then the stress distribution proceeds symmetrically.

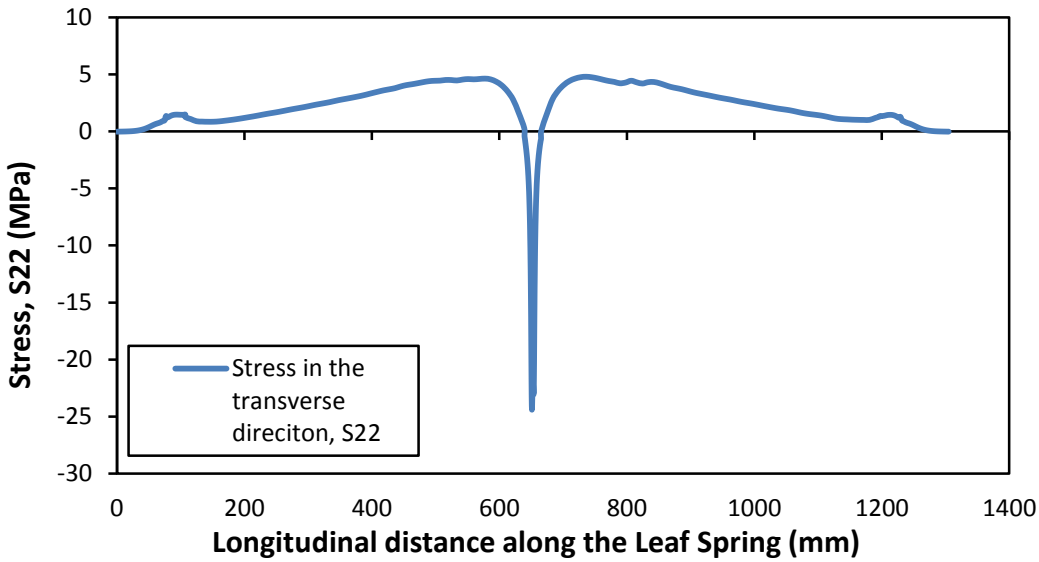


Figure 5.13. S22 stress distribution on the glass fiber/epoxy leaf spring upper surface along the longitudinal length

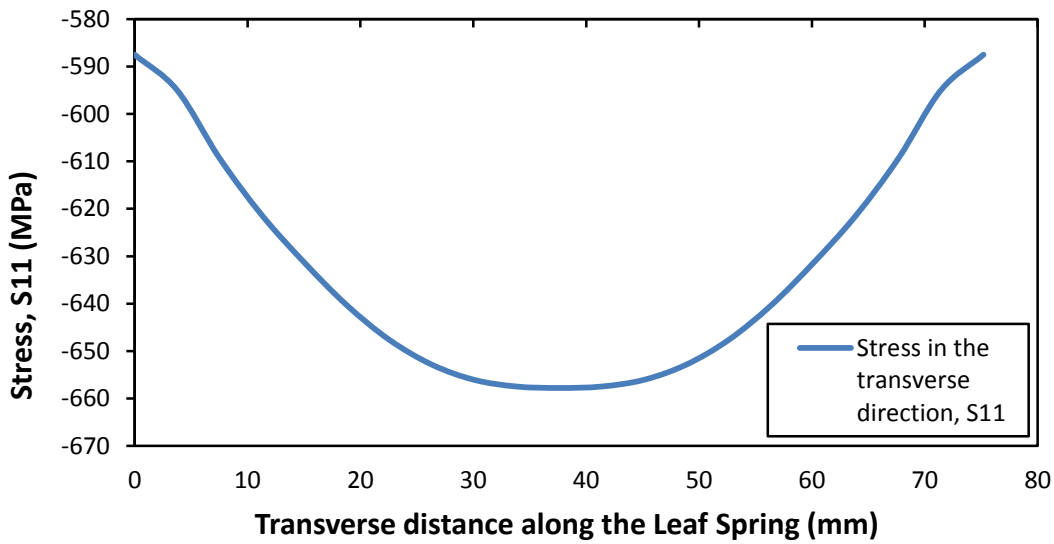


Figure 5.14. S11 stress distribution on the glass fiber/epoxy leaf spring upper surface along the transverse length

From Figure 5.14, one can note that the compressive stresses in the fiber direction increase about 10.81% from edges towards the middle along the transverse extent.

Tensile stresses are obtained on the bottom surface contrary to the upper surface, as expected. However, it is possible to see certain compressive stresses, which can be attributed to the supports, in the Figure 5.15.

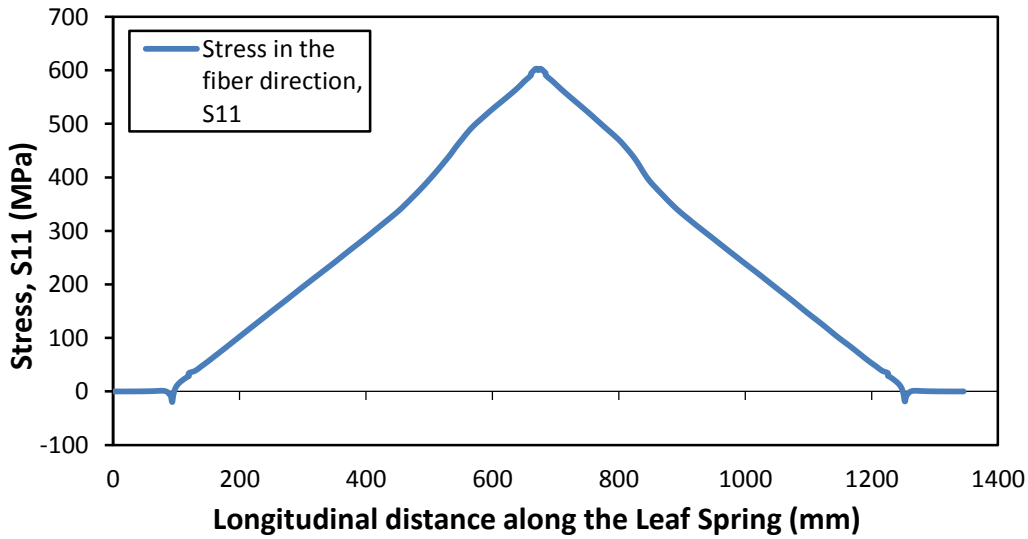


Figure 5.15. S11 stress distribution on the glass fiber/epoxy leaf spring bottom surface along the longitudinal length

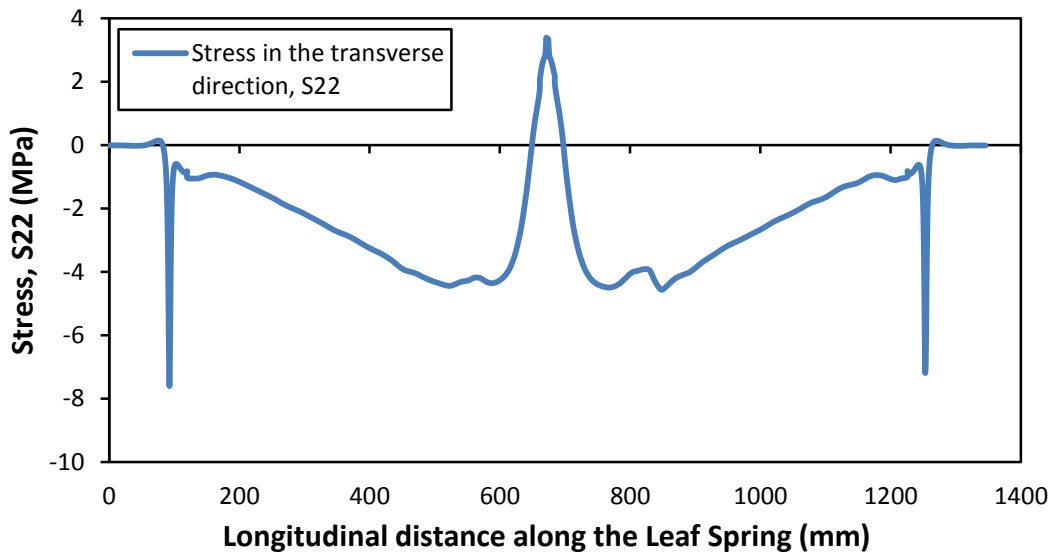


Figure 5.16. S22 stress distribution on the glass fiber/epoxy leaf spring bottom surface along the longitudinal length

As shown from the figure 5.16, the compressive stresses in the transverse direction are observed in the support regions. This trend is varied by the region corresponding to the loading point.

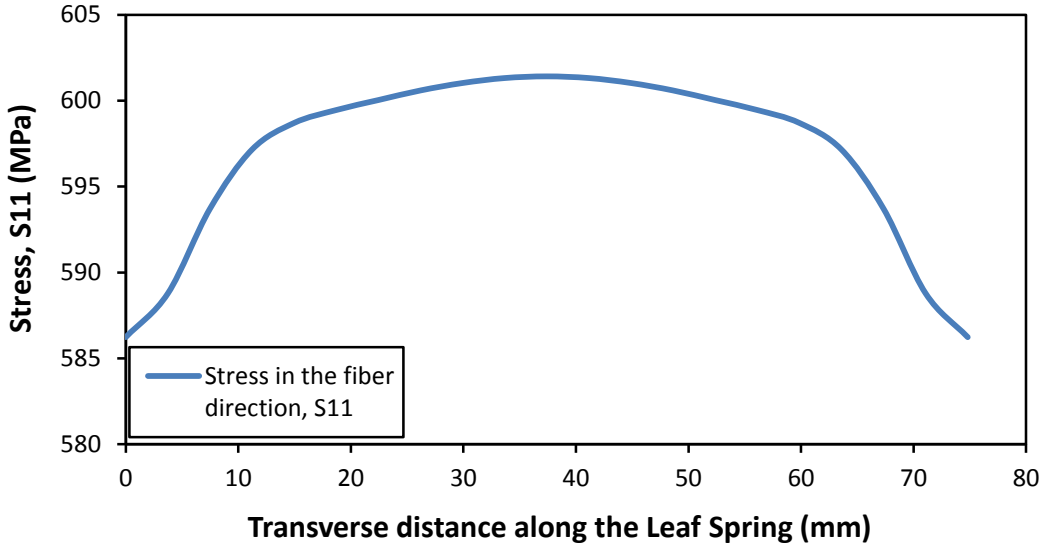


Figure 5.17. S11 stress distribution on the glass fiber/epoxy leaf spring bottom surface along the transverse length

It is worth noting that the tensile stresses in the fiber direction, on the bottom surface along the transverse extent, increase about 2.45% from edges towards the middle. From the results by comparison with the results on the upper surface, it should be noted once again that the dominating stress condition in the structure is compressive.

Mises stresses and shear stresses critical in the mid section of the structure owing to the nature of the flexural loading conditions are also summarized through Figures 5.18 to 5.22. As it can be seen from the figures that Mises stresses on the upper and lower surfaces depict a similar trend with the normal stress graphs given above.

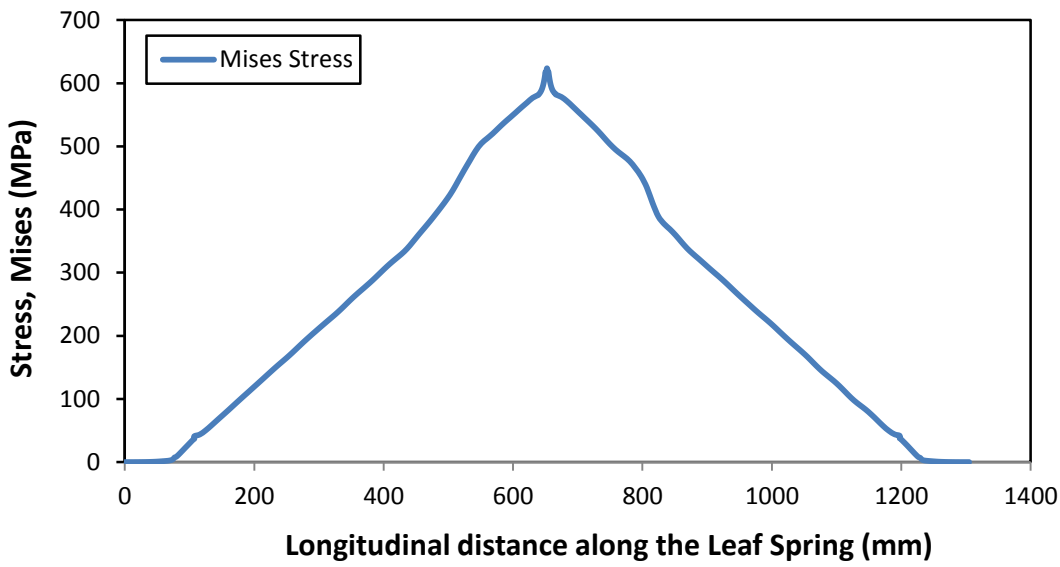


Figure 5.18. Mises stress distribution on the glass fiber/epoxy leaf spring upper surface along the longitudinal length

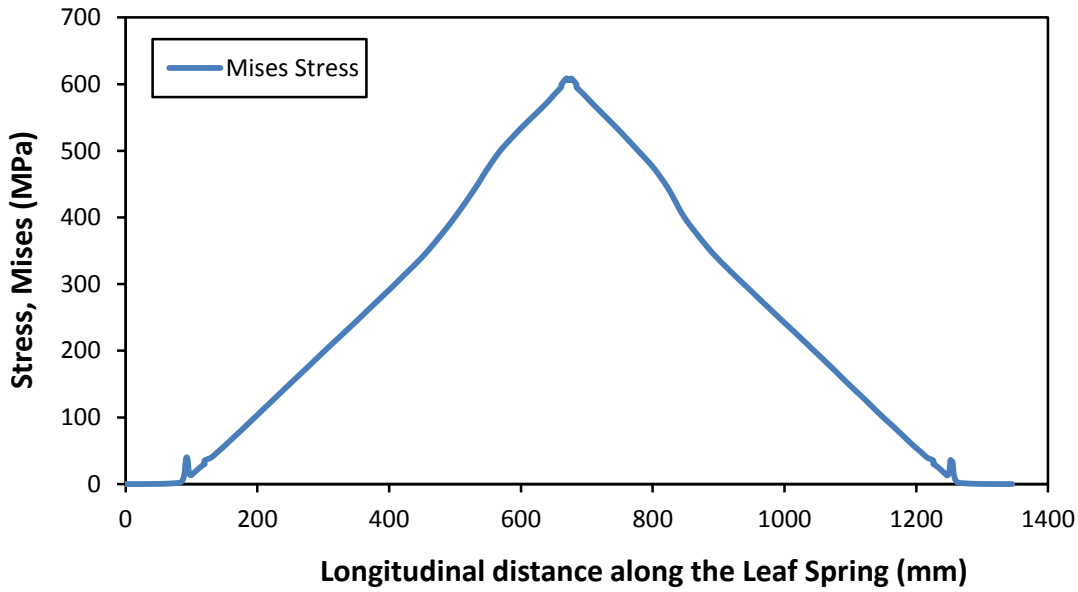


Figure 5.19. Mises stress distribution on the glass fiber/epoxy leaf spring bottom surface along the longitudinal length

Shear stress results of the designed model are also shown through Figures 5.20 to 5.22. The maximum stress values are obtained in the ply of 30, which is in the mid section of the structure, as expected. According to these figures, obtained results are safer in terms of the shear strength properties of the glass fiber/epoxy composite ply

(Soden, Hinton, and Kaddour 1998). Here, color bars are only used to demonstrate the result range on the structure.

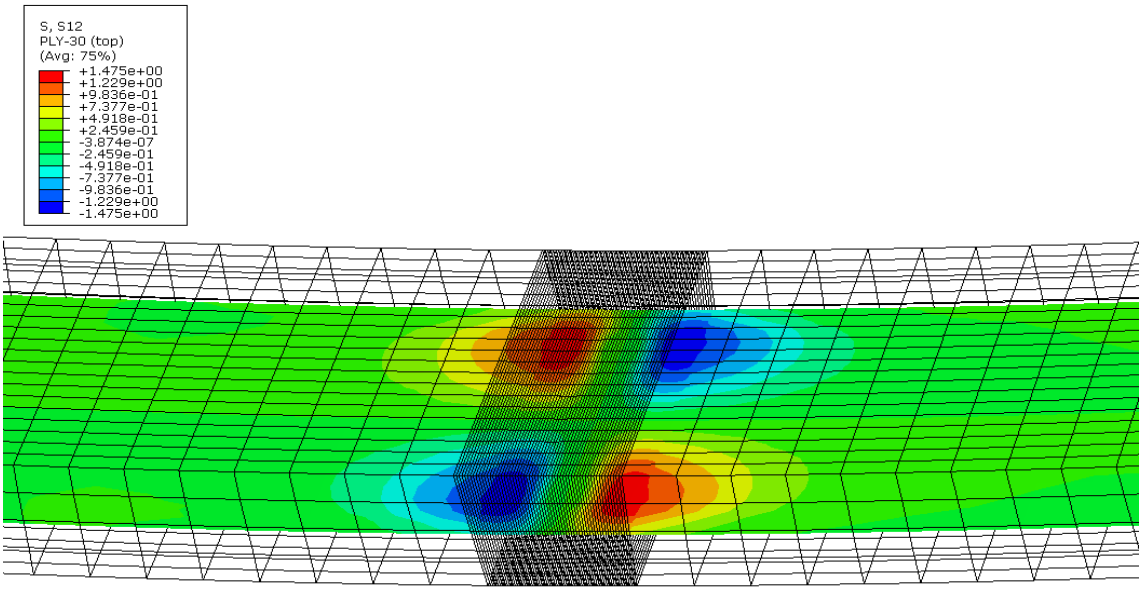


Figure 5.20. S12 In plane shear stress contour in the mid section

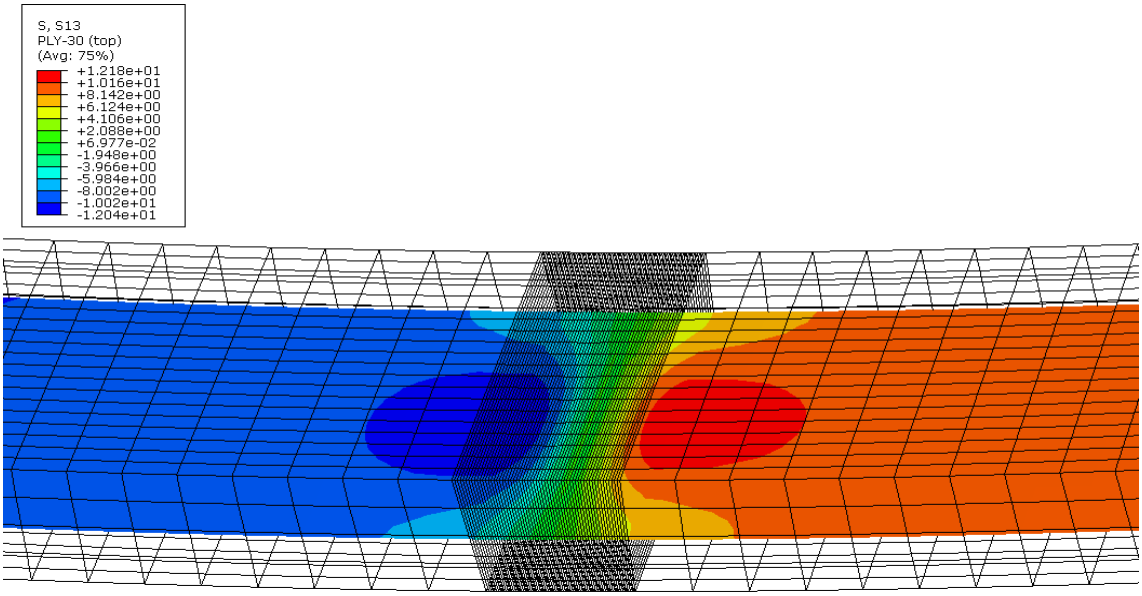


Figure 5.21. S13 Through thickness shear stress contour in the mid section

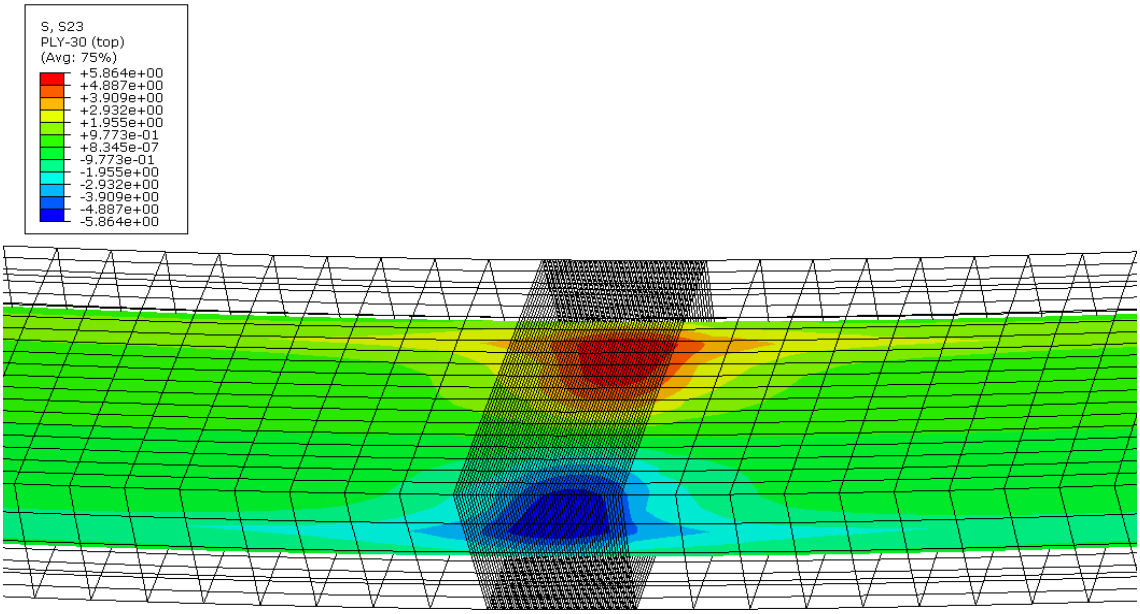


Figure 5.22. S23 Through thickness shear stress contour in the mid section

In the second design, carbon fiber/epoxy composite leaf spring model was investigated. This configuration was selected to increase the stiffness of the structure due to the mechanical property of carbon fibers. Based on the analysis results, the behavior and mechanical properties of the structure in terms of the stresses are indicated through Figures 5.23 to 5.34.

Figure 5.23 depicts the comparison between the required spring rate and the simulation results of the carbon fiber/epoxy composite leaf spring model (Design 2). As seen from the figure, displacement increases linearly as the load increases since we studied in an elastic region similarly. Based on this figure, it was observed that this configuration provides spring rate of 473.76 N/mm that is much stiffer than the required. This situation is attributed to the stiffer nature of the carbon fibers. Stress results in the critical regions are also presented for this design through Figures 5.24 to 5.34. From these figures, it can be observed that the maximum stress values are allowable again when the strength of carbon/fiber epoxy composite ply is taken into account and that the stress distributions demonstrate similar trend with design 1. On the other hand, the design does not provide the required spring rate condition. Accordingly, the material configuration was changed once and again in order to obtain proper configuration. Finally, design 3 consisting of the glass and carbon plies and providing the required spring rate was created.

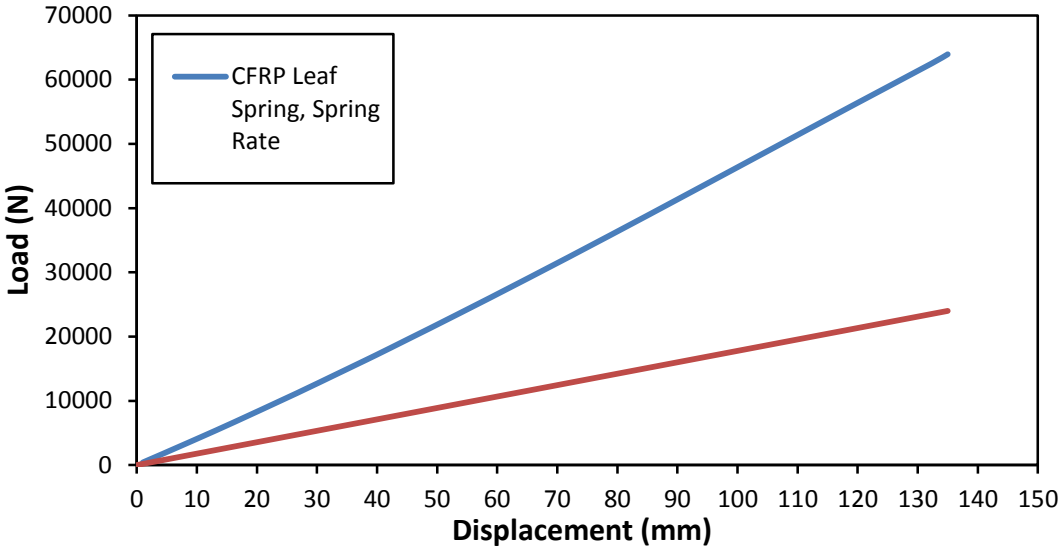


Figure 5.23. Typical load vs. deflection curve for the carbon fiber/epoxy composite leaf spring under flexural loading

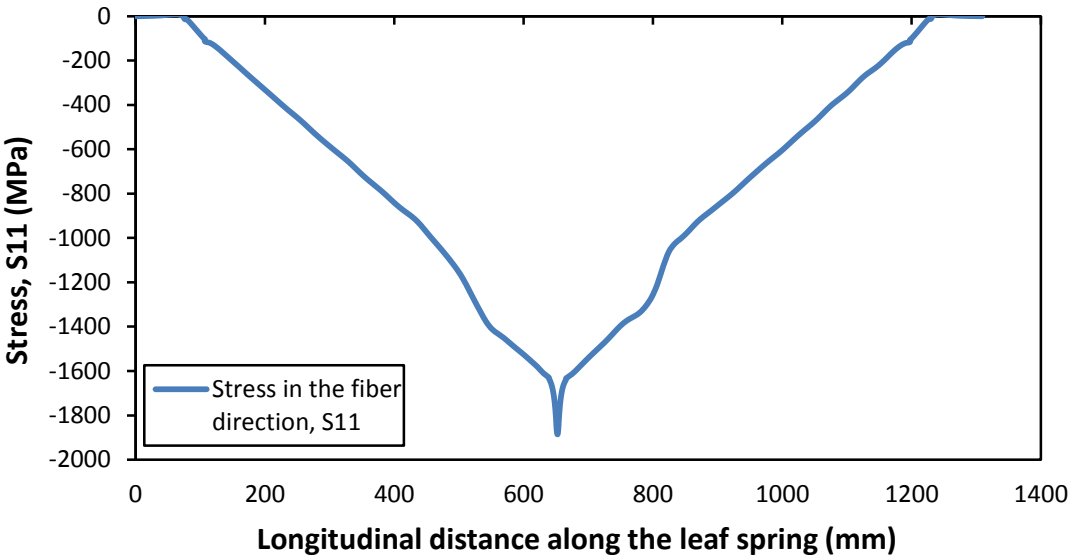


Figure 5.24. S11 stress distribution on the carbon fiber/epoxy leaf spring upper surface along the longitudinal length

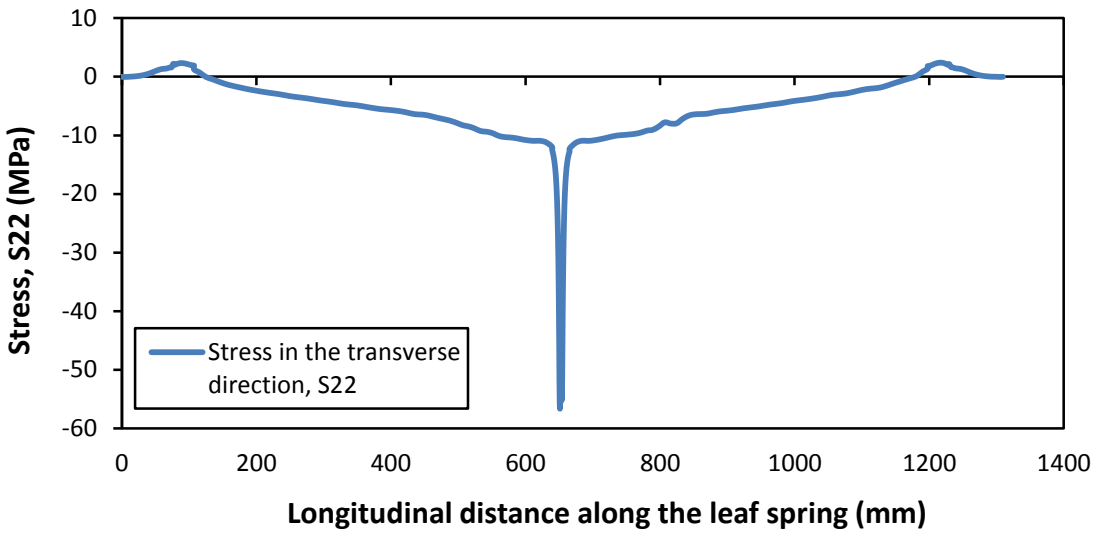


Figure 5.25. S22 stress distribution on the carbon fiber/epoxy leaf spring upper surface along the longitudinal length

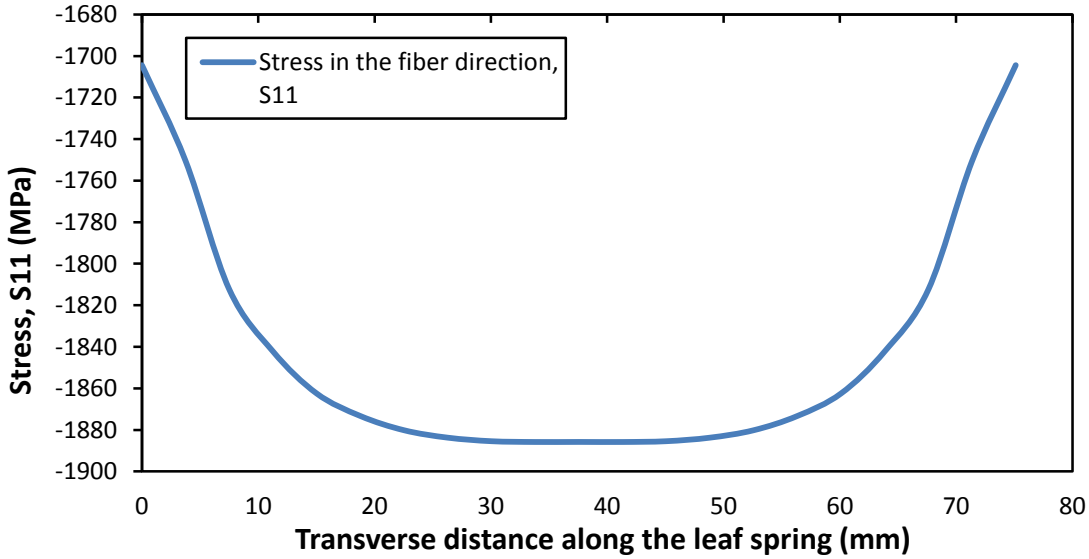


Figure 5.26. S11 stress distribution on the carbon fiber/epoxy leaf spring upper surface along the transverse length

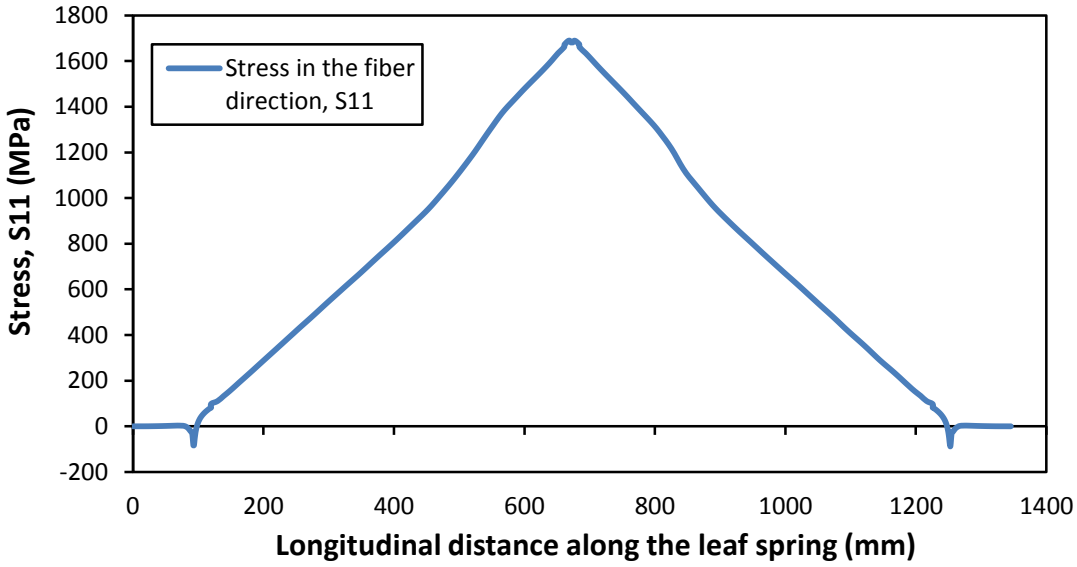


Figure 5.27. S11 stress distribution on the carbon fiber/epoxy leaf spring bottom surface along the longitudinal length

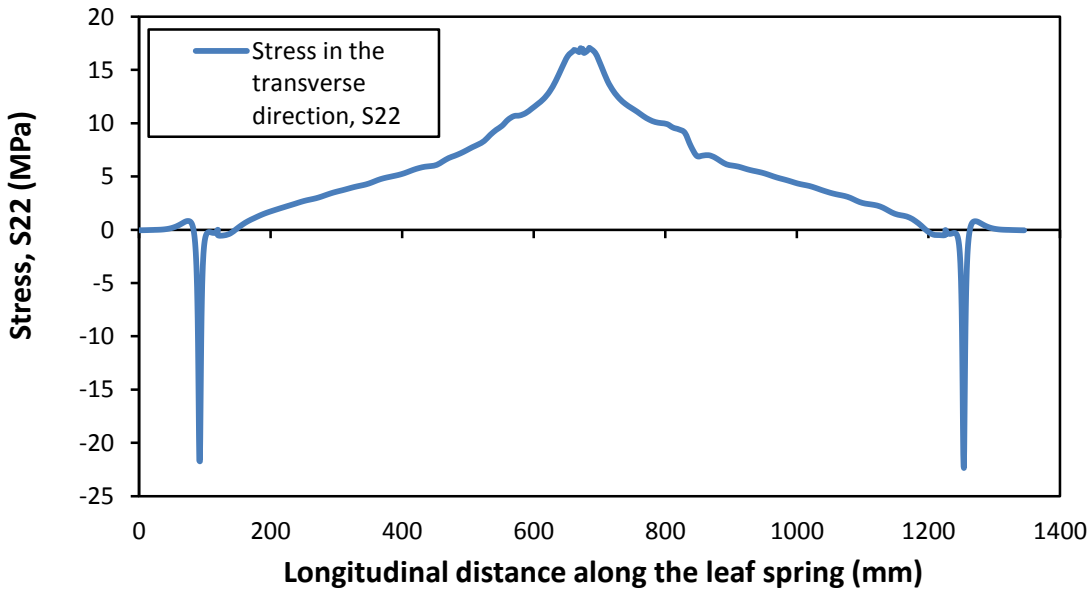


Figure 5.28. S22 stress distribution on the carbon fiber/epoxy leaf spring bottom surface along the longitudinal length

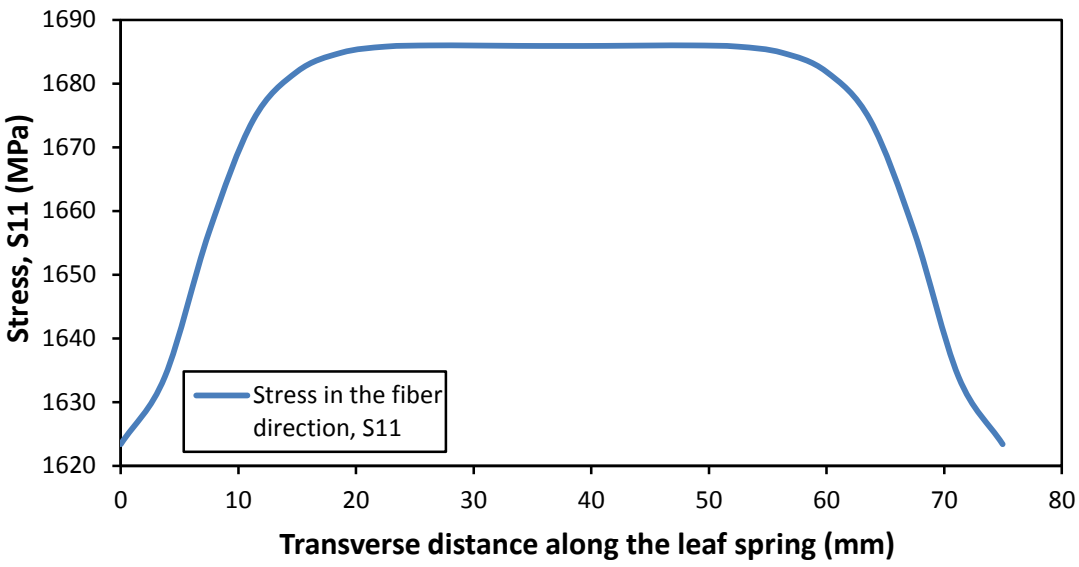


Figure 5.29. S11 stress distribution on the carbon fiber/epoxy leaf spring bottom surface along the transverse length

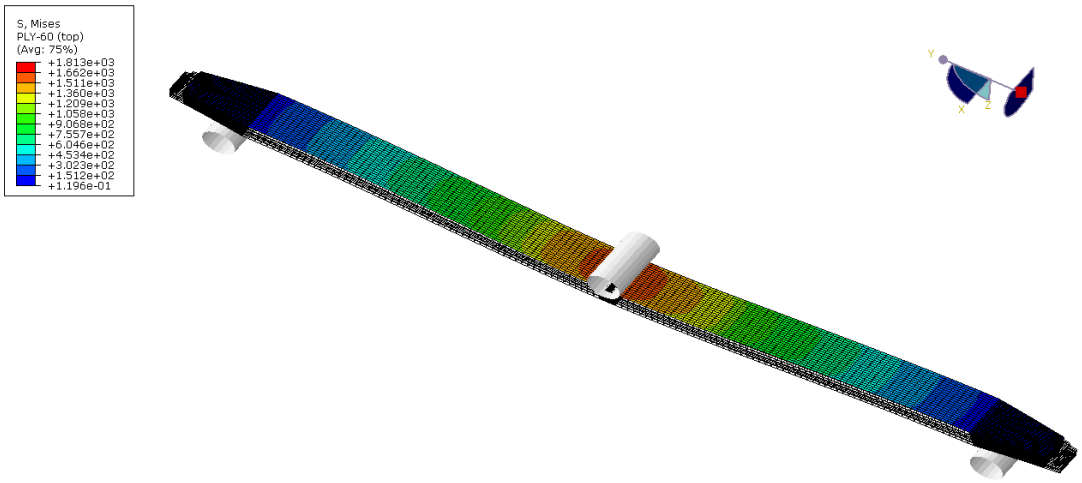


Figure 5.30. Mises equivalent stress contour on the upper surface of carbon fiber/epoxy leaf spring

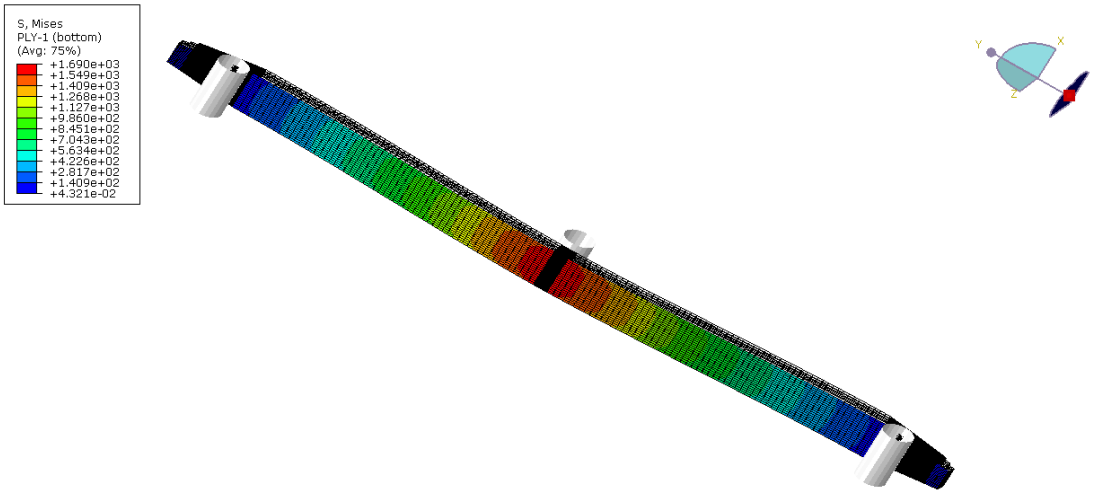


Figure 5.31. Mises equivalent stress contour on the bottom surface of carbon fiber/epoxy leaf spring

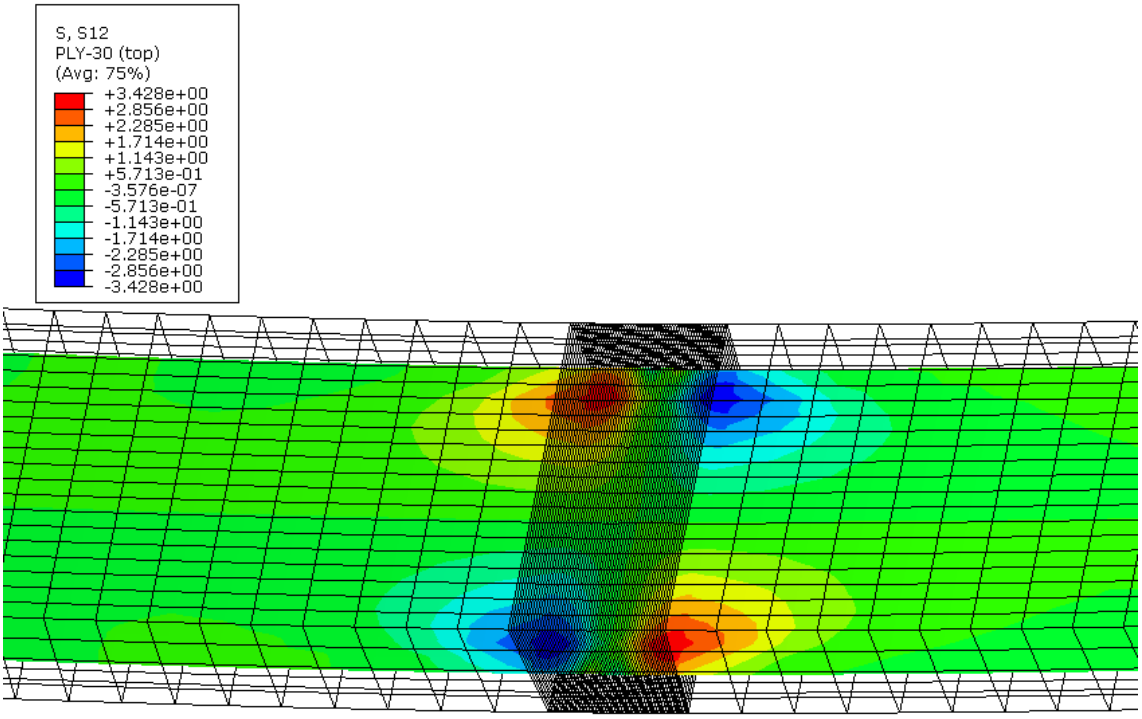


Figure 5.32. S12 In plane shear stress contour in the mid section

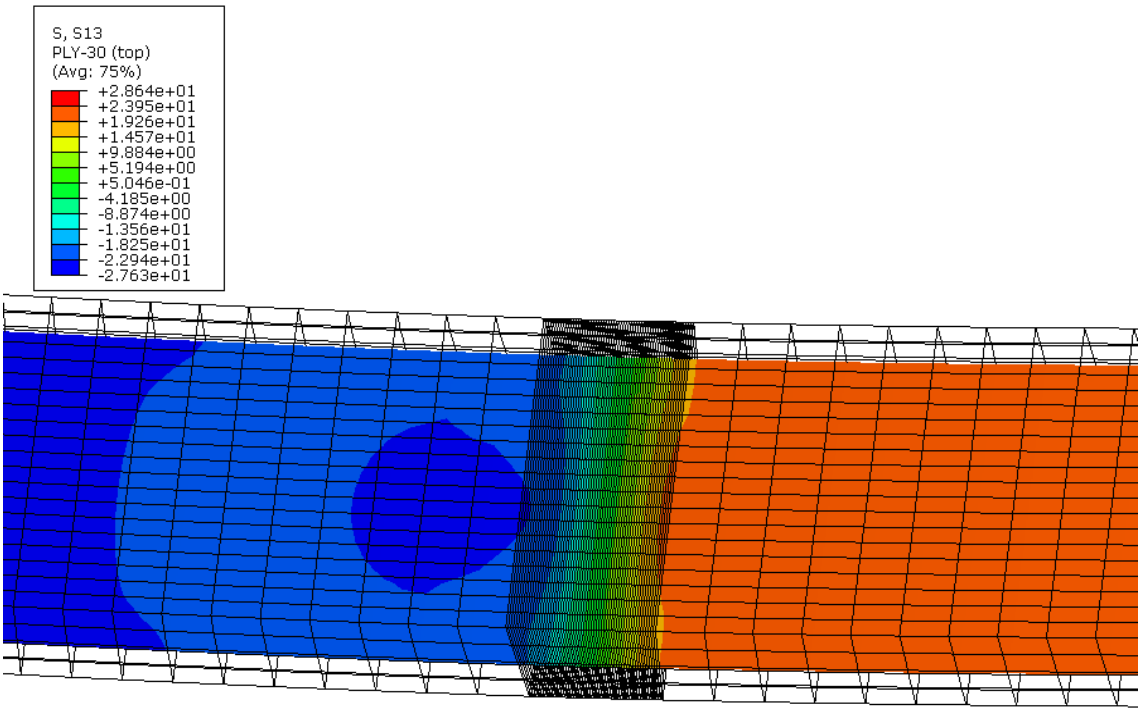


Figure 5.33. S13 Through thickness shear stress contour in the mid section

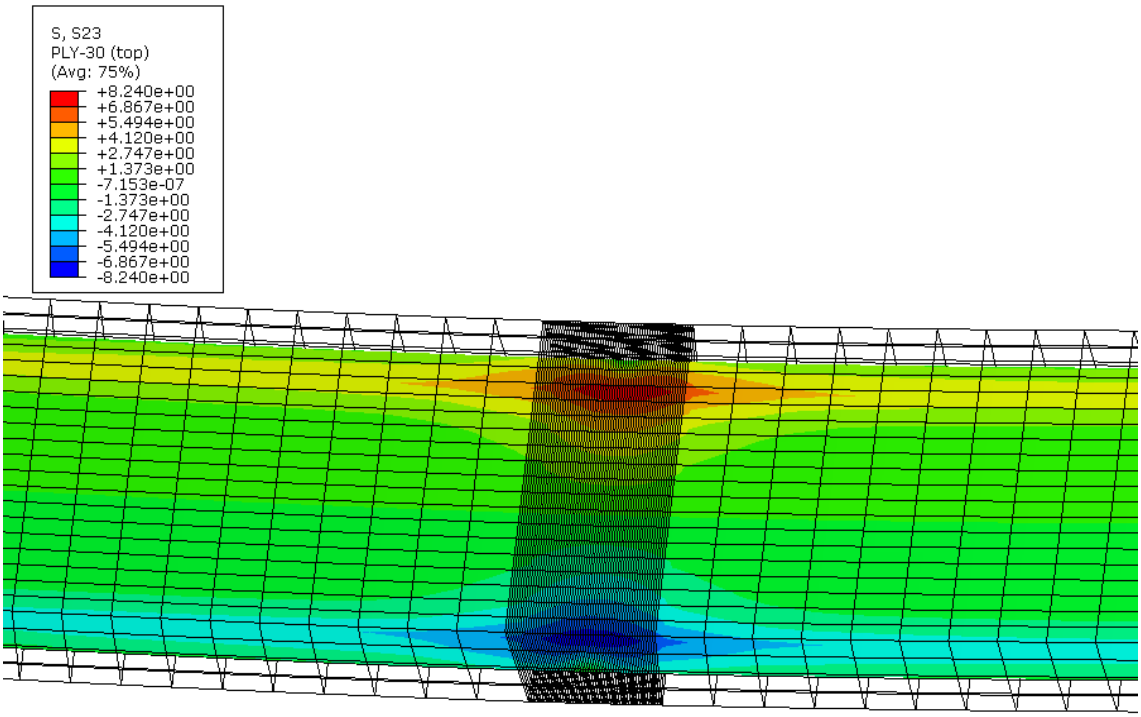


Figure 5.34. S23 Through thickness shear stress contour in the mid section

The aforementioned optimum configuration in the leaf spring was analyzed lastly and the results given below show the behavior and mechanical properties of the structure in terms of the stresses. The comparison of the load-displacement curves between Design 3 and the required can be shown in Figure 5.35. The numerical results are in agreement with the experimental results correctly with the 0.514% deviation with C3D8R elements as can be seen from the figure.

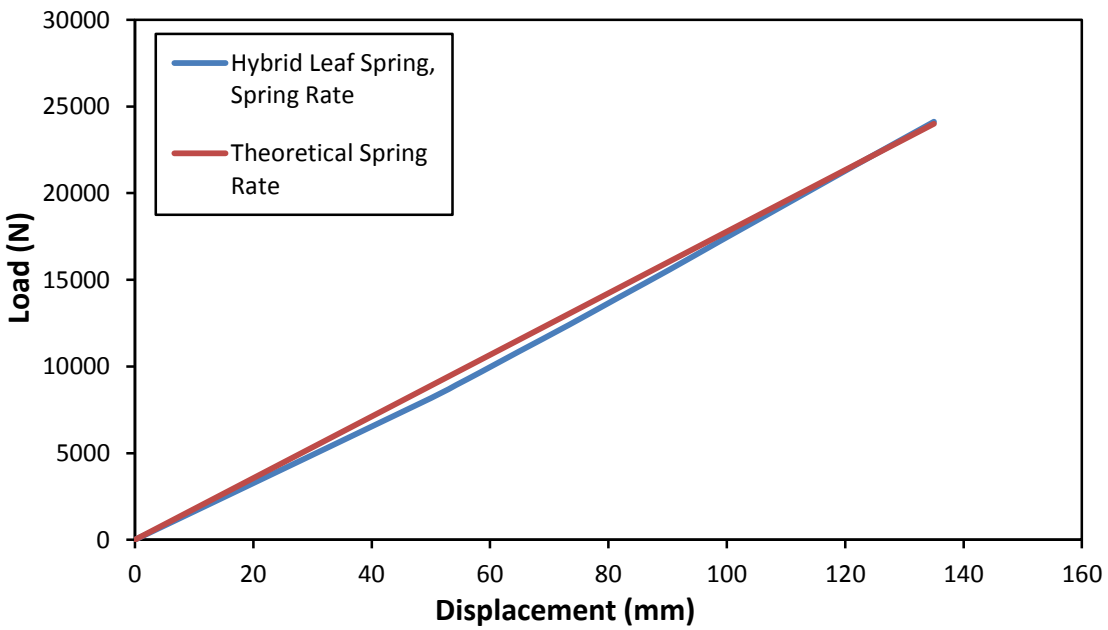


Figure 5.35. Typical load vs. deflection curve for the glass and carbon fiber/epoxy composite leaf spring under flexural loading

The normal stress values in the fiber direction show increase of 8.101 MPa on the upper surface of the structure depending the material properties of added carbon fibers as can be shown in Figure 5.36.

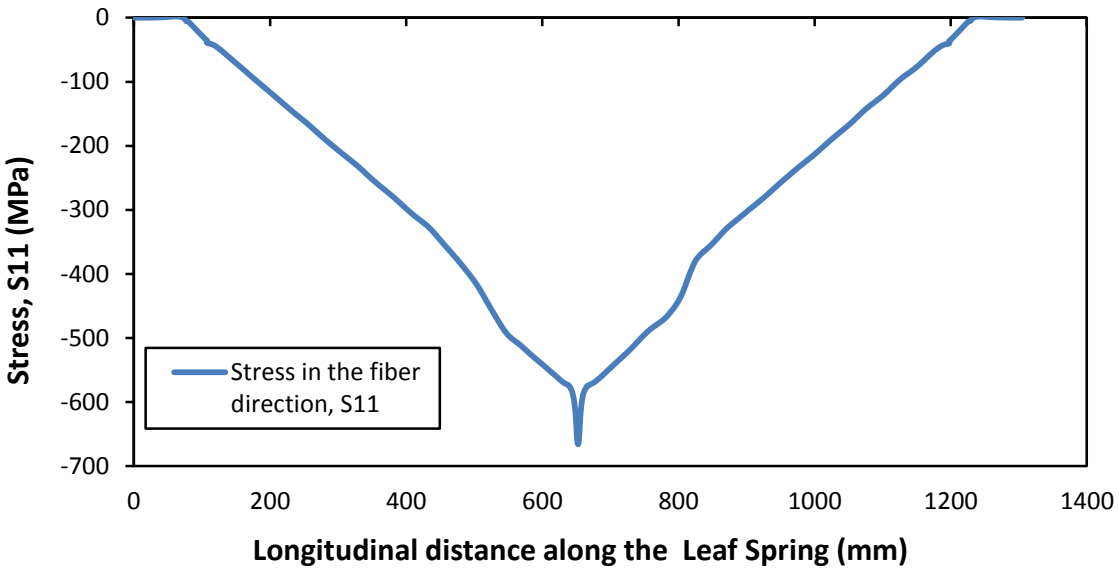


Figure 5.36. S11 stress distribution on the glass and carbon fiber/epoxy leaf spring upper surface along the longitudinal length

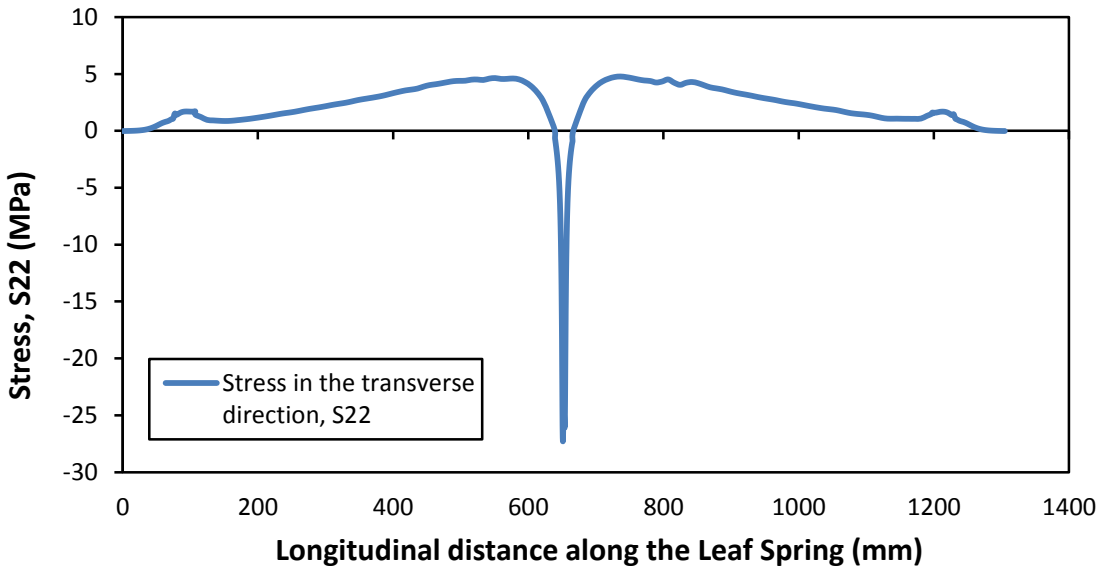


Figure 5.37. S22 stress distribution on the glass and carbon fiber/epoxy leaf spring upper surface along the longitudinal length

As indicated in Figure 5.37, maximum stress in the transverse direction is -27.29 MPa that is among the values obtained in first two designs. This behavior can be attributed again to the carbon fiber plies supplemented.

From Figure 5.38, one can note that the compressive stresses in the fiber direction along the transverse extent increase about 11.50% from edges towards the middle in the final design.

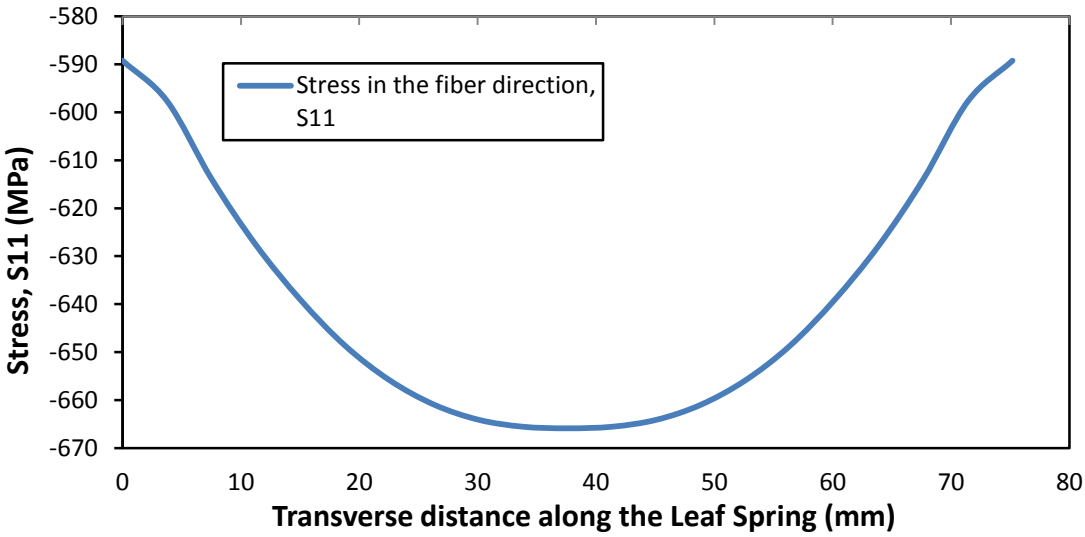


Figure 5.38. S11 stress distribution on the glass and carbon fiber/epoxy leaf spring upper surface along the transverse length

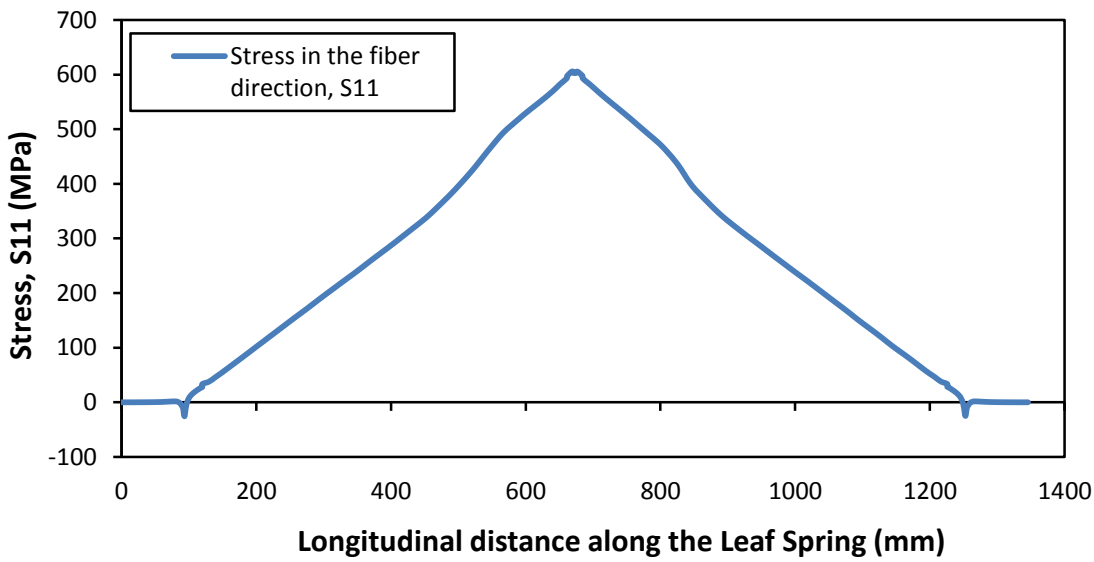


Figure 5.39. S11 stress distribution on the glass and carbon fiber/epoxy leaf spring bottom surface along the longitudinal length

Maximum tensile stress shows increase of 2.67 MPa on the bottom surface of Design 3 by comparison with Design 1.

As shown from Figure 5.40, the compressive stresses in the transverse direction are observed in the support regions similar with the other designs. In addition, maximum stress values on the support regions show increase of 20.14%. However, this trend corresponds to the increase of 1.5 MPa that is negligible and again allowable in terms of the strength properties of the plies.

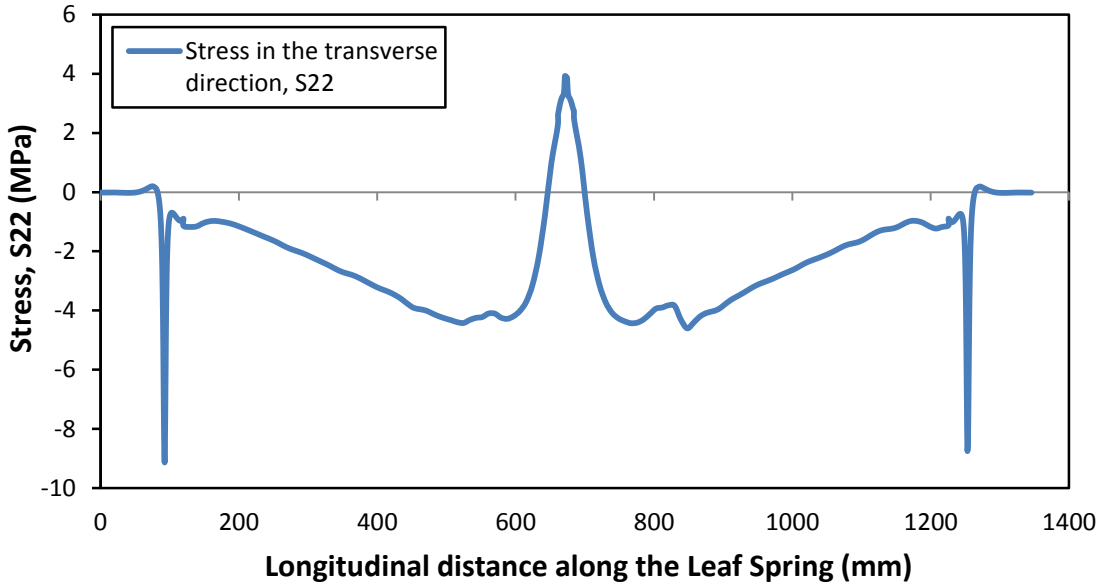


Figure 5.40. S22 stress distribution on the glass and carbon fiber/epoxy leaf spring bottom surface along the longitudinal length

It is worth noting from the Figure 5.41 that the compressive stresses in the fiber direction, on the bottom surface along the transverse extent, increase about 4.08% from edges towards the middle. This trend is safer from the point of the strength properties again.

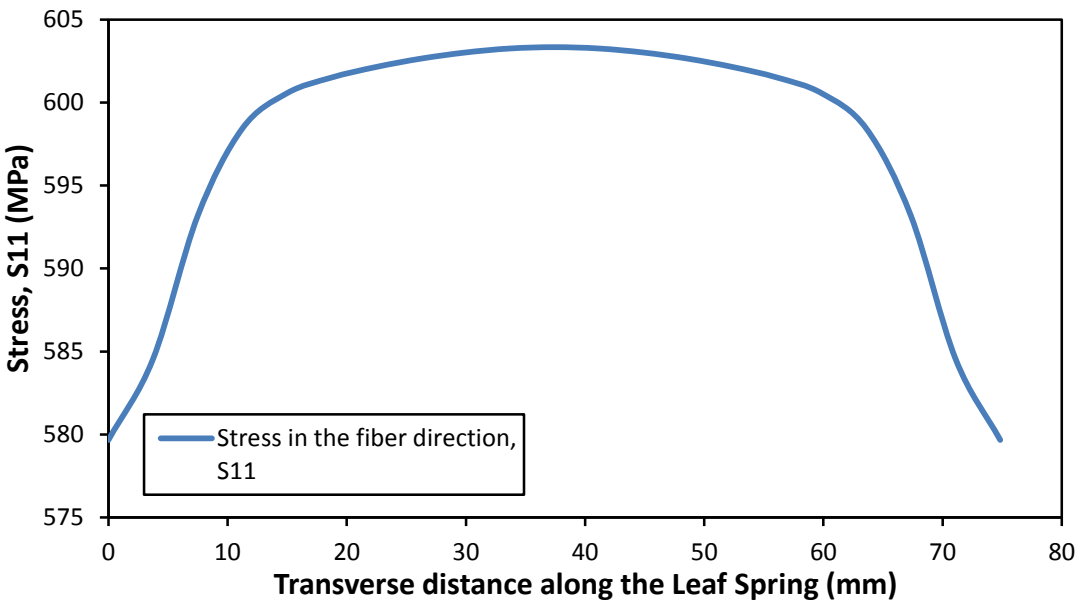


Figure 5.41. S11 stress distribution on the glass and carbon fiber/epoxy leaf spring bottom surface along the transverse length

Mises stress and shear stress contours are also summarized for the last design through Figures 5.42 to 5.46. It can be seen from those figures that Mises stresses on the upper and lower surfaces depict a similar trend with the normal stress results and that the shear stress values in the mid section of the structure are allowable. Only small increments are observed in terms of the shear stress results in comparison with Design1.

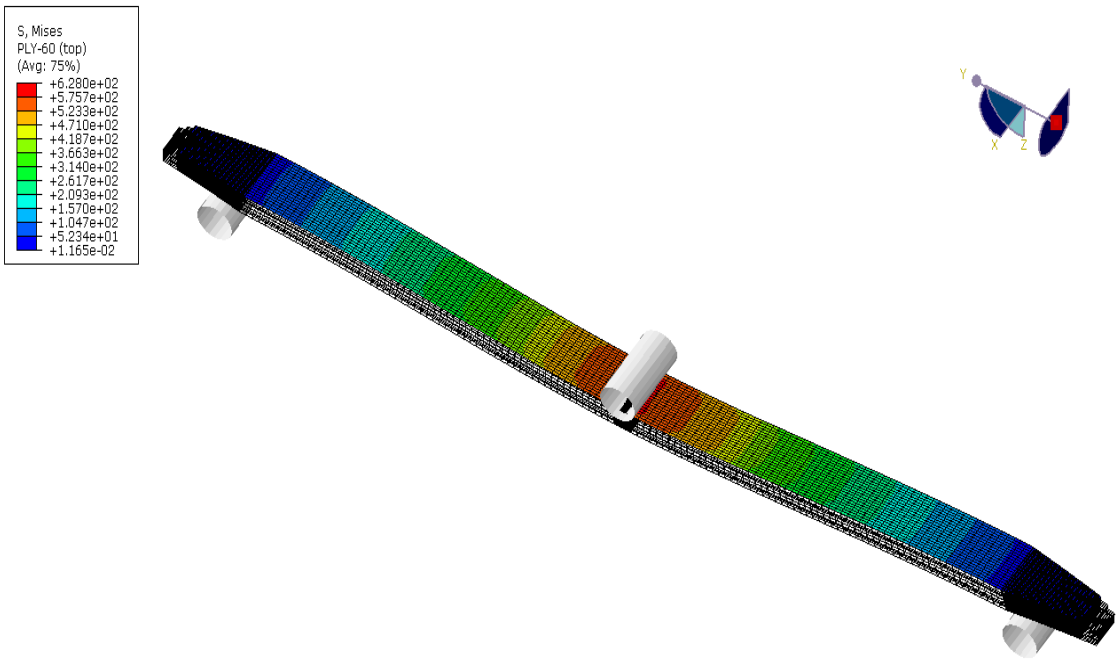


Figure 5.42. Mises equivalent stress contour on the upper surface of glass and carbon fiber/epoxy leaf spring

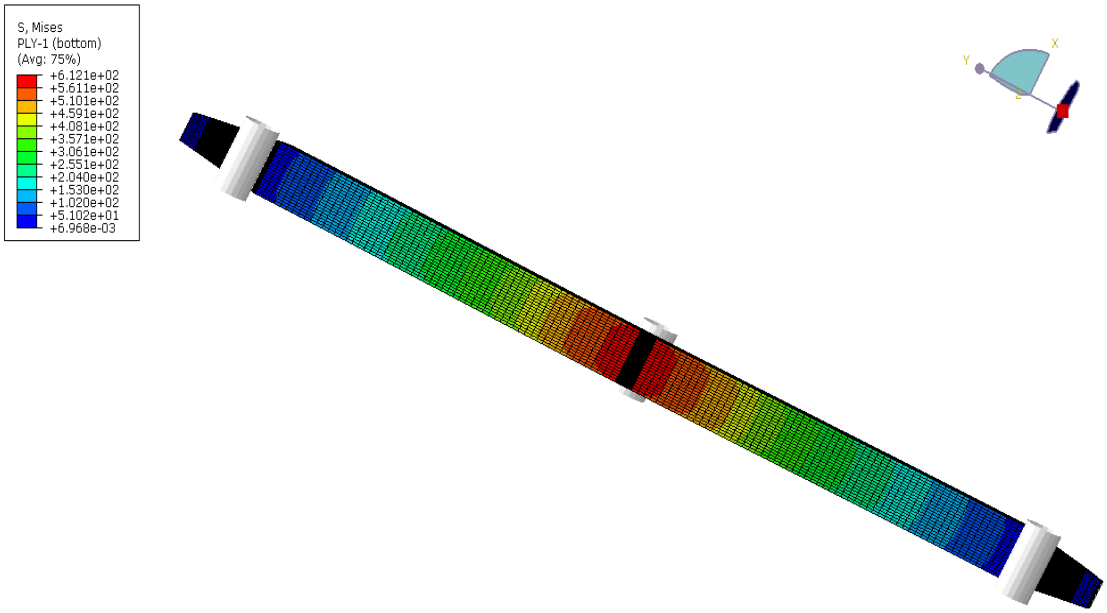


Figure 5.43. Mises equivalent stress contour on the bottom surface of glass and carbon fiber/epoxy leaf spring

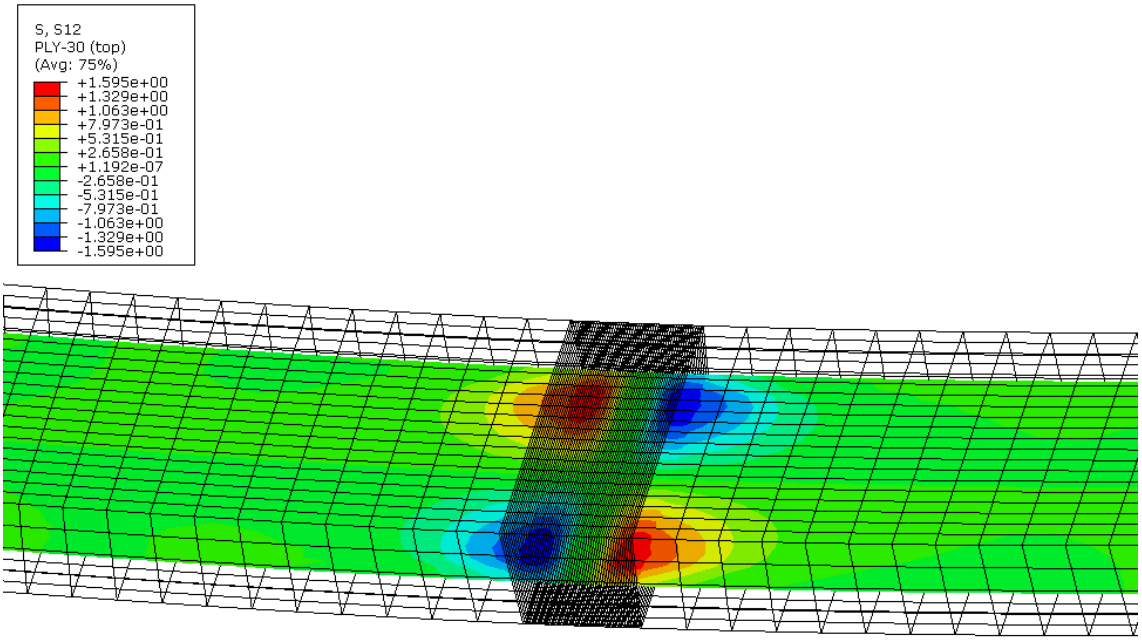


Figure 5.44. S12 In plane shear stress contour in the mid section

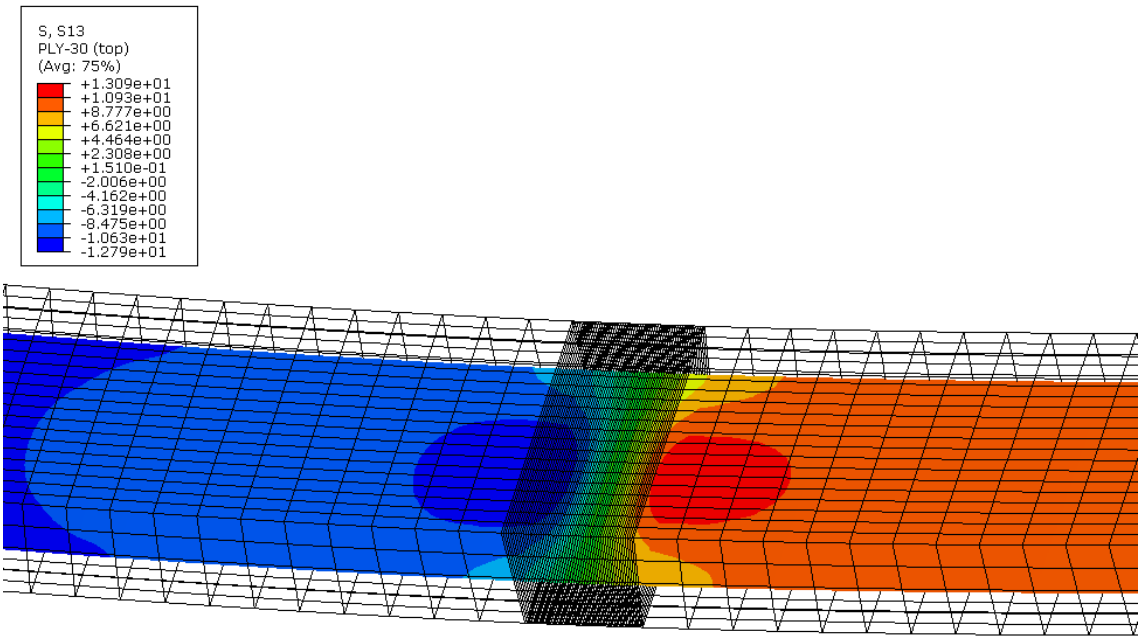


Figure 5.45. S13 Through thickness shear stress contour in the mid section

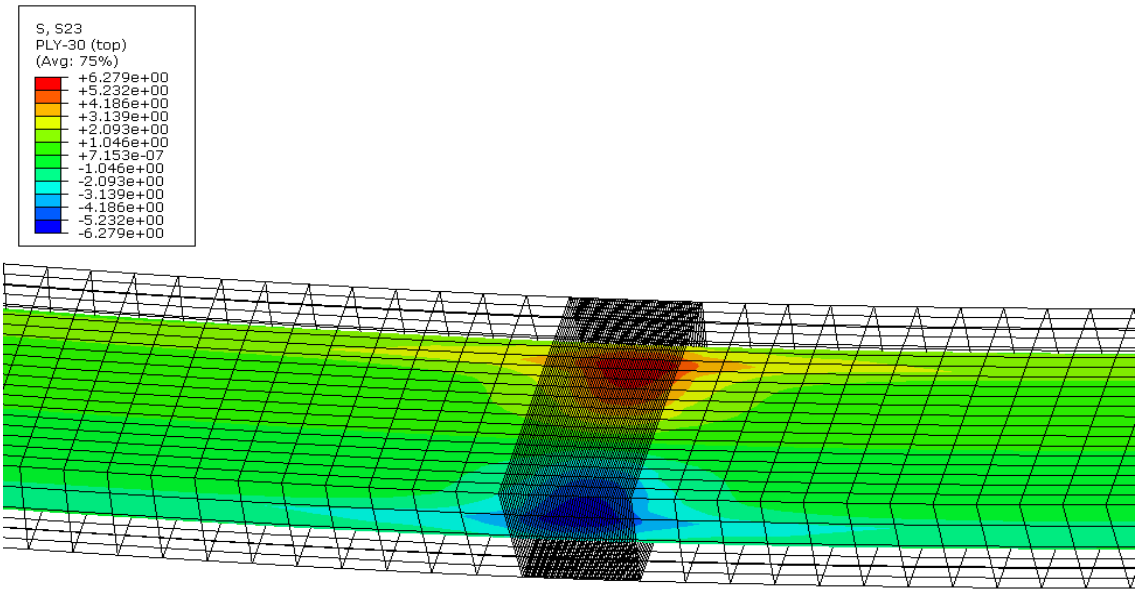


Figure 5.46. S23 Through thickness shear stress contour in the mid section

5.3. Natural Frequency Analysis of the Composite Leaf Springs

Natural vibration frequency of the leaf spring is another considerable matter in the leaf spring design. There is no doubt that to avoid the resonance, natural frequencies of the leaf spring should be larger than the possible maximum frequencies of the road irregularities. Therefore, natural vibration frequencies of the composite leaf spring were investigated and it has been demonstrated that the frequencies are greater than the maximum frequencies of the road irregularities. Moreover, first 5 mode shapes of the structure were also presented by using finite element computer program.

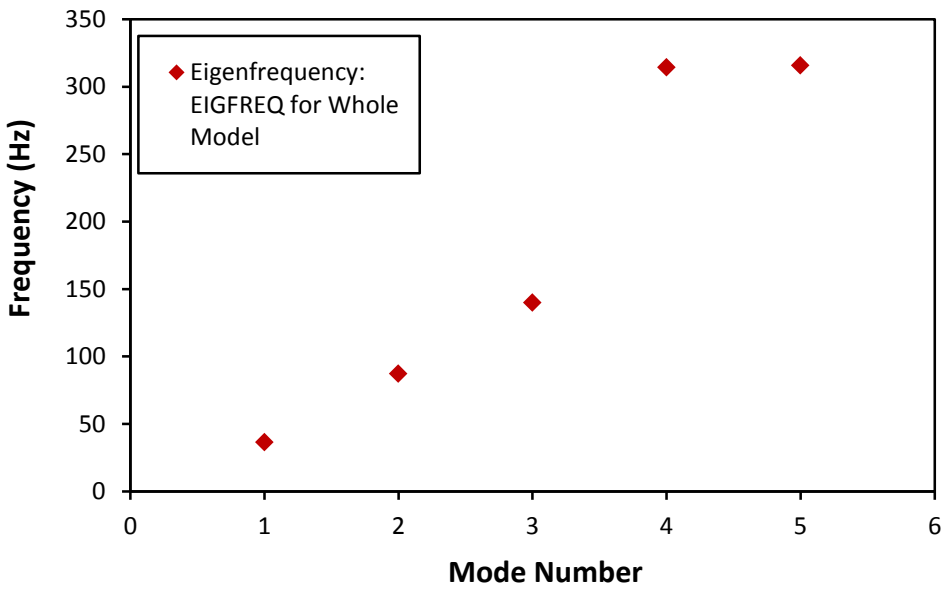


Figure 5.47. Eigenfrequencies of the glass/epoxy composite leaf spring

The E-glass/epoxy composite leaf spring was investigated in the first study. The boundary conditions to be applied were determined by taking into consideration the vehicle dynamics and the leaf spring assembly. Then, the first 5 eigenvalues and natural frequencies were determined through the frequency analysis of Abaqus. Eigenfrequencies of the structure can be shown in Figure 5.47. As can be seen in the figure, the natural frequencies are found as $Freq_1$=36.349 (cycles/time), $Freq_2$=87.123 (cycles/time), $Freq_3$=139.94 (cycles/time), $Freq_4$=314.18 (cycles/time), $Freq_5$=315.75 (cycles/time) respectively. These natural frequencies are separately important in vibrations as the structure may fail whether any of them coincide with the applied oscillating load. So, the frequency analysis should be studied carefully especially for the fundamental frequency known as the lowest natural frequency of the system (Vinson 2005). It is apparent from the aforementioned results that the fundamental frequency of the E-glass/epoxy composite leaf spring system is 36.35 Hz which is greater than the natural frequency of the normally road irregularities when the maximum frequency of any road is considered as approximately 12 Hz (Shokrieh and Rezaei 2003; Mithari, Patil, and Aitavade 2012). In addition, the eigenvalues of the structure for the first 5 mode shapes were determined and these are given in Figure 5.48.

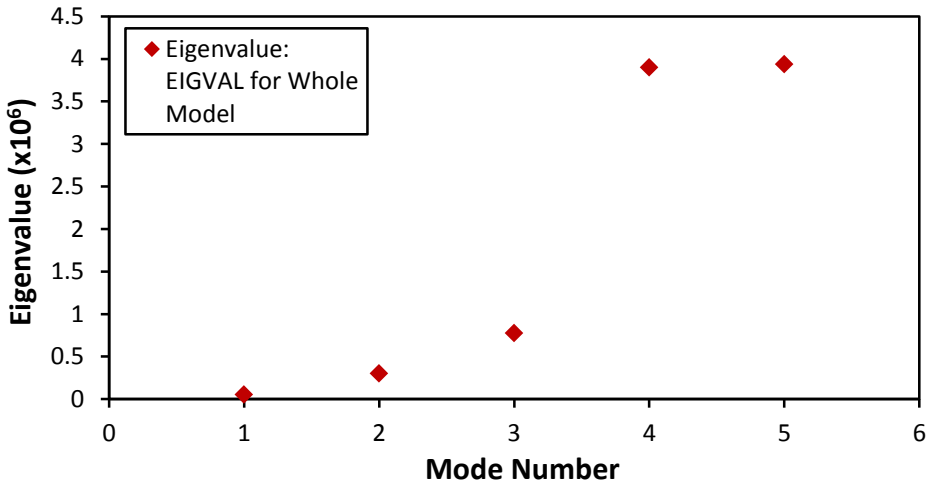
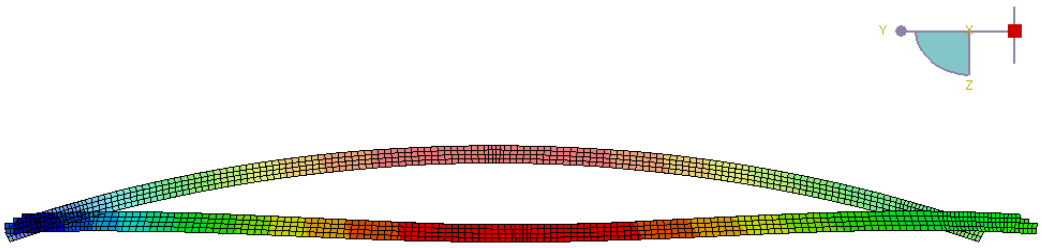


Figure 5.48. Eigenvalues of the glass/epoxy composite leaf spring

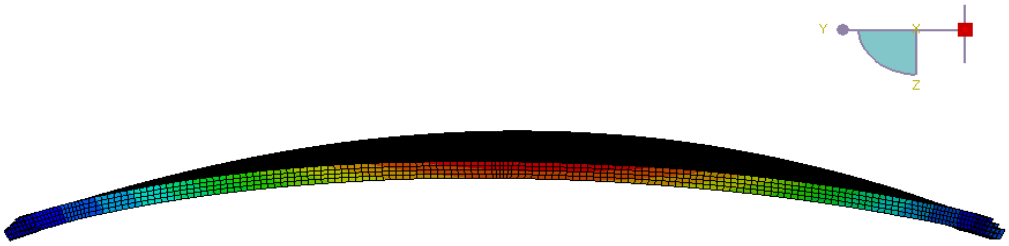
As a part of the analysis, the first 5 mode shapes of the structure were also determined by using Abaqus animation capability. Determining the mode shapes of any structure is considerable important for designers since they give the treatment of the system in free vibration. The first 5 mode shapes of the composite leaf spring are shown with deformation scale factor of 131.7 on deformed shapes with the undeformed shape of the spring represented faintly in Figure 5.49.



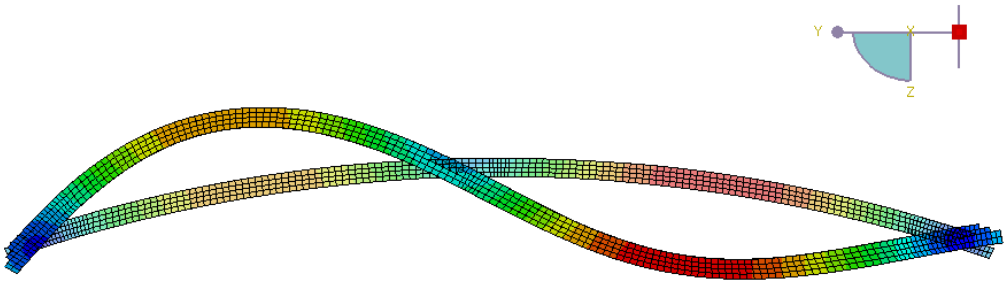
(a)

Figure 5.49. The first 5 mode shapes of the E-glass/epoxy composite leaf spring: (a) Mode 1, (b) Mode 2, (c) Mode 3, Mode 4, (e) Mode 5

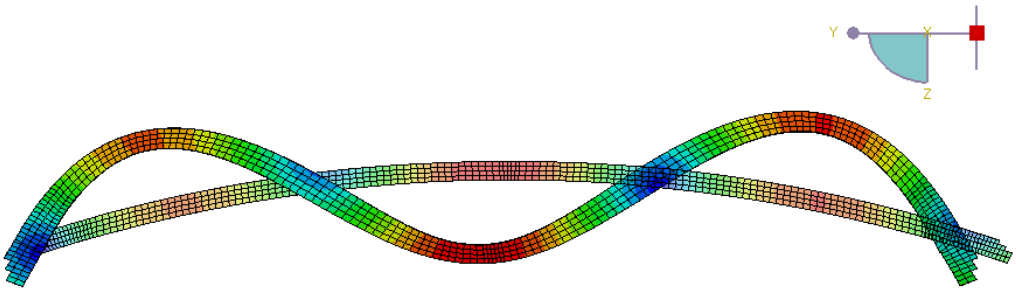
(cont. on next page)



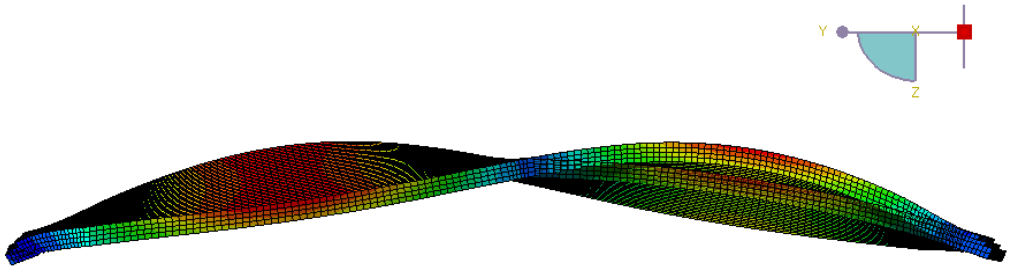
(b)



(c)



(d)



(e)

Figure 5.49. (Cont.)

In the second analysis, material configuration was changed and carbon/epoxy composite model was created. The boundary conditions applied were not changed. The first 5 natural frequencies and eigenvalues of the structure were determined similarly. Figure 5.50 and Figure 5.51 show the eigenfrequencies and eigenvalues of the second design respectively. The first 5 mode shapes of the structure were also determined by using Abaqus and can be shown in Figure 5.52. It is obvious from the results that the mode shapes of the second model are different from Design 1. This can be attributed to the mechanical property change of the structure.

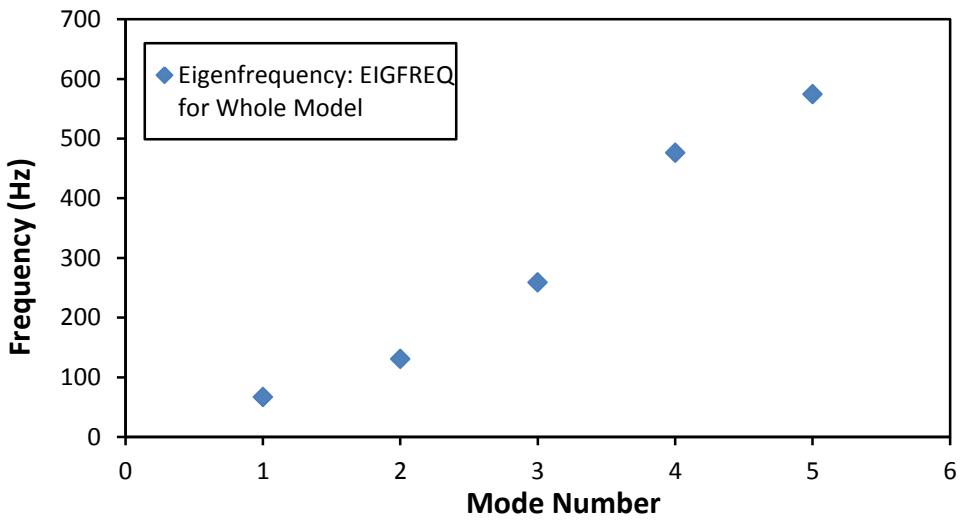


Figure 5.50. Eigenfrequencies of the carbon/epoxy composite leaf spring

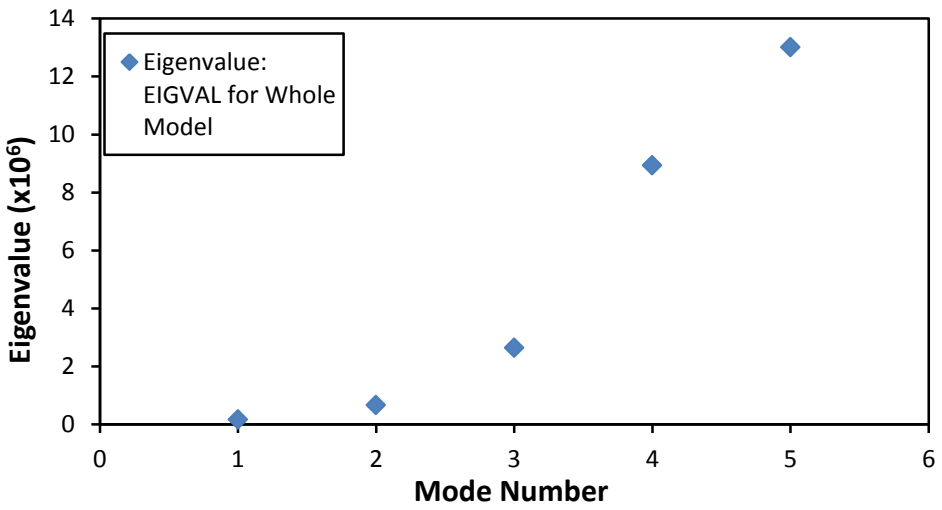
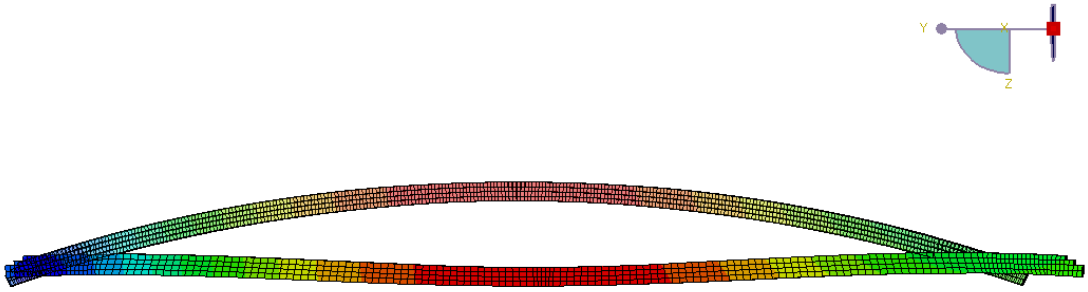
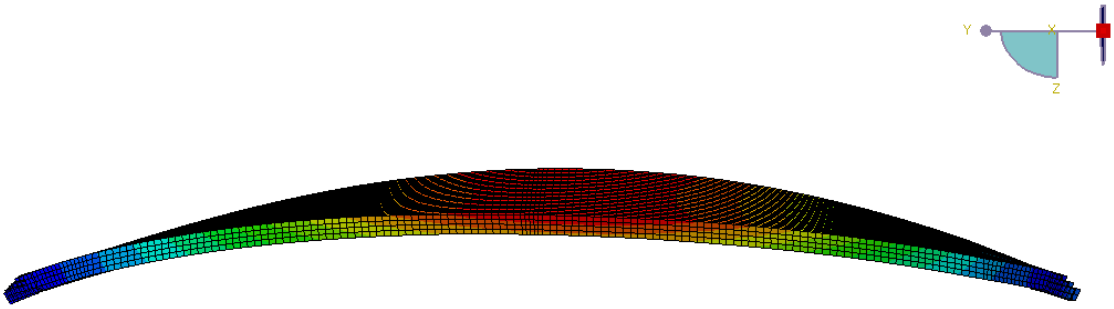


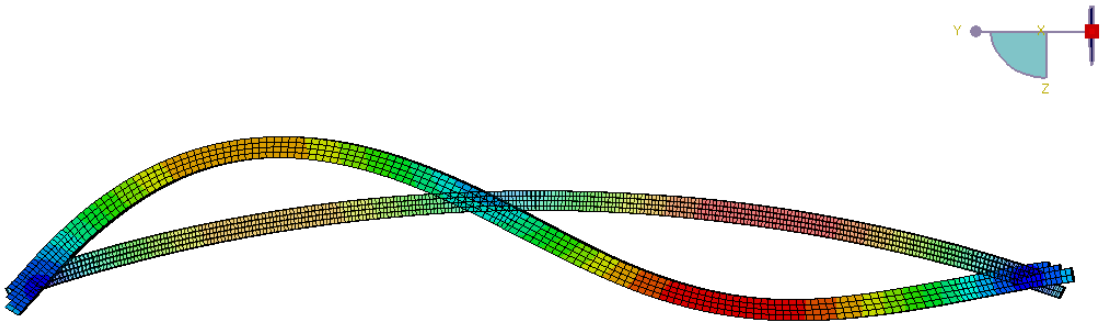
Figure 5.51. Eigenvalues of the carbon/epoxy composite leaf spring



(a)



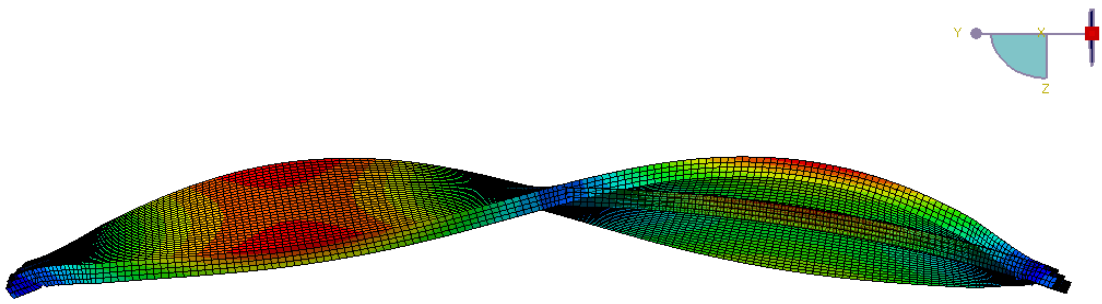
(b)



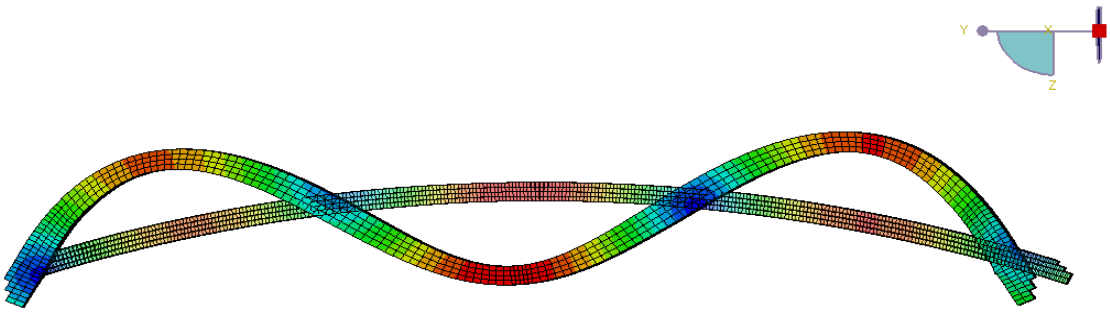
(c)

Figure 5.52. The first 5 mode shapes of the carbon/epoxy composite leaf spring: (a) Mode 1, (b) Mode 2, (c) Mode 3, (d) Mode 4, (e) Mode 5

(cont. on next page)



(d)



(e)

Figure 5.52. (Cont.)

In the last analysis, material configuration was changed once again and Design 3 was analyzed. Figure 5.53 and Figure 5.54 show the eigenfrequencies and eigenvalues of the final design respectively. The first 5 mode shapes of the final configuration were not changed by comparison with Design 1 since the mechanical properties and the BCs of the structure aren't changed excessively.

Figure 5.55 shows the comparison between the three alternative designs with the frequency analysis results. From the comparison between Design 1 and 3, approximately similar results were observed. However, it should be noticed that the carbon/epoxy configuration have greater natural frequencies for each mode shapes as the carbon fibers have higher stiffness than the glass fibers, and this increases the total stiffness characteristics of the system. It is also clear from the results that the first natural frequencies of the designs are approximately four times the frequency of road irregularities.

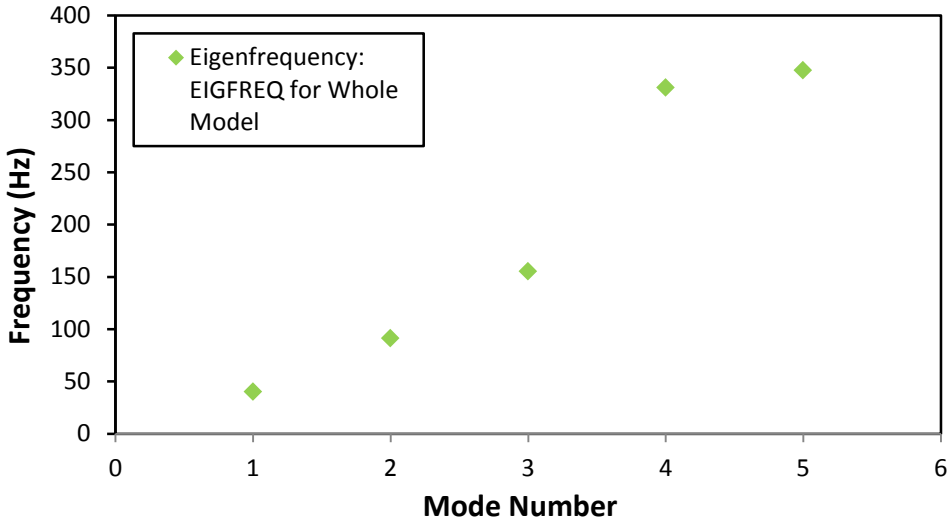


Figure 5.53. Eigenfrequencies of the glass and carbon/epoxy composite leaf spring

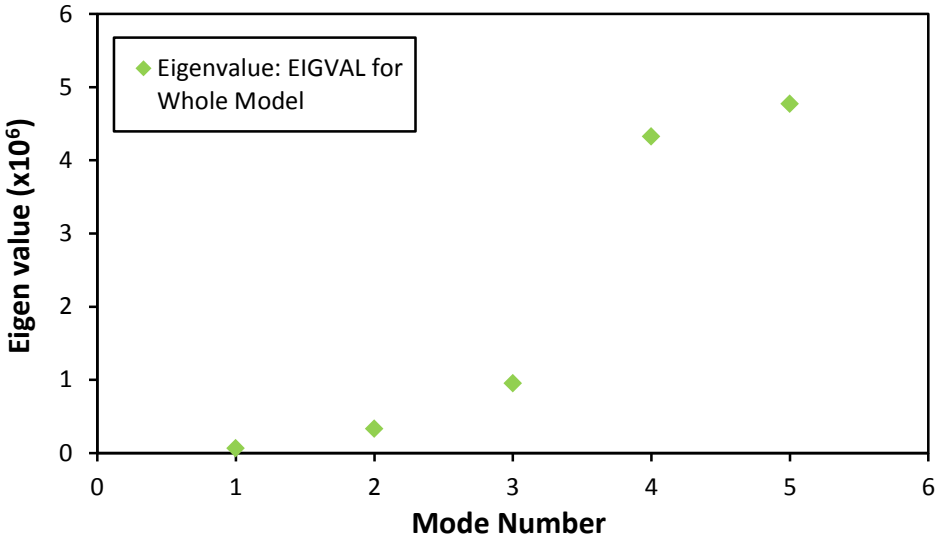


Figure 5.54. Eigenvalues of the glass and carbon/epoxy composite leaf spring

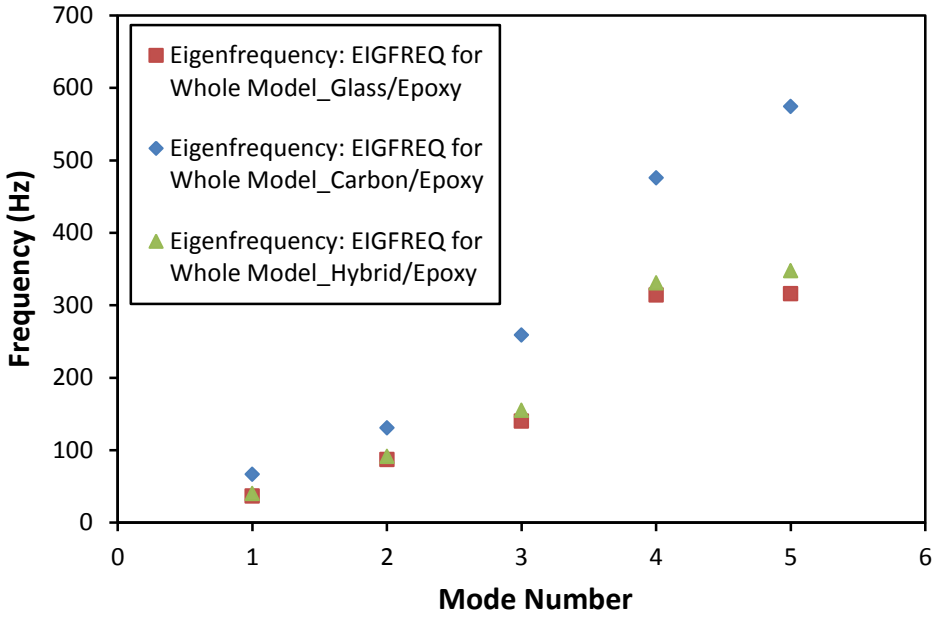


Figure 5.55. Natural frequency comparisons of the designed models

5.4. Behavior of Composite Leaf Spring Prototypes Manufactured

Three different composite-based mono leaf springs including diversified material configurations were fabricated within the thesis study. Composite-based mono leaf springs fabricated are listed in Table 5.3.

Prototype 1 contains 60 plies of E-glass/epoxy with 0° orientation similar with Design 1.

Prototype 2 includes glass and carbon / epoxy plies and represents the optimum configuration in the optimum composite structure similar with Design 3.

Prototype 3 is created by using glass and hybrid/epoxy plies similar with the stacking sequence of Design 3.

Table 5.3. Configurations of the composite-based leaf spring systems fabricated*

Prototype #	# Plies	Fiber Material	Orientation
1	60	Glass	$[0°]_{60}$
2	60	Glass and Carbon	$[0°_{6G}/0°_{2C}/0°_{22G}]_S$
3	60	Glass and Hybrid	$[0°_{6G}/0°_{2H}/0°_{22G}]_S$

*G= glass, C= carbon, H= [+45/-45] biaxial glass-carbon hybrid

The aforementioned prototypes were manufactured in a designed mould by using vacuum-assisted RTM technique. Setup of the manufactured composite-based mono leaf spring is shown in Figure 5.56 and the photos of those spring prototypes can be seen in Figure 5.57.

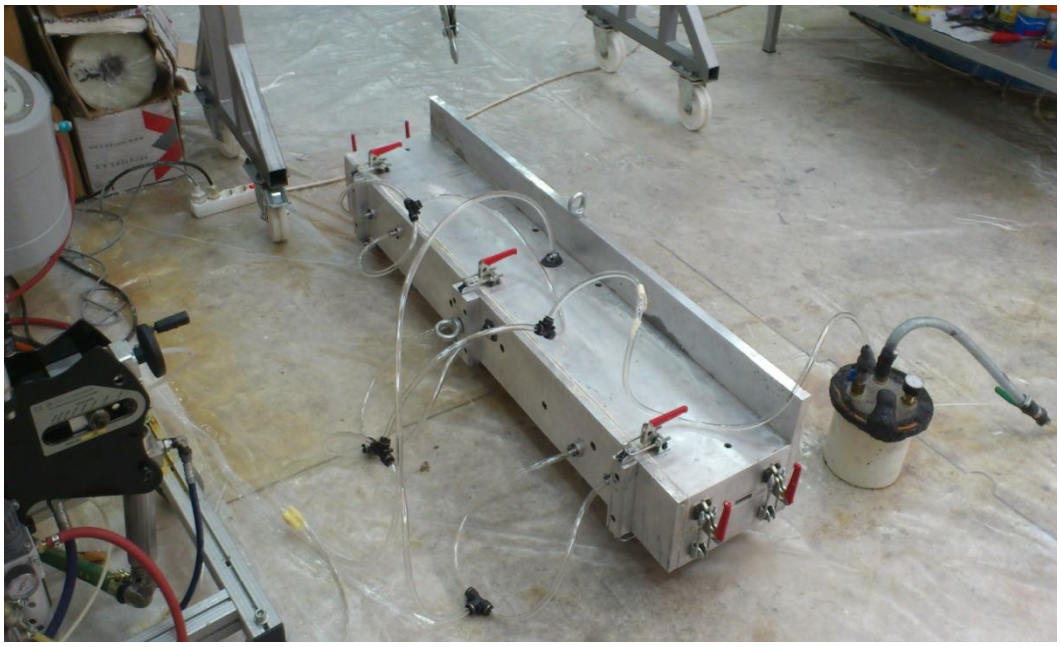


Figure 5.56. Manufacturing setup for the composite-based mono leaf spring

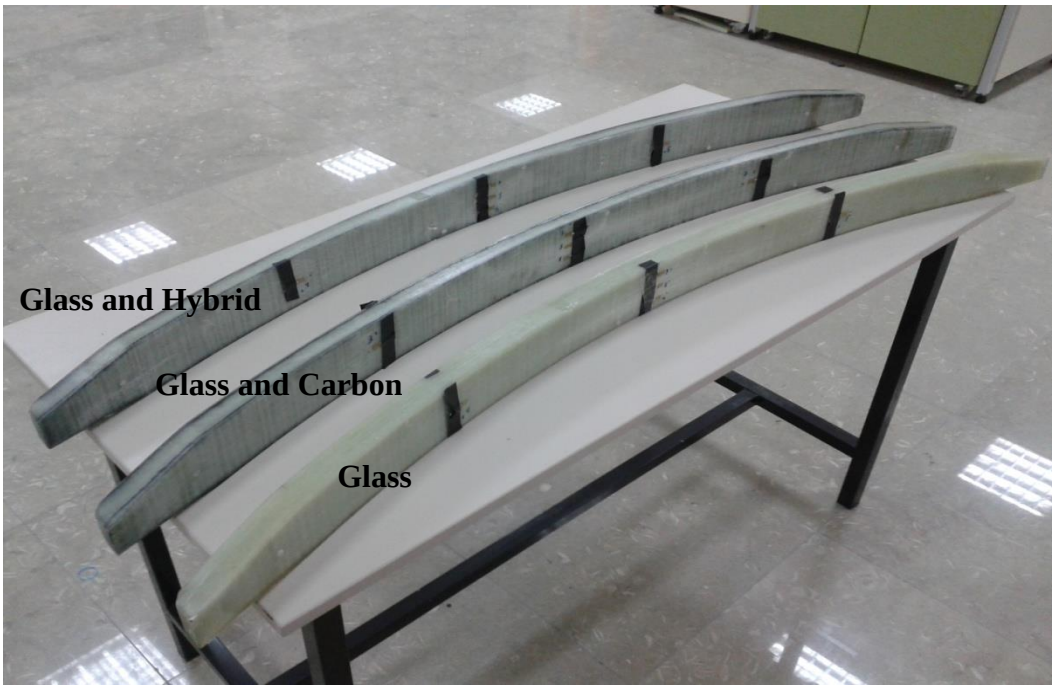


Figure 5.57. Photographs of the manufactured prototypes

Manufactured prototypes were also tested by using leaf spring test rig for determining the behavior of the prototypes experimentally. Figures 5.58 to 5.60 show the comparison between the numerical simulation and experimental test results in terms of the load-displacement response. It is observed for the samples of Prototype-1 that the simulation results are in good agreement with the experimental results about 4.79%, 1.64% and 2.43% deviation.

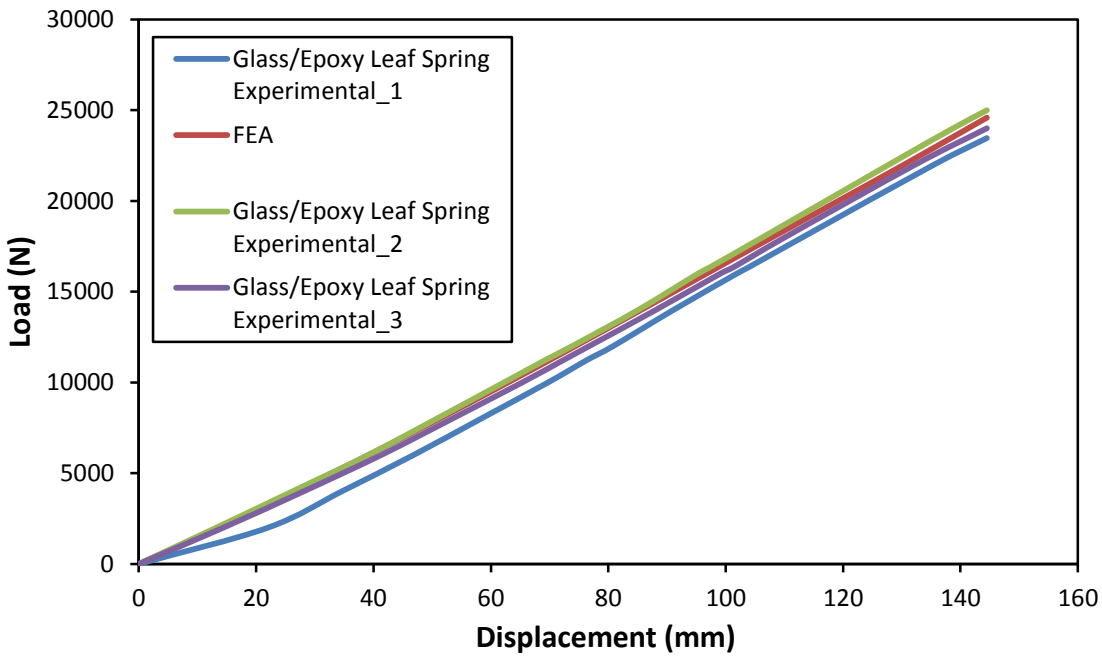


Figure 5.58. Numerical and experimental load-displacement response of Prototype-1

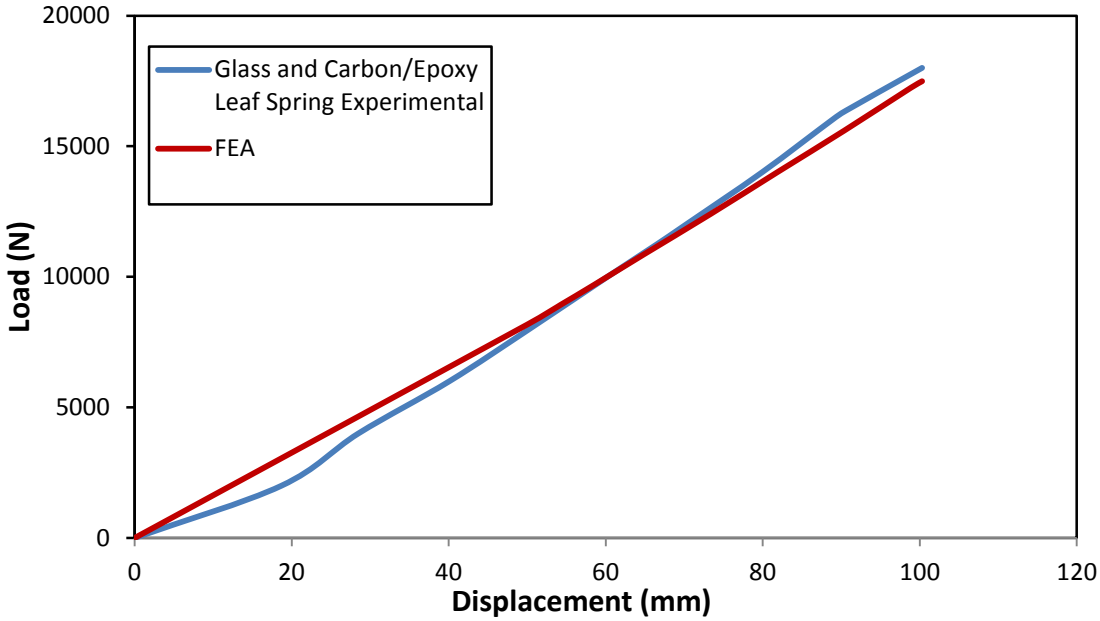


Figure 5.59. Numerical and experimental load-displacement response of Prototype-2

Figure 5.59 depicts that the predicted results for Prototype-2 are again in good agreement with the experimental test results about 2.93% deviation.

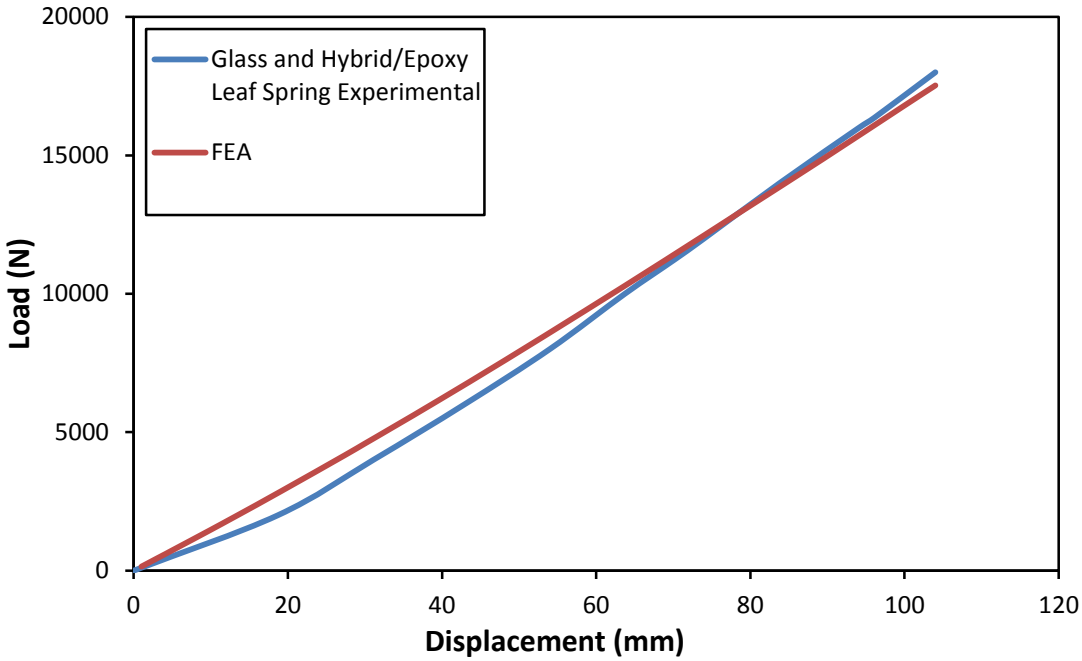


Figure 5.60. Numerical and experimental load-displacement response of Prototype-3

It is observed for the Prototype-3 that the comparison results are in compliance about 2.70% deviation. Consequently, the general treatment of the finite element simulation results is in good agreement with the experimental test results of the manufactured prototypes.

CHAPTER 6

CONCLUSIONS

Within this thesis, the composite leaf spring systems with different material configurations have been designed and the composite mono leaf spring behavior has been investigated by using 3-D finite element model. Abaqus/CAE 6.12-1 has been used in finite element modeling and analysis process. The E-glass / epoxy system has been considered as an optimum material in terms of strength and cost. Lay up orientation has been selected as 0° unidirectional because of the loading type. The vertical loading is decided as the most dominating and critical mechanical load applied on a leaf spring. The boundary conditions and the upper limit of the load were also determined by taking into consideration the vehicle weight, vehicle dynamics and road conditions. In this way, stress analysis and boundary conditions control of the composite leaf spring systems have been carried out. Three dimensional brick elements have been used in modeling of the created systems. Moreover, the natural frequency analyses of the leaf spring systems have been performed. It has been demonstrated that the results are larger than the maximum frequencies of the road irregularities. In this study, manufacturing of the designed leaf spring systems have also been carried out and those prototypes have been tested experimentally. In conclusion, the prototypes have shown significant weight reduction of about 80%.

First, an existing composite mono leaf spring used as a model structure was simulated to validate the created finite element model before the analyses. In addition, some of the model parameters were investigated to obtain the precision of the results to the parameters such as element type, contact definition and loading conditions. The grid independency of the analysis was also investigated to obtain more accurate result. It follows from the verification results that C3D20R and C3D8R elements are appropriate element types for the analysis of composite mono leaf spring models. On the other hand, time of the analysis is an important consideration for the researchers and the linear elements are cheaper than the second order elements. Consequently, C3D8R elements have been selected for the analysis of thick composite-based leaf spring systems.

The analysis results show that all designs are allowable in terms of normal and shear stress, and obtained results depict similar trend for each design since the boundary and loading conditions are same for all. However, Design-2 is quite stiff by comparison with the required spring rate. In addition, the carbon / epoxy composite systems are considerably expensive in terms of cost. Therefore, other two designs have been taken into consideration from the fabrication point of view.

Natural frequency analyses of the designed structures have also been performed in the study. The eigenfrequencies and the mode shapes of the structures have been determined. These results exhibit that the natural frequencies of the designed composite-based mono leaf springs are approximately four times the frequency of road irregularities.

Comparisons of the simulation results with the experimental test results for the manufactured prototypes show good agreement in terms of the load-displacement response though the fabrication processes of the springs may affect the structural properties in a negative way. Thus, finite element model of the composite-based leaf spring systems has been enhanced securely.

We have studied in an elastic region and we didn’t define any failure criteria within this thesis. However, leaf springs are crucial elements in a suspension system and subjected to cyclic loading. Hence, failure of the leaf springs should also be taken into account.

We have determined the eigenfrequencies and the eigenmodes for the undamped systems. However, leaf spring structures involve some sort of energy dissipation. Therefore, the eigenfrequencies and the eigenmodes of the damped structures should also be investigated as the damping ratio of the structures may affect the accuracy of the undamped results.

Determination of the constituents and configurations of the composite structures for achieving the projected composite material properties is another field in finite element modeling of composite structures. This should also be studied with computer programs that can perform micro mechanic simulations.

Finally, optimum configuration in the composite mono leaf spring model was investigated manually in this study. Using a computer program having an optimization approach might provide a better solution and time-saving.

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