DESIGN, MODELING AND OPTIMIZATION OF ELECTRIC TROLLEY LEAF SPRING USING RSM

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENT FOR THE AWARD OF THE DEGREE OF

MASTER OF TECHNOLOGY
(COMPUTATIONAL DESIGN)

TO

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SUBMITTED BY

AJITESH
Roll No.- 2K14/CDN/03

UNDER THE GUIDANCE OF

DR. PARAS KUMAR
Asst. Professor

DELHI TECHNOLOGICAL UNIVERSITY

DEPARTMENT OF MECHANICAL, PRODUCTION & INDUSTRIAL AND AUTOMOBILE ENGINEERING
DELHI TECHNOLOGICAL UNIVERSITY
BAWANA ROAD, DELHI-110042
JUNE 2021

DELHI TECHNOLOGICAL UNIVERSITY

(Formerly Delhi College of Engineering)

ShahbadDaulatpur, Bawana Road,

Delhi-110042

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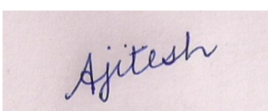
I, **Ajitesh,** hereby certify that the work which is being presented in this thesis entitled **"Design, Modeling and Optimization of Electric Trolley Leaf Spring using RSM"** is submitted in the partial fulfillment of the requirement for degree of **Master of Technology (Computational Design)** in Department of Mechanical Engineering at **Delhi Technological University** is an authentic record of my own work carried out under the supervision of **Dr**. **Paras Kumar** The matter presented in this thesis has not been submitted in any other University/Institute for the award of Master of Technology Degree. Also, it has not been directly copied from any source without giving its proper reference.



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(Formerly Delhi College of Engineering)

ShahbadDaulatpur, Bawana Road,

Delhi-110042

CERTIFICATE

This is to certify that this thesis report entitled, **"Design, Modeling and Optimization of Electric Trolley Leaf Spring using RSM"** being submitted by **Ajitesh (Roll No. 2K14/CDN/03)** at Delhi Technological University, Delhi for the award of the Degree of Master of Technology as per academic curriculum. It is a record of bonafide research work carried out by the student under my supervision and guidance, towards partial fulfillment of the requirement for the award of Master of Technology degree in Computational Design. The work is original as it has not been submitted earlier in part or full for any purpose before.

Dr. Paras Kumar

Asst. Professor

Mechanical Engineering Department

Delhi Technological University

Delhi-110042

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AJITESH
M.Tech. (COMPUTATIONAL DESIGN)
2K14/CDN/03

ABSTRACT

In current scenario, automotive sector is rapidly changing and exploring different fuels, materials and designs for better results. Weight of the suspension system which accounts 10-20 percent of total vehicle weight is one of these areas which need to be continuously explored for increasing mechanical efficiency of the vehicle. Various composites are already tested and evaluated to replace the traditional leaf spring for increasing performance of automotives.

The present work deals with design, modeling and multi factor optimization of leaf spring with the help of Finite Element Method and Response Surface Methodology. Master leaf of electric trolley suspension system was considered for this research work and Carbon Fiber Reinforced Polymer (CFRP) composite is selected to replace the existing (SAE 5160) material. Total 9 models of CFRP material are analyzed and compared in terms of various parameters like Von-misses stress, deformation, mass and fatigue life. FEM results are further utilized in Response Surface Methodology (RSM) technique to get optimized value for "width and thickness" of CFRP leaf spring.

Modeling is done in ANSYS Workbench 2021 R1 software along with real situation boundary conditions and actual loading (considering factor of safety 2). Validation of FEM model is done with the help of analytic model calculation. After getting the optimized design through "Design Expert" software, it is observed that around 70-80% spring weight is reduced along with increase in fatigue life when CFRP optimized model is used.

TABLE OF CONTENT

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

CAE	Computer Aided Engineering
CFRP	Carbon Fiber Reinforced Polymer
SAE	Steel Society of Automotive Engineers
FRP	Fiber-Reinforced Plastics
GFRP	Glass Fiber Reinforced Plastics
PMC	Polymer Matrix Composites
FEA	Finite Element Analysis
FEM	Finite Element Modeling
RSM	Response Surface Methodology
MBS	Multi Body Simulation
RTM	Resin Transfer Moulding
KN	Kilo Newton
N	Newton
mm	millimeter
MPa	Mega Pascal
GPa	Giga Pascal
max.	maximum
min.	minimum

Chapter-1

INTRODUCTION

1.1 Background

In the current situation, vehicle manufacturers have placed a strong emphasis on weight reduction. Weight reduction could be accomplished mainly via the use of enhanced quality of materials, superior manufacturing methods and design optimization. The suspension system which accounts for 10 to 20 percent of the un-sprung weight of the vehicles is one of the possible areas for weight reduction. It not only increases the vehicle's fuel economy but also improves the ride quality. The leaf springs are designed to absorb vertical vibrations and impacts triggered by the road imperfections and bumps, thus causes fluctuations of the spring deformation, storing energy in form of strain energy in the spring and finally releasing it progressively. As a result, boosting a leaf spring's energy storage capacity guarantees a more acquiescent suspension system. According to the research, the most appropriate material for a leaf spring is one which has the greatest strength and the lowest value of modulus of elasticity in the longitudinal axis. As the leaf springs are part of the un-sprung weight of the vehicle, so they are more impacted by the fatigue loads.

If any vehicle is exposed to loads during service, it produces strains, vibrations, and noise in its system components. To endure these stresses, the components must have enough strength, stiffness and fatigue characteristics. Above all, the vehicle's quality as a system should have high fuel efficacy, safety, and in last user comfort is greatly sought. All of the aforementioned requires highly sophisticated and complicated design and manufacturing processes throughout the manufacturing stage of automotives. It requires a thorough knowledge of the vehicle's internal systems as well as the responses of the various body structures to static and dynamic stresses. Different universities and automobile businesses have conducted several studies on performance, component responses to static and dynamic loads, crashworthiness, safety, and other related topics. Researches aimed at producing higher-quality goods are facilitated, especially with the increasing simulation capacity of computing software.

The use of Computer Aided Engineering (CAE) analysis in conjunction with prototype development and testing to solve the similar issues allows innovations of new designs with longer fatigue life, lower costs, less weight and better comfort. As previously mentioned, advancements in the field are accelerating in light of this goal. The suspension system of heavy vehicles is made up of leaf springs to make the vehicle ride comfortable and smooth. This is done by isolating the driver's body from vibrations caused by road imperfections. As the automobile industry becomes more competitive and innovative, existing products are modified and older products are replaced with new and advanced designs with innovative materials. Mostly all the efforts are aimed to improve the user's comfort, improving the suspension system, and as a result, many modifications have occurred over the time. Some of the most recent suspension system improvements include the invention of parabolic leaf springs and the development of newly explored composite materials for these springs. The composite materials have a huge potential to save a lot of weight.

Increasing competition and innovation in the automotive industry leads to the modification or replacement of the current parts with new innovative and sophisticated material products. In the current era of fast depletion of natural resources, the primary emphasis among the vehicle manufacturers is to reduce the weight of the vehicles. Less weight is directly proportional to less consumption of the fuel (natural resources) and in return saves energy, natural resources and produces less pollution. Weight loss may be accomplished mainly via the use of innovative mixtures of alternative materials, design optimization and improved manufacturing methods. Vehicle suspension systems are yet another field where these advancements are made on a regular basis. Nowadays, more efforts are centered to improve user's comfort. A satisfactory equilibrium among the ride comfort and budget in the manufacturing of leaf springs has become the need of the hour. Numerous changes have been already incorporated to the suspension system in last few decades to enhance the productivity in the vehicles. The invention of new designs of leaf springs and the usage of composite materials for these springs are some of the most recent suspension system improvements. This addresses the primary focus on the use of composite materials to replace steel from the traditional suspension leaf springs. Steel leaf springs have been revealed to be inferior to composite leaf springs. With less weight and less fatigue, the later has shown better strength and good weight-bearing characteristics. They have a higher capacity for storing elastic strain energy. The sole stumbling block is composite complicated structure to manufacture.

In this research work, the master leaf (of multi leaf spring) of an electric trolley (used in industries for internal transportation) suspension system is considered for study. The problem with the exiting leaf spring was its weight and low fatigue life. To solve the problem, different composite fibers were studied from available literature. Finally a Carbon Fiber Reinforced Polymer (CFRP) composite (bidirectional fiber) material was selected as a material to replace the existing Steel Society of Automotive Engineers (SAE) 5160 material. In this research work, various models of master leaf spring were designed, analyzed and in last optimized to get better design.

1.2 Leaf Spring

An elastic body that performs the function of distorting when it is loaded and returns to its initial form when the load is removed is called a spring. Theoretically, a leaf spring is also known as a carriage spring or laminated. It is an elementary kind of spring that is frequently used as suspension in wheel rolled vehicles. In automotives such as heavy duty carriage, light motor vehicles and rail systems, to absorb shock loads leaf springs are primarily utilized in suspension systems. The figure 1.1 describes the parts of the semi-elliptical leaf spring.

1.2.1 Construction of leaf spring (semi-elliptical)

- Semi-elliptical leaf springs are utilized in automotive. These leaf springs are comprised of a number of plates varying in length.
- The Master leaf is the main leaf which is the longest, while all other smaller leaves are called graded leaves.
- U-bolts are used to secure the spring to the axle.
- The leaves are held together by rebound clips.
- The central clamp is used to secure the leaf spring to the wheel axle. Also it is used to keep the leaves in position and tightened.
- Left and Right eyes are used to assemble the leaf springs with the vehicle body.

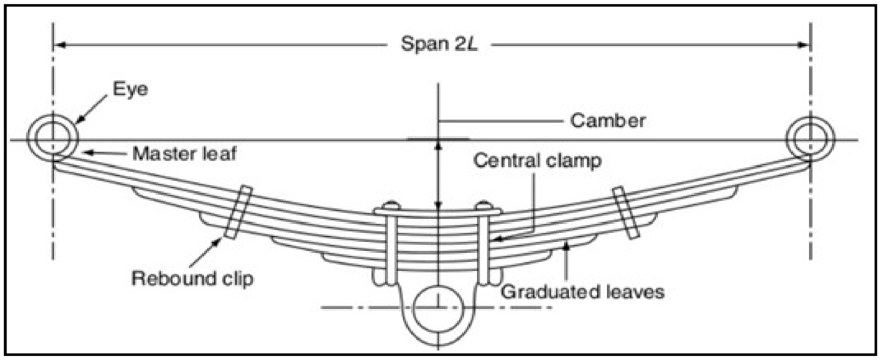


Fig. 1.1: Parts of the Leaf Spring (Budynas and Nisbet, 2012)

1.3 Composites

Composites are a broad group of materials that are distinguished by the fact that they are made up of two or more different components. The current study will focus on a kind of composite known as Fiber-Reinforced Plastics (FRP). FRPs are epoxy resin-based composites with fibrous high-strength components. Fiber-reinforced composite materials are made up of high-strength, high-modulus ‘fibers' embedded in or bonded to a ‘matrix' having a defined interface (boundary). Both fibers and matrix maintain their physical and chemical identities in this state, but together create a unique mix of characteristics that none of the components could accomplish on their own. Reinforcing fibers and a matrix that serves as a binder for the fibers are the two main components of fiber-reinforced composite materials. Coupling agent, coatings, and fillers are some of the other components that can also be used. Fibers are coated with these coupling agent and various coatings to enhance their wetting with the matrix and facilitate bonding across the fiber/matrix interface. As a result, the load transmission between the fibers and the matrix is improved. Fillers are often used to save money and enhance dimensional stability. FRPs have great strength and stiffness while being extremely light, and are often used as a substitute for metals in buildings where high performance and low weight are desired. FRPs are often used as low-weight, high-strength materials in the aerospace, automotive, and marine sectors. Both the matrix and the fiber contribute to the durability, making them much more robust than the fibers alone. The fibers have a greater effect on the strength, creating the composites strong during internal stresses development. These composites are utilized in civil buildings and works for patching the concrete pillars, bridge cable reinforcement as well as lamination of entire flyovers.

FRPs provide a number of benefits over steel, including the flexibility to adapt the material to the system's demands, corrosion resistance, increased material lifespan and durability, and reduced construction time and cost. But it is unfortunate that very less long - term testing is conducted for determining materials' ageing properties and limits. Furthermore, environmental ageing of these reinforced composites in the small as well as long term is little known. The capacity to insert sturdy stiffed fibers in the correct location, in the right direction, and in the proper volume fraction is the core of fiber-reinforced composite technology

The focus of this study will be on bidirectional reinforced polymers. The fibers in a FRP may take one of two forms: unidirectional reinforcement, in which the fibers are continuous along one direction of the composite, or bidirectional reinforcement, (also known as woven) in which the fibers are knitted in a fabric shape and span two directions of the composite.

The fibers may be woven into the matrix in either continuous or discontinuous lengths. Glass, carbon, jute, and kevlar fibers are the most common commercially available fibers. Other fibers are employed in small amounts such as boron, silicon carbide, and aluminium oxide. A polymer, metal, or ceramic may be used as the matrix material.

Glass Fiber Reinforced Plastics (GFRPs) are FRPs with glass fiber reinforcements, often referred to as fiberglass, and are the primary material utilized in the manufacturing of composite leaf springs. Glass has isotropic characteristics and is a non-crystalline substance. The most common glass fibers are called E-glass after abbreviating the term electrical, which denotes the fibers' electrical conductivity characteristics. S-glass fibers, which are used in the aerospace sector, are also named after the acronym of the term strength. Other kinds of glass fibers, such as C-glass and R-glass, have names that describe their characteristics as well. S-glass fibers are split into subgroups, with S2-glass being one of them.

Composite materials contain a matrix component in addition to the fiber component. The matrix component in composites may be any known material used for hardening the fibers; however polymeric matrices are the most frequently utilized. A thermoplastic, rosette or rubber matrix may be found in Polymer Matrix Composites (PMCs). Thermo sets, on the other hand, are the most frequently utilized as composite matrices in GFRPs owing to the simplicity with which they can be manufactured.

Composites offer a range of methods to be produced, in addition to high stiffness and stress at a reduced weight. One of the benefits of composite materials is that instead of making composite first, then component after the fabrication, both the component and the composite material are made at the same time, as demonstrated later in the manufacturing of composite leaf springs. The ultimate characteristics of the composite will be determined by the matrix and fiber volume fractions, which may be stated using the law of mixes.

A composite material may take on a laminar shape, which means it is made up of a certain number of layers, also known as plies or laminates, each of which has a matrix and fine fiber constituents. The fiber orientation as well as the fiber and matrix percentages and materials may vary from laminate to laminate. The composite material has a specific ply sequence defined by the various fiber orientations in the plies and all laminates combined make up the laminate or ply stack. The final characteristics of the composite structure are determined by the ply, stacking, sequence, volume percentages of the components and number of laminates in the laminate. The number of plies may be even or odd, resulting in anti-symmetric or symmetric laminates (Fig. 1.2) which will influence the composite structure's performance and characteristics.

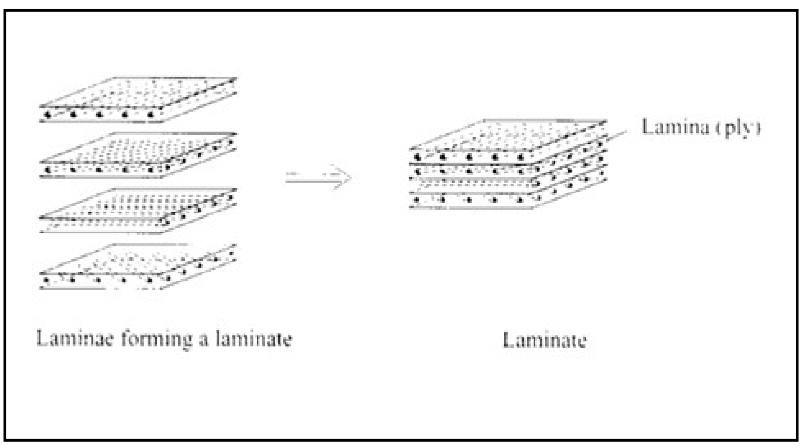


Fig.1.2: Laminate Composites (Gopalakrishnan et al., 2016)

1.4 Applications of Composite Materials as Leaf Spring

So far, much research has been conducted on the use of fiber reinforced composites in a suspension system in automobiles. The integration of composite components instead of metallic parts has improved due to the sufficiency of composite materials for the structural purposes. Now days composite materials are widely used in the suspension system to make lighter and better suspension unit. Many researchers have shown the upper hand of specific composites over metals in this area by experimentally showing the data and records. Various manufacturers produce composite leaf springs for all commercially available vehicles. In past, C.J. Morris developed a fiber reinforced polymer leaf spring to fulfill the purpose of the rear suspension that comprises of steel in lower arms and coil springs. To achieve a low spring rate, the three-door Ford Escort model was selected. Constant cross section design was chosen because it was most suitable for the preferred manufacturing method and allowed the fibers to completely align throughout the length of the spring without any hindrance. As glass fiber is a cost-effective material, so the filament winding-compression molding method was chosen. The production technology and glass fiber were preferred for the reinforcing material. As a result, prototype manufacturing was completed and the spring model's vehicle connection was achieved using steel end fittings. After that the rough road durability test- “a common test technique for determining which chassis component would fail first” was conducted. From the test findings, he concluded that the spring was not damaged by the favorable fits. In addition, vibration, noise, and harshness characteristics as well as the durability test were determined and the findings were comparable to the results of the standard Escort measurements. Subsequently, it was showed that the vehicle weight was decreased by about 3.2 kg, and guaranteed the system's longevity. All this has been possible due to high strength with respect to weight of the fiber reinforced polymer mono leaf rear suspension system.

In another case, both the mono-leaf and multi-leaf composite leaf springs were available. The researchers selected mono-leaf composite leaf springs over multi-leaf springs because they are easy to fabricate and there is not interleaf friction in mono leaf which can cause harm. Multi leaf springs on the other hand have also been studied by few numbers of researchers. In one research, a double-leaf design was selected in such a manner that the top leaf would be damaged first, and then the lower leaf would be able to withstand the pre-settled weight. The double-leaf composite spring was assessed with comparable strength characteristics and the current spring of the steel.

The stiffness, spring rate and strain of the composite-based leaf spring were estimated using Finite Element Analysis (FEA). The numerical findings were found to be in accord with the results obtained from the experiment. At last, the static test findings revealed that the double-leaf spring design (fig. 1.3) could support up to 155KN.

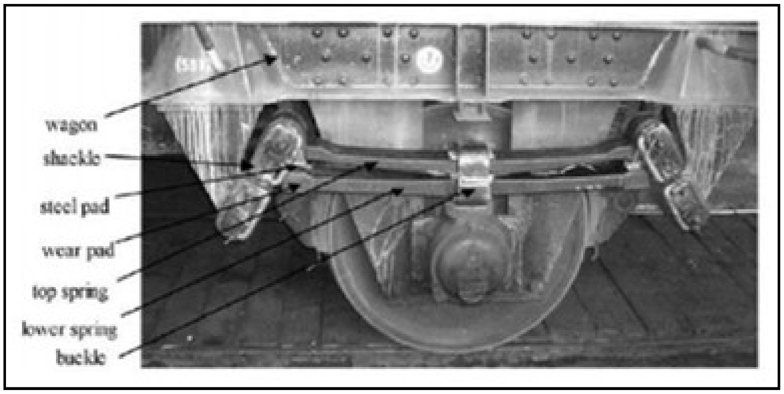


Fig.1.3: Wagon on Composite Double-Leaf Spring (Hou et al., 2005)

Many vehicles' structural components are exposed to the cyclic stress. The cyclic stress has a major impact on the life of the structure. As a result, it is critical to specify the number of stress cycles before that spring will fail. A leaf spring is one of them that are exposed to a variety of stresses including vertical, transverse, torsion, cyclic, and so on. As a result, the researchers must acquire design stresses that are considerably lower than the material's strength characteristics in order to achieve acceptable fatigue life. Owing to the exceptional strength with respect to the weights and particular strain energy storing capability, the unidirectional E-glass fibers were chosen as reinforcing material. The fatigue life in the planned leaf spring showed satisfactory results in the terms of design stresses and material strength characteristics. Then analytical estimation of the number of stress cycles before failure was performed. Using the computer software Abaqus / CAE 6.10, FEA simulation of the proposed leaf spring was conducted under static stress alone. The findings of the FEA were used to regulate the maximum stress failure criteria. All of above shows that composite leaf springs performed well in the field of fatigue life when compared to conventional leaf springs.

1.5 Fabrication of Composite Leaf Springs

To find an efficient and cost-effective production method for composite materials is a big challenge, so fabrication step for composite leaf springs should be carefully considered at each successive level. The composite leaf springs could be made using hand lay-up, filament winding, Resin Transfer Moulding (RTM), pre-preg, or vacuum infusion techniques.

Hand lay-up technique is the oldest technique of leaf spring formation which consist of various steps starting from mold preparation of required leaf dimension to cutting of fibers sheet into the required shape and then manually laying of plies one over another along with the pouring of resin as per the required ratio. Along with this whole process a roller is utilized to remove entrapped air. This technique is complex, time taking and requires skill to get a good composite leaf. Figure 1.4 shows the whole process oh hand lay-up technique.

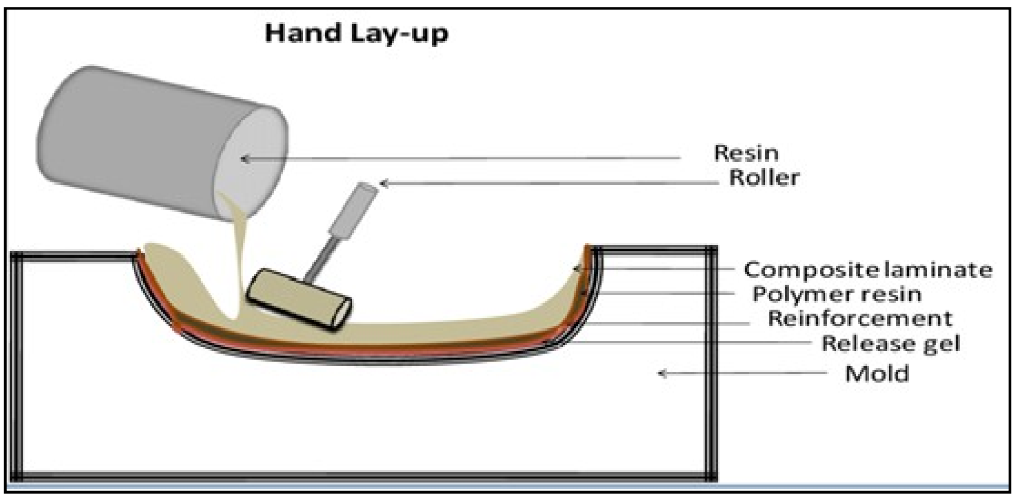


Fig. 1.4: Hand Lay-Up Technique (Hakeim et al., 2016)

The use of pre-preg technology allows the faster operation. Another method is RTM, which is cost-effective. For constant spring design, the filament winding method may be explored. This method may also be utilized for high-volume manufacturing, and the curing process can be carried out at greater temperatures and pressures. Figure 1.5 shows the process layout of pre – preg technology which can be used to manufacture composite leaf at a faster rate.

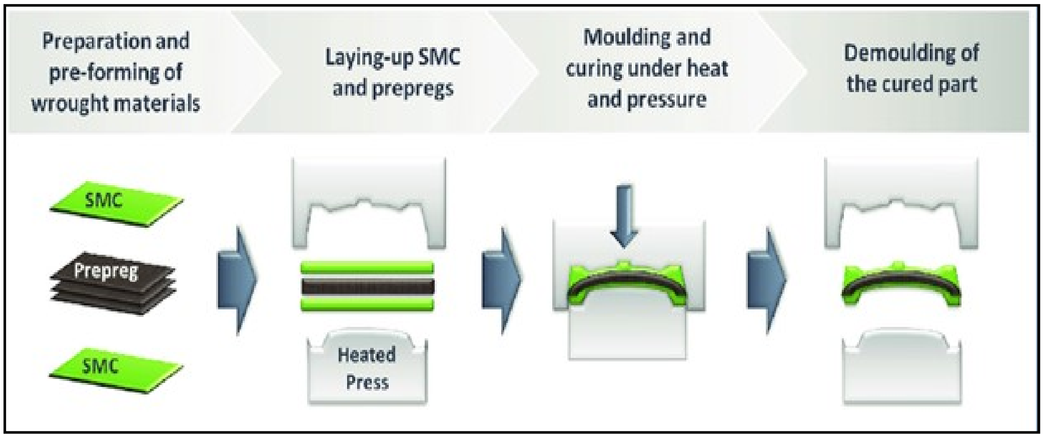


Fig. 1.5: Pre-preg Technology Schematic Layout (Wulfsberg et al., 2014)

Due to the arising demand of duplicate manufacturing of automobile components, fabrication in composite part demands a high level of efficiency in the automotive sector. As a result, manufacturers are increasingly demand for innovative processing methods and chemistry. The industry has selected continuous fiber reinforced epoxy systems because of their high strength and low cost. However, whenever it comes to mass manufacturing of automobile components, then their time-consuming reaction process is a major issue. As a result, high-performance epoxy systems were created to meet the industry's demand for quicker processing. Furthermore, certain drawbacks occurred as a result of the rapid curing, which reduced strength characteristics and surface quality.

Hand lay-up, RTM, and pre-preg technology are all examples of epoxy composite processing techniques. When compared to the other alternative techniques, the technology of pre-preg used in the production of composite leaf springs offers superior performance and cost. Therefore, researchers developed a manufacturing method that incorporates pre-preg technology into the fabrication process. Prototype of a composite leaf spring manufactured from the hand lay-up technique is shown in the figure 1.6.

Fig.1.6: Prototype of composite leaf spring (Venkatesan and Devaraj, 2012)

1.6 Finite Element Modeling and Analysis

The FEA is a numerical and statistical technique which is mostly referred by researchers to get the approximated results in a lesser time by the solution of partial differential equations which is developed by applying various boundary conditions, external applied loads etc. FEA is a time-saving technique for calculating the stress and strain of leaf springs. Researchers may verify their models by comparing FEA findings to experimental outcomes or analytical calculations. As a consequence, getting outcomes in closer proximity is critical.

In past, researcher modeled constant width semi-elliptical, constant thickness, and cantilever E-glass/epoxy composite leaf springs (Narayana, 2012). The Pro/E was used for modeling and the ANSYS software was used to analyse the models. The FEA-derived displacement and stress components were compared to those of steel leaf springs. The eigen values of the composite leaf spring were used to investigate the comfort of the vehicle. As per the results of stresses in all the 10 springs, models were found to be correct in terms of the strength limitations and mode shape to maintained suitable comfort for the passengers.

Theoretical calculations play an important role in the design and study of leaf springs. Because numerical solutions provide approximate findings. It is crucial to compare FEA results with analytical answers. Pozhilarasu and Pillai (2013) compared the bending stress and spring rate of a multi-leaf E-glass/epoxy composite leaf spring to a standard leaf spring of steel. The analysis was performed using ANSYS 11.0. From the standpoint of deflection and bending stress, FEA results were compared to the analytical calculations. The results exhibited that the multi-leaf composite leaf spring may be used to provide excellent machine-driven performance in weight reduction.

Another essential analytical parameter is finite element selection, which should be carefully examined. The form, kind, and thickness of the composite structure to be evaluated may influence element selection. The FEA of the multi-leaf GFR leaf spring was reported by Yinhuan et al., (2011). The spring's mathematical model and FEA were created using the ANSYS software. They selected the solid element due to the orthotropic characteristics of composite materials. In their research, they utilized three-dimensional contact elements to describe interleaf contact between the leaf faces. When a single spring was used as an example, FEA findings revealed that the values of stress were lower than that of the steel spring.

In many engineering disciplines, the uses of laminated composite materials have grown ubiquitous. Hence, in the recent year, an increase in interest for optimization of materials based on composites is seen. A computer algorithm or the finite element technique may be used to accomplish the optimization. The spring's thickness and breadth at the centre and ends were chosen as design factors. As design limitations, the Tsai-Wu failure criteria and deflection were used. A three-dimensional, eight-node brick element with appropriate aspect ratio was used for the finite element model of the spring. As a consequence, they determined that, in terms of analytical findings, a thickness of 42 mm and width of 32 mm at the centre, while the thickness of 16 mm and width of 84 mm at the ends provided acceptable results in vertical load of 1925 N. They analyzed from the findings that FEA geometry optimization might be useful as a precursor to composite leaf spring design and analysis.

The ANSYS procedure may be split down into three distinct stages.

- **Pre-Processing**

This is the most crucial stage in the study of leaf spring. Any modeling program could be used to create geometry and then transferred to simulation software for analysis. The act of subdividing an area to be represented into a collection of tiny components is known as mesh generation (grid generation). The process of defining and breaking up the model into tiny pieces is known as meshing. A network of mesh, defined by the arrangement of various elements and nodes geometrically expresses a finite element model in general. Nodes are locations where characteristics like displacements are computed. Elements are defined by a collection of nodes that determine the model's localized mass and stiffness characteristics. The number of meshes defines elements as well as allows for reference related to deflections and stresses at particular model locations. Hexahedral, tetrahedral, and brick mesh elements are the most frequent mesh elements utilized in the ANSYS solver.

- **Solver**

During preprocessing, the user must put in a lot of effort, while during the solution phase; it is the computer's time to do the work. The user just has to click on the solution symbol. Matrix formations, inversion, multiplication, and solution for unknowns are all performed internally by software. For static analysis, for example, determine displacement and then strain and stress.

- **Post-Processing**

The last stage in ANSYS is Post-processing, which involves analyzing the ANSYS findings. The true usefulness of ANSYS simulation, on the other hand, is often discovered in its capacity to give precise forecasts of integrated quantities like displacement and stresses. Viewing the findings, verifications, and conclusions, as well as considering what actions might be done to enhance the design, is what post processing entails.

1.7 Response Surface Methodology

RSM employs a variety of methods, techniques and tools (mathematical, statistical, graphical), to create, enhance and optimise a process. It may also be used to issue modelling and analysis when our response variables are affected by many independent factors.

The following stages are typically included in RSMs:

1. The experimenter must shift from the current operating circumstances to the neighbourhood of the response's optimal operating conditions. In the case of optimising the response, the steepest ascent technique is used. The same technique may be used to reduce the response, which is known as the steepest descent method.

2. Once the experimenter is close to the optimal answer, he or she must check complex model to suit the relation between the response and the factors chosen. To do this, special set of experiment design called as RSM designs are utilized. The best model is utilized to determine the optimal operating parameters that result in a maximum or minimum response.

3. It is conceivable that many answers will need to be improved at the same time. An experimenter, for example may aim to increase strength while reducing the amount of flaws. In such situations, the optimal settings for each of the answers may result in contradictory values for the factors. It is necessary to choose a proper setting that gives the best suitable results for all of the selected constraints. During this step, desirability functions come in handy.

1.7.1 Applications of RSM

RSM is widely used in the optimization of analytical procedures today, owing to its advantages over traditional one-variable-at-a-time optimization, such as the ability to generate large amounts of data from a small number of experiments and the ability to evaluate the interaction effect between the variables and the response surface. To apply this approach to experimental optimization, you must first select an experimental design, fit an appropriate mathematical function, and then assess the quality and accuracy of the fitted model before making predictions based on the experimental results. The symmetrical second order experimental design most often used for the development of analytical methods is still the central composite design. Until recently, the use of desirability functions for multiple response optimizations was restricted to the chromatography field, related techniques, and electrochemical approaches. Its ideas, on the other hand, may be used to the creation of processes employing different analytical methods that need the simultaneous search for optimum circumstances for a collection of answers. Finally, an adaptive learning method that combines neural networks with experimental design may be used to represent a dependency relation as an alternative to classical modelling. In comparison to the conventional RSM, this method has shown to be more accurate in data learning and prediction.

• The most common RSM uses are in the industrial sector.

• RSM is critical in the design, formulation, development, and analysis of new research findings and products.

• It may be used to enhance current research and products.

• Determining chemical composition, food science, biological industries, etc. use applications of RSM very frequently.

1.8 Stat-ease Design Expert

"Design Expert" software is a statistical and mathematical tool in which one can use RSM technique. Test matrices for screening up to 50 variables are available from it. Analysis of variance is used to determine the statistical significance of these variables (ANOVA). Graphical tools aid in determining the effect of each element on the intended results and identifying data anomalies. A power calculator may assist in determining the number of test runs required. To determine statistical significance, an ANOVA is used. A numerical optimizer, based on the proven prediction models, assists the user in determining the optimum values for each of the variables in the experiment. To evaluate the residuals, "Design–Expert" offers 11 graphics in addition to text output. By changing the values of all components in simultaneously, the programmed identifies the major impacts of each element as well as the interactions between them. With a limited number of trials, a response surface methodology technique may be used to map out a design space. By changing the values of all variables in parallel, RSM gives an estimate for the value of responses for every conceivable combination of the factors, allowing it to understand a multi-dimensional surface with non-linear forms. The optimization feature may be used to determine the process's optimal solutions.

1.9 Statement of the Problem

Leaf spring is an integral part of the automobile system since long time but still weight of steel leaf spring is the major area of concern. Automobile industry is rapidly shifting to electric battery from petroleum fuel and at this time minimizing the weight without compromising the safety and quality of the ride is most important. Minimizing the weight of spring without compromising the factors like fatigue life, stresses developed, deflection etc. is the requirement of today.

Our study is concentrated over leaf spring of electric trolley (Fig 1.7) which is used in industries for movement and transportation of goods. SAE 5160 steel multi leaf spring used in this electric vehicle weighs around 15% percent of the total electric trolley vehicle weight. This steel leaf spring can be replaced by a light material leaf spring. Being electric, its efficiency (travelling and working range) can improve much more if we can decrease the weight in any form. The figure 1.7 and 1.8 represents the electric trolley and its suspension system which are considered in this research problem. In our research work we will analyze main leaf spring of this multi leaf spring to get comparative study.

Fig 1.7: Electric Trolley for Transportation of Goods with-in Industries

Fig 1.8: Suspension System of Electric Trolley

Chapter-2

LITERATURE REVIEW

2.1 History of Leaf Springs

Since the Romans floated a two-wheeled device called Pilentum by utilizing robust wooden poles, leaf springs have been utilized in various ways. The first steel leaf spring was placed on a vehicle by the French in the 18th century, and it was a single flat leaf spring installed on a carriage. Elliot of London invented the venerable leaf spring, which is still used by certain manufacturers in automobile suspension systems today. He stacked one steel plate on top of the other, connected them together, and then chained both ends to a vehicle's chassis. While launching the model-T in 1908, Henry Ford made a change to the suspension system by installing one spring at each axle transversely instead of one at each wheel. They utilized high-strength vanadium steel for the suspension of French racing cars, resulting in weight and cost savings in many areas of this vehicle without compromising its longevity. Although the idea of front-wheel drive became popular in the 1970s, automobile manufacturers continued to use coil springs on rear-wheel-drive American vehicles. In Europe and Japan, leaf springs were often utilized in automobiles. Leaf springs, on the other hand were utilized in large commercial vehicles including vans, trucks, SUVs, and train carriages. The benefit of wider load dispersion over the vehicle chassis over coil springs in large vehicles was that the weight was conveyed to a single location. Nowadays, most commercial vehicles, whether light or heavy, are equipped with two sets of perpendicular leaf springs per axle to support the vehicle's weight, where load carrying capacity is more important than suspension response accuracy. A leaf spring has another benefit over a coil spring in that the end of the leaf spring may be directed along a certain route.

The idea of the parabolic leaf spring was a more contemporary application in the area of suspension system design. This design is defined by the use of fewer leaves with varying thicknesses from centre to ends that follow a parabolic curve, i.e. a varied cross-section of the leaves along the length. Interleaf friction is a frequent cause of early failure in multi-leaf springs, resulting in a short fatigue life of the leaf spring assembly. Other areas of contact are avoided with the use of spacers. The primary benefit of parabolic springs, apart from weight savings, is their increased flexibility that improves the quality of ride in vehicle. The advantage of parabolic springs is that they are more comfortable to ride on and are not as firm as traditional multi-leaf springs. They are often used on buses to improve comfort. In 1997, Paul Heijstee of T.I. Console in Spain developed the parabolic spring as the Santana spring, and many manufacturers followed suit. Ray Wood of Wise Owl Innovations in Canada was immediately interested and carried out many modifications to the previous parabolic leaf spring concept but failing to improve it. Later, British Springs Limited blatantly duplicated the original Santana spring and forced the assistance leaf to the second leaf. Then GME, a tiny manufacturing firm located in the United Kingdom, came along and cloned the BSL spring. Chris Perfect Components of the United Kingdom manufactured the final spring and became the first UK distributor for TIC springs in 1998. Chris Perfect Components has made many modifications to the TIC spring design.

2.2 Literature Review

The literature on different types of leaf spring like semi elliptical leaf spring, parabolic leaf springs, materials like different grades of steels, composite materials etc, techniques like shot preening, heat treatment etc and in last various computational techniques used for analysis and designing of leaf spring are studied. A Number of researchers & designers have done work on leaf springs and it is summarized as:

Dowing (1991) developed a cumulative damage process to forecast the fatigue failure of materials under complex stress-strain records. The connection between stress-strain behavior and fatigue life is investigated on 2024-T4 aluminium.

Abrate (1995) studied the effect of number of plies and their respective orientation on the mechanical properties of composites. It was observed that composites feature a high degree of anisotropy, which necessitates careful lay-up selection to maximize material potential. It has been discovered how to construct laminated plates with restrictions on strength, stiffness, buckling loads, and fundamental natural frequencies.

Al-Qureshi (2001) carried out research on composite spring analysis, design, and manufacturing. A car's suspension leaf spring has been seen with a material modification to glass fiber reinforced plastic, which exhibits geometrical and mechanical characteristics comparable to that of the multi-leaf spring. The leaf spring was studied both in the laboratory and on the road.

Toorres and Voorwald (2002) discussed about improving the fatigue strength of the material under four shot peening conditions which in turn creates compressive residual stress field in their surface layers. The relaxation of CRSF was observed due to the fatigue process of repeated stresses. Improvement of fatigue strength by selection of most effective shot peening condition for the specimen was discussed experimentally.

Rios (2002) illustrated shot peening process to improve fatigue resistance which imparts compressive residual stress in surface layer of the material under influence which makes the nucleation and crack propagation more difficult caused by fatigue.

Mayer (2006) described three types of railway eye end connectors for leaf springs. Static testing and FEA were used to get different leaf spring properties. Through FEA findings, a high-intensity inter laminar shear stress concentration was discovered, and a delamination issue was identified.

Kumar (2007) performed fatigue and static analysis of steel as well as composite multi leaf spring using life data analysis. Life data analysis, a statistical technique was used to predict life of the composite by fitting a statistical distribution to the life data of composites. The design of leaf springs has also been analyzed analytically as well as experimentally for validation.

Corvi (2007) utilized composite mechanics equations and with the help of Timoshenko beam theory and finite element technique, a PC software model was developed for early design analysis. The viability of utilizing this software was to create early design considerations and construct preliminary designs to evaluate the impact of changing design parameters has been shown using a leaf spring.

Jayaswal and Kushwah (2008) explored various realistic methods in the parabolic leaf spring manufacturing unit for improving productivity with a focus on rejection reduction. This research work was done for productivity enhancement in leaf spring production with a focus on reducing rejections with regard to end gap between leaves and camber tolerance. A mismanaged end gap was discovered with a 27 percent contribution to rejection. Camber deviates during centre hole punching and after heat treatment oil quenching.

Refngah et al. (2008) studied variable amplitude loading conditions with fluctuating stress-strain cycles and predicted fatigue life while industrial manufacturers were only conducting constant amplitude loading tests. A data collection device with four strain gauges connected to the leaf spring placed on a truck travelling at 60-70 km/h was used to capture data from physical loading of the parabolic spring. The use of FEA to monitor strain-based damage assessments resulted in a more dependable design in terms of fatigue life under varied amplitude loading.

Farahani and Mivehchi (2010) created a damage parameter to track the lifespan of mechanical components under varying loads. On the hysteresis stress–strain loops of materials, the researchers took into account the impacts of materials memory, short cycles, and loading sequence. Under varied amplitude loading spectra, the connection was effectively established over the life of three samples, one low carbon steel and two aluminium alloys.

Kanbolat et al. (2011) studied material characteristics and proposed a hybrid technique for obtaining fatigue life and leaf geometry against environmental conditions. It is based on finite element solutions that evaluate the impact of manufacturing factors, geometrical tolerances, and changes in material properties. Physical road load data was used to create a correlation, which was then verified using design of experiments.

Borkovic et al. (2011) determined two different heat treatment circumstances and two outmost directions of alloying element segregation; the fatigue life of 51CrV4 spring steel. For two different heat treatment conditions, Authors used the loading modes and two outmost directions of alloying element segregation. Heat therapy has been suggested as a factor that contributes to fatigue resistance. Because of the variation in tempering temperatures of spring steel fewer than two situations, the mechanical characteristics altered.

Yadav et al. (2012) discussed that the thickness of a leaf spring changes in a parabolic pattern, from the centre to the outside edge. The amount of stress in a parabolic leaf spring is first calculated using the finite element technique, and then the stress is successfully minimized using the annealing algorithm. The objective function was stress minimization, the variables were camber and eye distance, and the constraint was displacement.

Karthik et al. (2012) used the finite element technique to estimate fatigue life under non-constant amplitude proportional loading. For various materials, the stress and strain approaches were examined in order to observe the distribution of stress, damage, and life in order to choose a better material and optimal method.

Malikoutsakis et al. (2013) worked on 7.50 to 8.0 tonnes, Authors selected truck axle leaf springs for the study. They worked on a multidisciplinary optimization of the leaf spring, focusing on the automobile wheel joint mechanism. The improved mechanism's design parameters have been established. The leaf spring has been evaluated using the finite element technique for a variety of situations that cause increased stress. The experimental testing of prototypes has also been used to validate the system.

Patnaik et al. (2013) worked on a small loader truck's parabolic leaf spring stress and displacement has been measured of the spring. Artificial neural networks were used to analyse the camber and leaf span of a parabolic leaf spring in order to maximize stress and displacement (ANN). Variation of eye-to-eye distance and camber height has been done to evaluate their impact on output parameters. A number of professional driving people examined the improved leaf spring and determined it to be superior than before. They utilized strategy of experiments in order to understand the behavior of parabolic leaf springs

Yu and Kim (2013) performed analytical work to look into the basic characteristics of dimensioning a FRP leaf spring which was double tapered. The tapered (double) shape along with thickness was varying linearly, width varying hyperbolically, and length area was constant. A cross section of discussed dimensions has been chosen for their work to replace steel multi leaf springs among many types of taper configurations, i.e. either double or single taper, which again includes configuration in triangle, trapezoidic and parabolic forms. Glass fiber and epoxy were used to create FRP leaves. When compared to experimental findings obtained on a hydraulic spring testing equipment, the prototype FRP leaf spring demonstrated better durability and fail-safe properties.

Geoffroy et al. (2013) described the importance of shot peening in leaf springs manufacturing. He performed the investigation of residual stresses through X-ray diffraction and fatigue tests on a sequence of samples that were focused to ten different peening schedules. Double peening until a depth of 0.02 mm results in fatigue life improvement.

Roy and Saha (2013) used numerical approach to observe the deflection response of cantilever type leaf springs. The variations in stress, strain and moment have been observed for variable mechanical properties of the concerned material. Galerkin's approach was considered for mathematical formulation. The solution to big deflection problem was achieved by simulating through MATLAB. The work was validated and some new outcomes were developed. The effect of material grading was shown for various type load conditions.

Rahman et al. (2013) examined the stress and deflection of the beam, a numerical simulation was conducted utilizing various deflection theories. He came to the conclusion that the non-linear analysis was more important when it came to the reaction of the beam under point load. He noticed that the nonlinear theory-calculated bending stress was less than the traditional leaf spring of the same volume. The max.stress has also been seen deflecting away from the fixed end.

Baviskar (2014) utilized analytical and static analyses using a CAE methodology to reduce stress concentration. Three distinct master leaf spring models with various cross-sections have been developed and considered for the study. For comparable loads and boundary circumstances, the master leaf spring with the smallest cross section was severely strained. Von-misses stresses were highest in the eye portion of the master leaf, according to this study.

Arora et al. (2015) studied the effects of varying curvature between mating leaves on assembly stresses. Authors reduced the maximum stress generated in the leaf spring, subsequently the stress distribution was found to be more uniform in all leaves. This was accomplished via a comparison of the analytical method, the SAE spring design approach, and experimental work. Due to these assembly stresses, the fatigue life was also shown to be enhanced.

Arora et al. (2015) utilized computer software to calculate the fatigue life of a 65Si7 leaf spring. CAE methodology, experimental analysis and SAE analytical method were used to ensure that the produced findings were genuine. The CAE analysis was chosen as an alternate analytical method due to its low variation of 6–7%, among other factors. The SAE findings differ by up to 15% from the experimental results.

Durus et al. (2015) studied the fatigue life of a Z type leaf spring via testing under different loading situations till failure. For correlation, an S-N plot of components was created. For the leaf spring correlation, a strain-based FEA was used. They tested the leaf springs durability using the first, second, and third correlations.

Gomez et al. (2015) addressed the topic of fatigue life maximization for leaf spring flexure pivots. For this reason, they focused on stress reduction. They looked at the possibility of reducing stress by optimizing leaf form. For their aim, a variety of methods and formulations were used, and the enhanced thickness was shown to be independent of angular rotation. For validation, a non linear FE analysis was performed, which revealed significant stress reductions. The revised profile was compared for different properties such as stiffness, strain energy, and so on, leading to the conclusion that shape modification may be used to increase fatigue life.

Kong et al. (2016) identified the performance of various leaf spring eye designs in order to prevent failure under various driving situations, which may result in serious accidents. They tested the leaf spring under extreme loading circumstances, such as braking, cornering, and so on. They utilized a multi-body dynamics model to generate a variety of load situations for FEA. To test the spring eye's capacity under various loading situations, four alternative designs of leaf spring eyes were created and evaluated.

Foote (2016) founded and acknowledged controlled shot peening as a method of increasing fatigue strength, according to the findings. The majority of the research ignores the impact of internal damping under different shot peening settings. Dampening thought lead to a better grasp of the actual causes for the apparent decrease in fretting weariness. The majority of studies focused on improving fatigue life via shot peeing, which imparts compressive residual stress in the material's top layer, complicating the nucleation and propagation of fatigue fractures. The majority of them used the fracture mechanics model, while a few tried to increase fatigue life using the stress approach model. Researchers that are interested in fatigue behavior attempted to determine the impacts due to the roughness of the surface. The importance of surface roughness when evaluating the surface contact between two bodies cannot be overstated. Because crack initiation is influenced by surface characteristics, the local stress field created by surface roughness is critical. There may be goals of infinite life, zero weight, infinite strength, or 100 percent dependability when designing any mechanical component for fatigue failure. All these variables can be studied all together rather than their individual study. After shot peening, fatigue life of the a component improves, which raises additional problems such component design, size, and material, which should be changed for economy and efficiency. Designers prefer accurate fatigue estimates for real components, although they are still susceptible to errors.

Atig et al. (2017): attempted to study reliability based approach and fatigue behavior of particular design models of leaf spring is accessed while considering uncertainties of geometric, mechanical as well as material factors like uncertainties in material properties, unavoidable fluctuations in geometrical parameters etc. Monti-Carlo technology is used in FEM to get fatigue reliability of model and then RSM technique is considered to get the data of large number of experiments. Finally fatigue behavior of leaf model is analyzed with the variation of various geometric and material factors and their influence on fatigue reliability is noted down. It is noticed that RSM is a very good technique to get the required result in short period of time as Monte-Carlo took huge amount of simulation time comparatively for same result.

Maloch and Cornak (2019) addressed the issue of multi-leaf spring modeling in their article. Independent suspension is being installed in a growing number of cars due to its undeniable benefits over dependent suspension. Even yet, in certain instances, a dependent multi-leaf spring is recommended for medium or large vehicles built for off-road conditions. With a tandem bogie arrangement, you may increase your mobility even further. A large number of inputs are needed for the behavioral analysis of the dynamic motion of the aforementioned vehicles. Because they are in close touch with the road surface, most of the damage comes from the suspension components. Some of them are optional, while others are necessary for achieving an acceptable coefficient of correlation among suggested models and their validation with experiment findings. The behavior of a multi-leaf spring under specific conditions is one of those critical inputs. the Hysteresis phenomena along load- displacement curve are the primary determinants of behavior. FEM may be used to solve the problem if only size and material of the leaf spring is known and the other characteristic are unknown. A stiffness characteristic may be generated using the simulation data. As a result, the paper is broken down into the following sections: First, a short introduction was given, followed by the study of current state of the arts. Second, hysteresis was found when a basic model was constructed. The leaves were then pre-stressed in a manufacturing setting, and load-displacement measurement was taken for variety of friction coefficients in between the surface of leaves. Finally, the technique used was summarized as well as assessed.

Kim et al. (2019*)* investigated the impact of leaf form by using a model of semi-analytic leaf which was developed with the help of Euler beam theory and a comparison was done with the FEM model. The position of contact points changes as the form of the leaf changes. Experiments have indicated that the noise is caused by a tiny collision between the leaves, based on this study. In order to examine the impact of shape change, the Euler beam model is found to be more effective.

Pagani et al. (2019) carried static as well as dynamic study of composite leaf spring in this research work. During the landing of aeroplane, leaf spring splays an important role for absorbing the shocks, so the materials used in landing gears of aeroplane is investigated in this article. In order to assess the forces that occur on the fuselage during the impact of the aircraft on the ground, an exact simulation of the entire landing gear system must be conducted. The FEM was considered to create a model of the leaf spring, which was then used to evaluate its motion using a Multi Body Simulation (MBS). The findings illustrate how straight and curved leaf springs transfer force to the fuselage. In order to assess design sensitivity, several thickness and material values were considered. Finally, graphs and tables depict the connection between the various parameters of geometrical design, material properties of the composite material and the forces on main body of an aircraft, which may be utilized in future landing gear design and development.

Loganathan et al. (2020) studied and analyzed the CFRP leaf spring in order to reduce fuel consumption and improve efficiency. As the automotive and aviation industries are looking for a superior alternative material that has excellent specific strength, light in weight, and is extremely durable. The study of automobile leaf springs in terms of material change from conventional SAE 5160 steel (Chromium steel) to Carbon Reinforced Polymer Composite to achieve significant strength, associated weight reduction with reduced fuel consumption, and improved vehicle performance is the focus of this work. The findings of flexural fatigue life and damage suffered for both materials are presented in this paper using FE Analysis. Various ply orientations are also taken into account in order to improve the fatigue life of composite materials.

Raju et al. (2020) utilized a Taguchi method in order to analyze the static analysis of leaf spring. As leaf springs are kind of spring in car suspension systems. A leaf spring's primary purpose is to sustain vertical loads while also isolating road-induced vibrations. A typical leaf spring design from a commercial small load carrier vehicle was selected for research in this project. The research is looking for a novel leaf spring material. Materials such as silicon manganese steel, carbon fiber, silicon carbide, Co-Cr-Ni alloy, Al oxide (99% alumina), and beryllium alloy are compared to standard materials to determine their compatibility. SOLIDWORKS is used to model the leaf spring, while ANSYS 16.0 Workbench is used to perform static analysis. The goal of this research was to compare the stresses and deformation of different types of materials. Different materials were subjected to static analysis and compared to one another in order to find the best material for manufacturing. Carbon fiber, when compared to other materials has superior characteristics according to the findings of the static study. Furthermore, the loading circumstances and material selection have a significant impact on the functioning of the leaf spring. As a consequence, the Taguchi technique may be used to verify the findings obtained for the material Carbon fiber. Carbon Fiber, which is a composite material, may be regarded an excellent material for the building of leaf springs, according to the total static analysis and validation via the Taguchi Method.

Noronha et al. (2020) did a comparative study of various materials that can be used in manufacturing of leaf spring. As we know owing to the great load bearing capacity and cheap production cost, leaf spring is extensively utilized in automotive sector. Because of their low weight and excellent strength with respect to weight, composites have progressively become very popular in the automotive sector. The possibility of utilizing a cheaper and lighter material for car suspension system is investigated in their study. On the basis of load bearing capability, low cost of material, less deflection and more capacity to store strain energy, stresses developed, natural frequencies, mass reduction, high life before fatigue failure and high corrosive resistivity, new material was finalized for replacement of existing steel spring. In this research traditional steel material spring is compared with various composite leaf springs such as Kevlar-epoxy, carbon/glass epoxy, and isotropic aluminium 6062. The advantage of considering composites over steel and aluminium material is analyzed with the help of static and dynamic analysis, finally findings revealed that Kevlar-epoxy composite performed best among considered materials in the study because it developed lesser Von-misses stresses and stored higher strain energy comparatively, which finally resulted in good ride comfort . Because of reduced mass and better rigidity, Natural frequency of carbon-glass epoxy and Kevlar-epoxy composites are higher. Owing to better material characteristics, Kevlar-epoxy has a longer life cycle than any other materials. When compared to EN45 steel, the utilization of Kevlar-epoxy results in an 82 percent weight deduction in the leaf weight; this reduces the un-sprung weight, good ride comfort, increased life of the spring as well as overall improvement of suspension system efficiency.

Krishnamurthy et al. (2020) did a study on the leaf spring that is frequently used in car suspension systems. Single composite leaf spring was constructed from several layers of the leaves piled in multiple layers for light commercial vehicles, typically with increasingly shorter leaves. Leaf springs were long, thin plates that are connected to a trailer's frame and sit above or below the axle. The weight of the leaf spring is decreased in this suggested work by substituting traditional steel material with different composite materials. ANSYS was used to assess its parameters in an experimental setting. Modeling software is used to create the leaf spring, and FEA is used to determine stress and deflection. Values are also compared numerically and empirically. As a result, the novel suggested material is proven to be more cost-effective and lighter than traditional materials.

Nataraj and Thillikkani (2020) examined the breakdown of the leaf spring suspension system used in TATA LPT 1613TCIC type heavy load truck vehicle in this study. Micro structural analysis as well as material specification was used to investigate changes in the chemical composition. Visual examination and scanning electron microscope (SEM) analyses were used to examine the failed leaf spring fractured portion. The failure of the fractured component was inferred from the fractography research related to the cyclic load. The model truck vehicle's leaf springs were fatigued as a result of this weight. Then, to determine the root cause of the leaf spring suspension system, a FEA of leaf springs was carried out. The failure characteristics for the truck vehicle were also optimized for safe road operation. In contrast to current model lifecycles, the suggested leaf spring has a longer fatigue life.

2.3 Research Gaps

After reading the history and literature, it is determined that still some areas of leaf spring are available which need to be explored for better future of automotive industry. Research Gaps identified throughout the study is as follows:-

- Many different types of composite materials are used for replacing steel leaf spring but woven fiber i.e. bidirectional fibers reinforced polymer composites are comparatively not evaluated properly. Whereas these woven fibers eliminate the problem of de-lamination of outer layer of composite fibers in leaf spring application and can play an important role in solving the weight problem of metallic leaf spring.

- Very few researchers have considered the impact of more than one variables in designing the leaf spring, mostly weight was reduced by using new material. But various other factors like fatigue life etc. are not taken into considerations which are very important while replacing one material with another.
- A small number of researchers focused on using computer optimization techniques like RSM etc to optimize different leaf spring design characteristics at the same time.

2.4 Research Objectives

Master leaf of SAE 5160 steel multi-leaf spring is selected as the main component for this research work. Main motive is to do replace the spring via computer-aided designing, modeling and optimization techniques considering various boundary conditions and loading circumstances, and then comparing the CAE findings with the analytical model calculations to validate the models. The following are the primary goals for this research project:

• Minimizing the weight of spring

• Cost saving for longer period

• Optimized design

The above-mentioned research goals may be met by altering the leaf spring design, as well as by replacing the material. The advantages that may be gained by fully completing this study effort are as follows:

• Material and time saving

• Precision & accuracy

• New and improved design

• Increased analysis speed

Chapter-3

METHODOLOGY

3.1 Introduction

The methodology is an approach to describe the problem in a systematic and coherent manner. Every research is based on a particular methodology which forms the foundation for achieving the desired outcomes. Methodology describes everything from problem identification to solution of problem by various methods, tools and techniques.

This chapter briefly describes about the problem identification, methods used to solve the identified problem, material selection, mathematical and statistical tools, modeling softwares (CATIA and ANSYS) used in the research work.

In this research work, initially dimensions of existing leaf spring were measured and Computer Aided Design (CAD) model was drafted in CATIA of same dimensions. The basic motive of the research was to improve the overall design of leaf spring by optimizing the mass (so that overall weight of the electric trolley can be reduced) without compromising with other factors like fatigue life, stresses etc.

The tools used in this research are CATIA, ANSYS and Design Expert software for getting the desirable results. As described above, CATIA is used for modeling the CAD of all the models taken for consideration. A total of 9 CFRP models are considered for the analysis so that their results can be considered for optimization through RSM. All 10 models (9 CFRP + 1 steel spring model) analysis is done in ANSYS 2021 R1 and validation of the ANSYS Model is done via comparison with analytical model results. Optimization of design is done by RSM tool "Design Expert" software by creating RSM model and expressions between various factors and responses. Finally, analysis of optimized results (got from RSM solution) is done using various graphs and charts.

The basic approach used to replace the existing leaf spring (SAE 5160 steel) with CFRP leaf spring is shown in the figure 3.1. It describes the whole process through a conceptual framework.

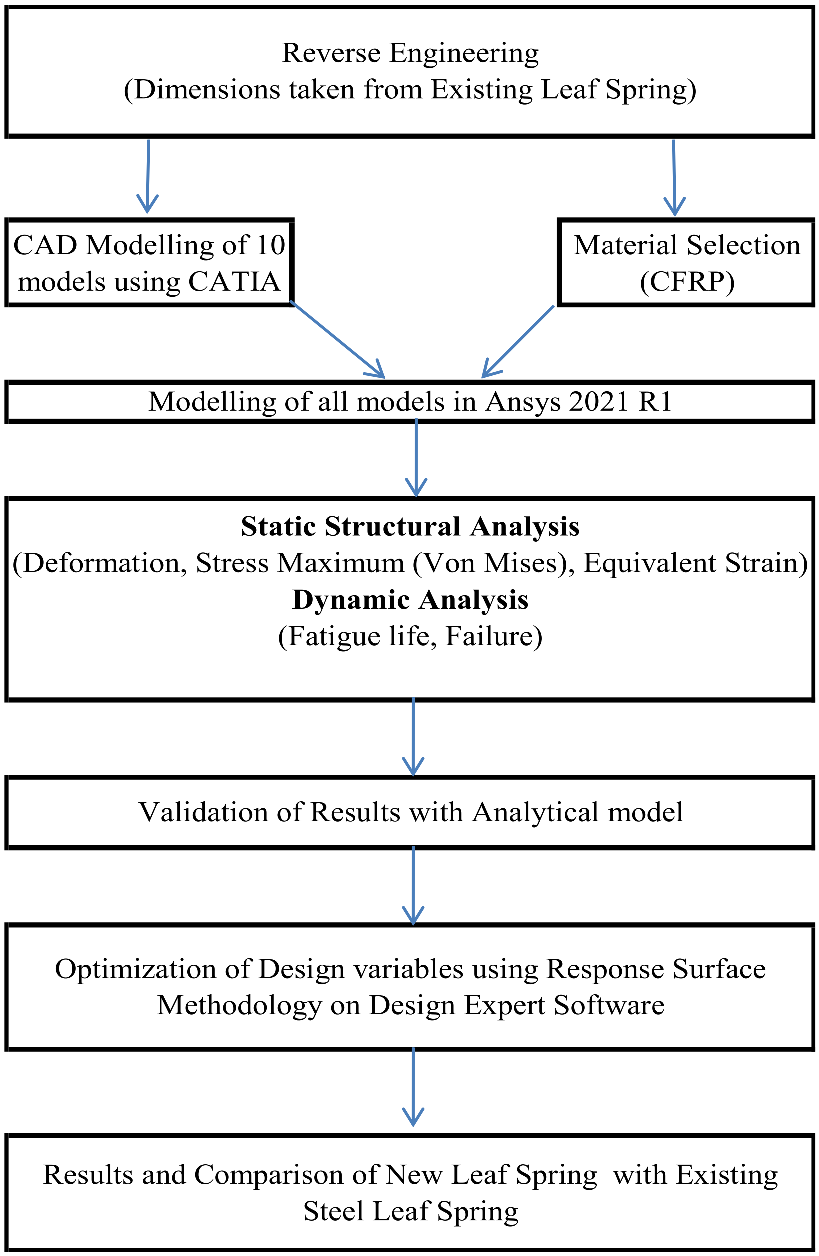


Fig 3.1- Flowchart Computed to Design the Research

3.2 Material Selection

Material selection is the most important step of designing a particular new model. After study the literature work, it is understood that composite can replace the steel in many engineering applications ranging from automotive industry to aerospace industry. Composites being lighter and high strength with respect to weight have been the first preference of researchers to improve the design.

Carbon Fiber Reinforce Polymers (CFRP) are selected to replace the SAE 5160 steel leaf spring. SAE 5160 steel which is used in electric trolley (discussed in chapter-1) are quenched and tempered chromium steel. These steels have high corrosion resistance due to presence of chromium in it. The composition of this steel is 97.1% Fe, 1% Mn, 0.9% Cr, 0.61% C, 0.35% Si, 0.04% S, and 0.035%. With respect to chromium steel, CFRP composites have high strength with respect to weight. CFRP composites have high strength with respect to weight and have high tensile strength, durability, heat resistance etc. CRFP are made of carbon fibers and Epoxy is used as an adhesive which is very strong and hard material which helps to improve strength and chemical resistivity. Considered CFRP composite is made up of woven fibers which are reinforced in layers. Composite materials properties are highly affected by the orientation of fibers in laminate and as per literature survey it is observed that fibers orientation at -45 and +45 degrees shows better results. The stiffness and strength of composite materials are influenced by the orientation of the fibers in the laminate. Properties of CFRP composite material is calculated by the use of rule of mixture (Jones

Calculation of CFRP Properties

Determination of Composite Density

$$\rho c=\rho f*Vf+\rho m*V \qquad (3.1)$$

ρc=(1.95∗1000∗0.7)+(1.45∗1000∗0.3)

ρc=1800 $Kg/m3$

Determination of Longitudinal Modulus E11

$$\mathbf{E11= (Ef*Vf)+(Em*Vm)} \qquad (3.2)$$

$E11$=23. GPa

Determination of Transverse Modulus E22

$$\mathbf{E22=(Ef*Em)/(Vf*Em+Vm*Ef)} \qquad (3.3)$$

$E22$=23GPa

Poisson's Ratio

$\nu 12$=($Vf*\nu f$)+($Vm*\nu m$) (3.4)

$\nu 12$= 0.2

$\nu 21$=0.4

$\nu 23$=0.2

Shear modulus of fiber

Gf=$Ef/2$(1+Vf) (3.5)

Gf=8.214GPa

Gm=4.03GPa

Shear Modulus of Composite

$G12$=$Gf*Gm/Vf*Gm+Vm*Gf$ (3.6)

$G12$=9.0 GPa

$G23$=$E22$(1-$\nu 23$)

$G23$=8.2143 GPa

Carbon fiber properties are referred from "Mechanics of composite materials" book 2nd edition by Robert Jones .

3.3 Research Design, Procedures and Tools Used

After selection of material, various softwares were used in a sequence to get the desired outcome. As described earlier, CATIA was used for CAD Modeling of all leaf spring models (described in chapter 4). ANSYS was used for modeling and simulation work. RSM software "Design Expert" is used for optimization of leaf spring.

After CAD modeling, all models are imported from CATIA to ANSYS Software. ANSYS software works on the principle of FEA. As discussed earlier, FEA is a numeric technique which is mostly referred for getting approximated result by the solution of partial differential equations which is developed by using various boundary conditions, external applied loads etc. A comprehensive layout of the modelinGPart in ANSYS is shown in the figure 3.2.

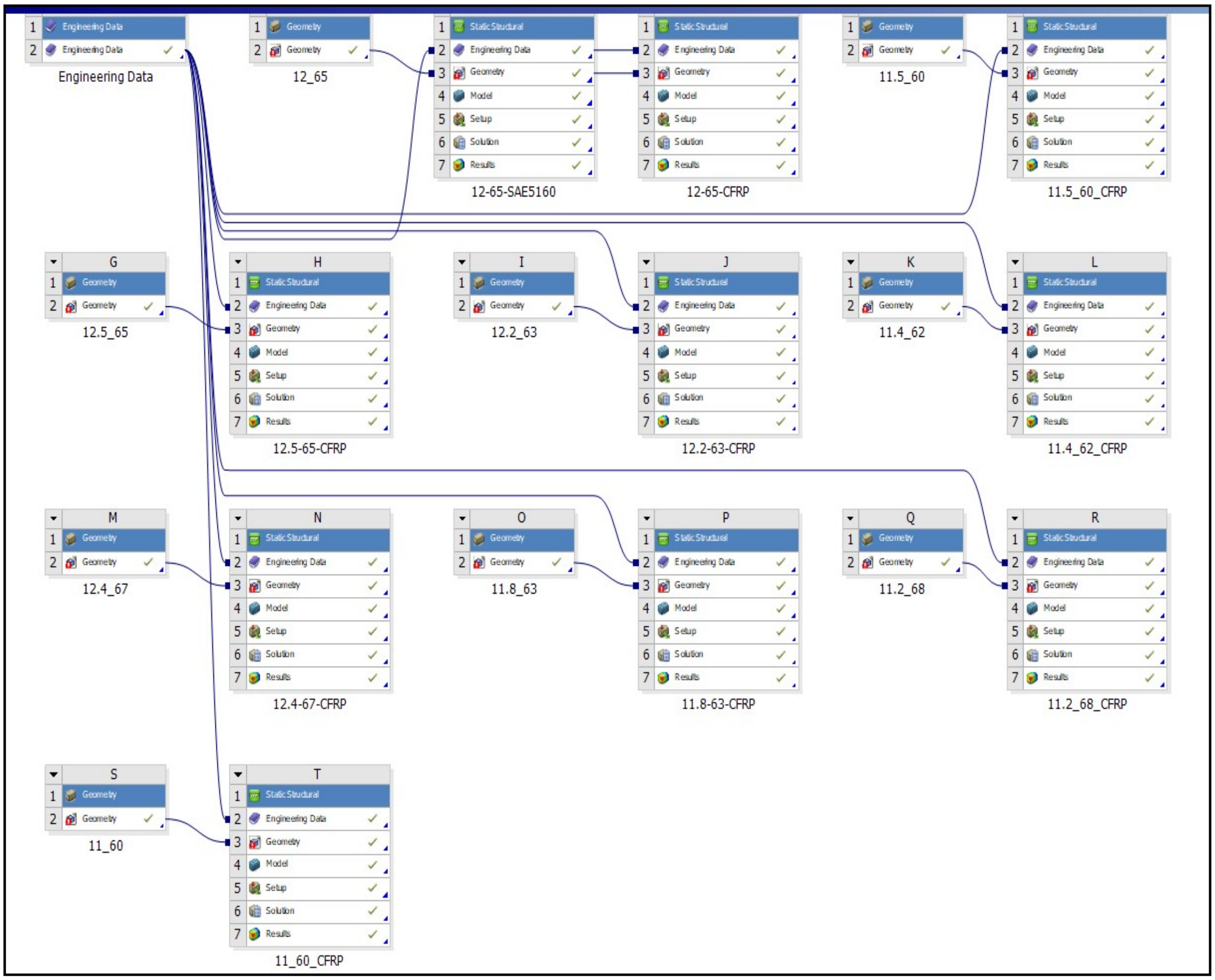


Fig3.2: Layout of the Modeling Part in ANSYS

In our study, FEA is done via. ANSYS 2021R1 software for steel and CFRP (CFRP) springs.

ANSYS modeling is divided into mainly 3 parts:

- Modeling (Pre-processing)
- ANSYS workbench solving/ analysis of results
- Post processing (interpretation of results)

The detailed work of modeling and Analysis is discussed in chapter 4.

For optimization part, RSM is used as it conducts large number of experiments in a very short span of time which enables researchers to save time and money. It is world recognized statistical and mathematical tool which calculates the effect of various factors on the certain number of responses of interests. It is a tool which calculates and identifies the optimal responses by doing various numbers of experiments in short span of time. In this research, Design Expert software used the ANSYS results data to optimize the design of leaf spring. Width and thickness of leaf spring are optimized through RSM technique considering various constraints of responses chosen i.e. fatigue life, deflection, Von misses stress, mass etc.

For optimization through RSM, firstly we need to identify the independent factors and responses variables. Independent factor's lower and upper limit should be inputted in Design Expert software with respect to which alpha and face values of factors will be decided by software itself. Selection of responses is equally important as responses will play very important role in optimizing the factors. In this research work, width and thickness are taken as independent factors and 4 parameters i.e. stress, displacement (deformation), fatigue cycle and mass of leaf spring models are considered as responses. All the experimental data required for modeling of various RSM model in Design Expert software is taken from the result part of ANSYS model. Values of all 4 responses with respect to independent factors are taken and inputted to create mathematical model for all the responses. Model selection (linear, quadratic, 2F1, cubic) is done on the basis of ANOVA, F test, Adjusted and predicted R^2 values difference and adequate precision ratio. After selection of particular model for all responses, mathematical equations are derived in terms of actual factors and coded factors. Modal graphs can also be generated using Design Expert software.

A flow diagram describing the processing of RSM is shown in figure 3.3

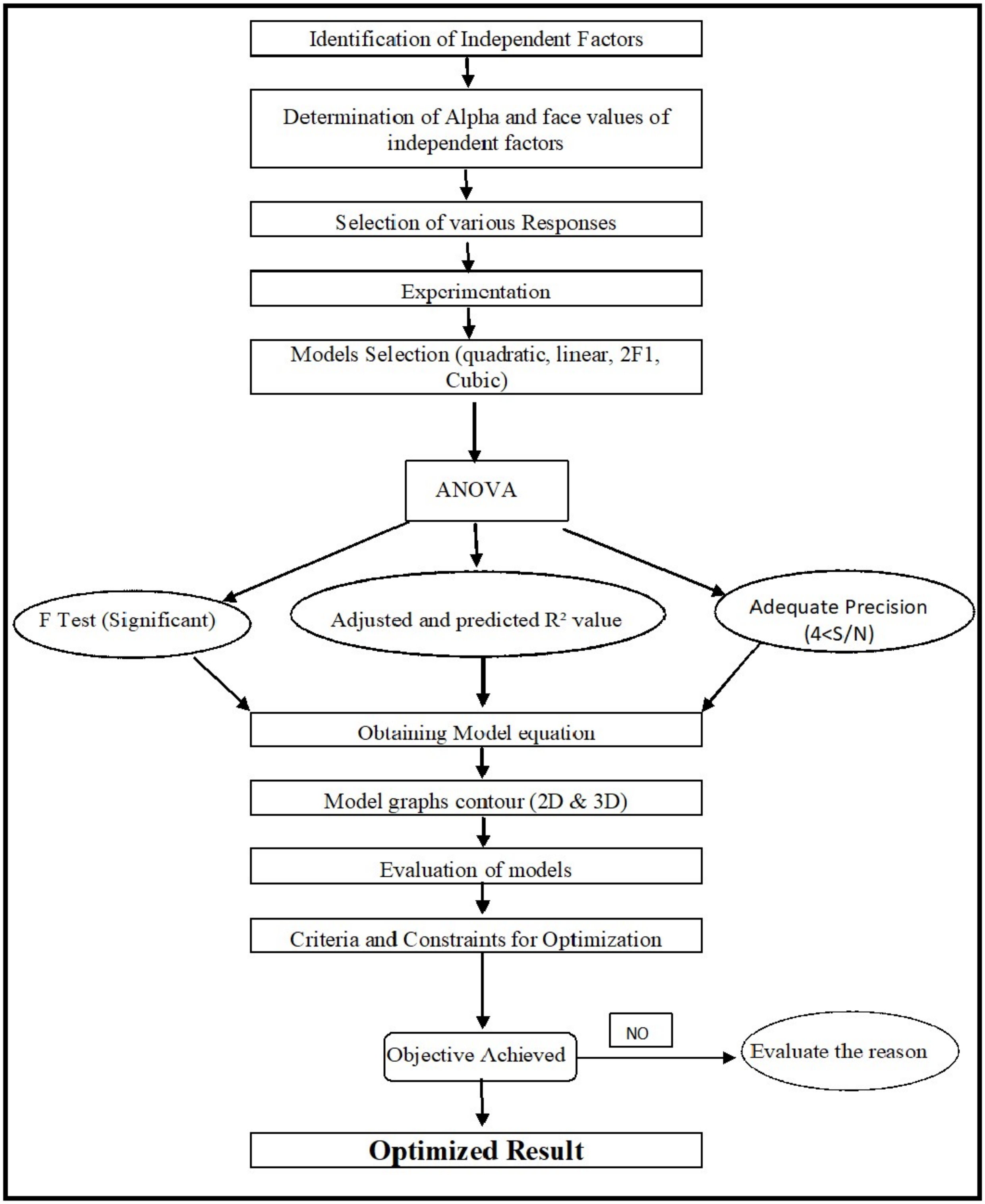


Fig 3.3: Flow Diagram Describing the Processing of RSM

Various mathematical equations are generated in terms of actual as well as coded factors which are further analyzed to get the optimized solution. These equations are elaborated in the chapter 5 of the thesis. All the responses variables equations are constructed by selecting particular model like quadratic model for mass, linear model for Von-misses stress etc. After obtaining mathematical equations and models for all the responses, various constraints are set for all the responses to optimize the independent factors. In this part, Design Expert software conducts various numbers of experiments (109 in this research) considering random values of independent factors (width and thickness) within range to get the optimized solution. A detailed discussion of RSM modeling and optimization is discussed in chapter 5.

3.4. Data Analysis

The results obtained from ANSYS are used in RSM software for creation of mathematical modeling of selected responses. Various statistical tools like ANOVA (Analysis of Variance), standard deviation etc are examined for obtained ANSYS data. Subsequently results of all 9 models of CFRP composites are analyzed and compared separately with result data of Steel leaf spring. The data analysis is done through various bar graphs and charts which are explained in chapter 6. Main outcomes of the analysis are:

- Maximum Stresses developed in all CFRP leaf springs are compared with the help of bar graphs.
- Masses of all 9 CFRP leaf springs are compared to the steel leaf spring mass.
- Deflection and Fatigue cycle in all leaf springs is compared and analyzed using charts.
- All these parameters of optimized CFRP leaf spring are compared with existing SAE5160 Steel leaf Spring.

Chapter-4

ANSYS MODELING AND ANALYSIS OF LEAF SPRING

4.1 Introduction

This chapter describes about the various models, techniques and softwares used for the obtaining the results in coherence manner. Initially all models were created in drafting software i.e. Computer Aided Three-dimensional Interactive Application (CATIA V 5) which had different dimensions and then all the models were imported in FEA (FEA) software i.e. ANSYS WB R1 2021 for Structural analysis work. Analysis of particular structure is very important as it decides whether a specific structural design is safe or not with respect to the external forces or internal stresses. For particular designing of a mechanical component, determining the primary reason of failure is very important.

ANSYS is a FEA software used to simulate interaction among different disciplines of physical structure, vibration, fluid dynamics, physics electromagnetic and heat transfer. It performs static structural analysis to asses complete deformation, stress developed etc and can also study the fatigue behavior, life and characteristics in dynamic conditions. FEA consists three main process namely, pre-processing, structural analysis and post-processing.

In Pre- processing, we need to input all necessary details like, properties of the material, finite element discretization (meshing) and solution parameters i.e boundary conditions, types of loading etc. In second part of modelling, software performs matrix formations, inversion, multiplication & solution for Eigen values of those matrices which gives results for the required factor like displacement, strain, stress etc for static analysis. In Post-processing, ANSYS results are obtained and analyzed. Post processing is getting results, verifications of outcome, and conclusions. Further to this, it helps researchers to identify the design variables to improve the performance of particular design.

4.2 Drafting of Leaf Spring Models

Drafting of the Leaf models is carried out in Computer Aided Three-dimensional Interactive Application (CATIA) software which is multi platform for CAE(CAE), 3D Modelling, Computer Aided Design etc. CATIA is French company "Dassault Systems" developed software and is mostly preferred in design analysis as it supports multiple stages of product designing and development be it in initial stages of drafting or final stage of analysis. But in our study, we have used CATIA as drafting software only and created 9 models of leaf springs varying in thickness and width.

The multi-leaf steel spring which is use in electric trolley (mentioned in the problem) was measured and main leaf of that multi leaf spring is analyzed in our study. The fig. 4.1(A) and (B) depicts leaf spring models of different thickness and width which are created in CATIA. The geometrical dimensions of all the developed models are arranged together in table 4.1.

Table 4.1: Detailed Geometrical Dimensions of all the Models

Sl No.	Description	Material	Length (mm)	Width (mm)	Thickness (mm)
1	12_65 SAE5160	SAE	1200	65	12
2	12_65 CFRP	CFRP	1200	65	12
3	12.5_65 CFRP	CFRP	1200	65	12.5
4	12.4_67 CFRP	CFRP	1200	67	12.4
5	12.2_63 CFRP	CFRP	1200	63	12.2
6	11.8_63 CFRP	CFRP	1200	63	11.8
7	11.5_60 CFRP	CFRP	1200	60	11.5
8	11.4_62 CFRP	CFRP	1200	62	11.4
9	11.2_68 CFRP	CFRP	1200	68	11.2
10	11_60 CFRP	CFRP	1200	60	11

Various models of leaf spring are decided based on the geometry of the electric trolley suspension system arrangement where the steel leaf spring is assembled and based on that a particular range of width and thickness have been targeted i.e. like width range have been considered from 55.00mm to 68.00mm whereas thickness have been from 11.00 to 13.00 mm.

Also effective length of all the spring leaf models is same i.e. 1200mm. Also camber length in all leaf spring models is same i.e. 120 mm

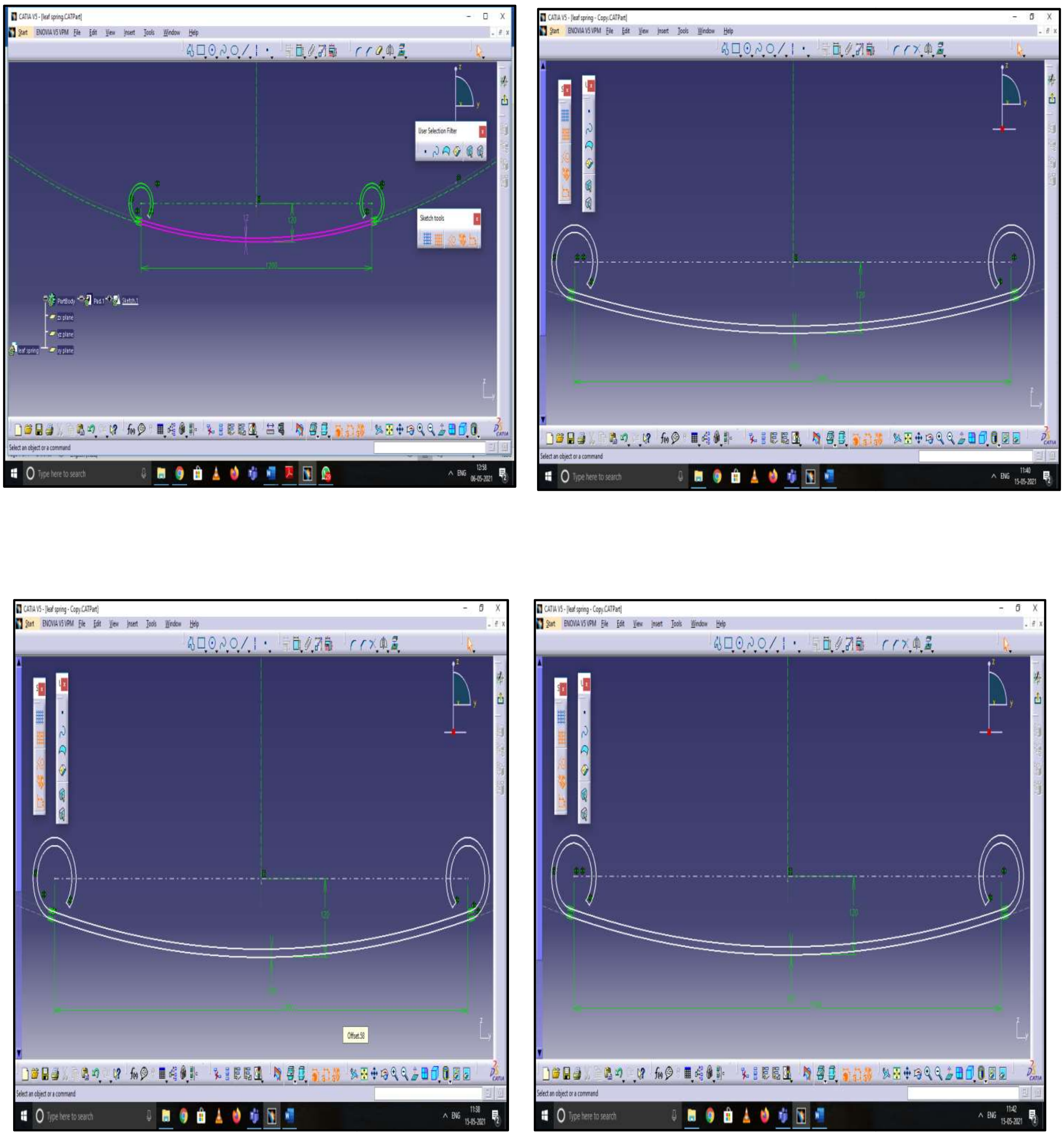


Fig. 4.1 (A): Leaf Spring Models created in CATIA

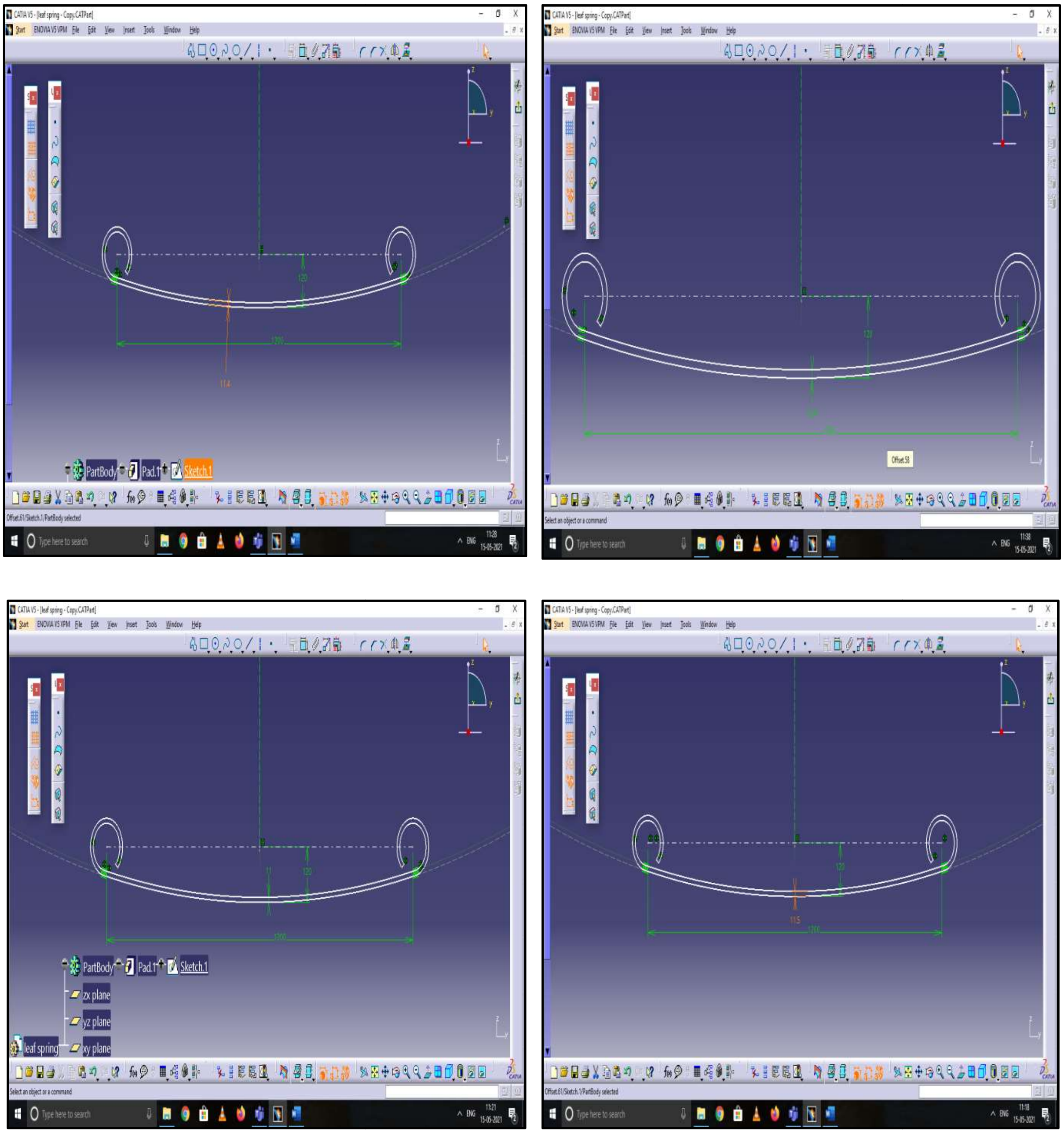


Fig. 4.1 (B): Leaf Spring Models created in CATIA

4.3 Finite Element Modeling and Analysis

The FEA is a numerical technique which is mostly used to get the approximated result by the solution of partial differential equations which is developed by using various boundary conditions, external applied loads etc. In our study FEA has been done in simulation software ANSYS workbench 2021R1 for steel as well as CFRP leaf spring models. ANSYS workbench 2021 is recently developed version. As mentioned earlier, these simulation softwares works on FEA techniques which is nothing but a mathematical representation of physical system comprising model, material properties, boundary conditions. All these are parts of pre-processing only. Similarly working of ANSYS is divided into 3 main parts which is

- Modeling (Pre-processing)
- ANSYS workbench solving/Analysis of results
- Post processing (interpretation of results)

4.3.1 Pre-Processing

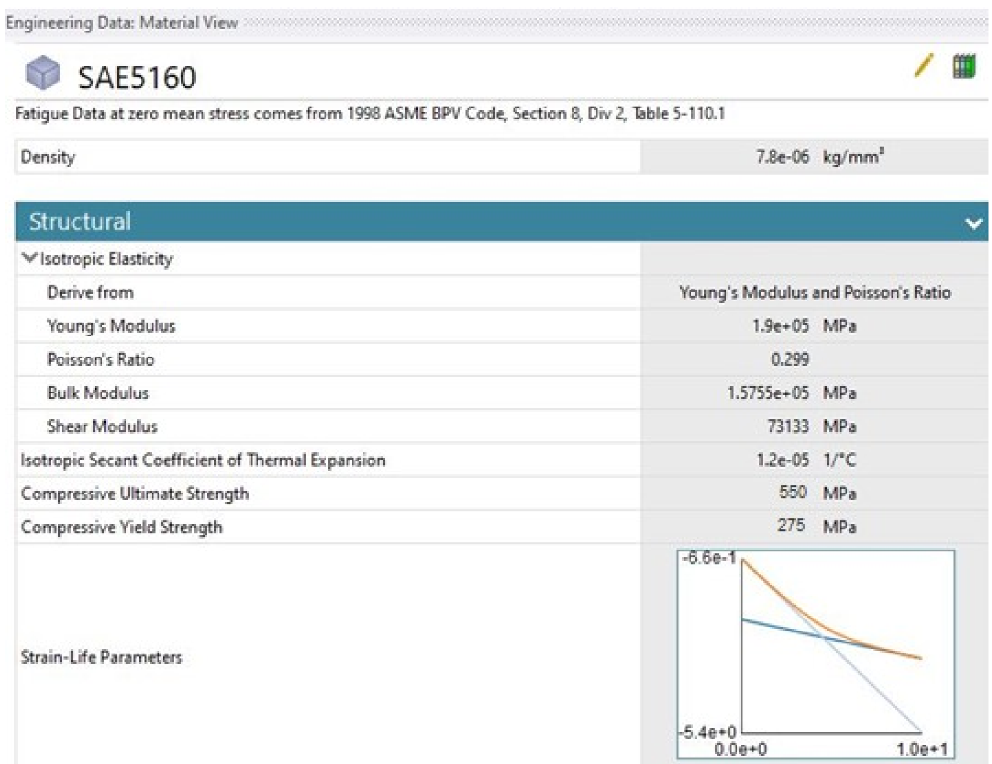
Pre-processing of FEM consist of various steps like import of model geometry from the CAD software in form of STEP, IGES format (e.g. from CATIA, SOLID-WORKS, PRO-E, AUTOCAD), meshing of the model into nodes and elements for better result, application of proper boundary conditions as related to actual condition, material property information input, external load information etc.

4.3.1.1 Import model from CATIA

All geometric models including ENT5160 steel spring model is imported into ANSYS from CATIA in IGES format. All these 10 models are shown in initial phase of this chapter along with tabular form.

4.3.1.2 Define Material Properties

In this we put the material properties of steel SAE5160 steel and CFRP composite in ANSYS. Figure 4.2 (A) and (B) depicts the properties inputted in ANSYS Workbench for SAE 5160 steel part-1 and part -11 respectively. The material properties of the existing leaf spring material have been taken from the existing literature related to the study (G.Loganathan et al.). SAE 5160 steel which is generally used in many engineering structures are quenched and tempered chromium steel. These steels have high corrosion resistance due to presence of chromium in it. The composition of this steel is 97.1% Fe, 1% Mn, 0.9% Cr, 0.61% C, 0.35% Si, 0.04% S, and 0.035%.


Engineering Data: Material View

SAE5160

Fatigue Data at zero mean stress comes from 1998 ASME BPV Code, Section 8, Div 2, Table 5-110.1

Density	7.8e-06 kg/mm³
Structural	
Isotropic Elasticity	
Derive from	Young's Modulus and Poisson's Ratio
Young's Modulus	1.9e+05 MPa
Poisson's Ratio	0.299
Bulk Modulus	1.5755e+05 MPa
Shear Modulus	73133 MPa
Isotropic Secant Coefficient of Thermal Expansion	1.2e-05 1/°C
Compressive Ultimate Strength	550 MPa
Compressive Yield Strength	275 MPa
Strain-Life Parameters	

Fig 4.2(A): Properties of Steel SAE5160 , (Part-I)

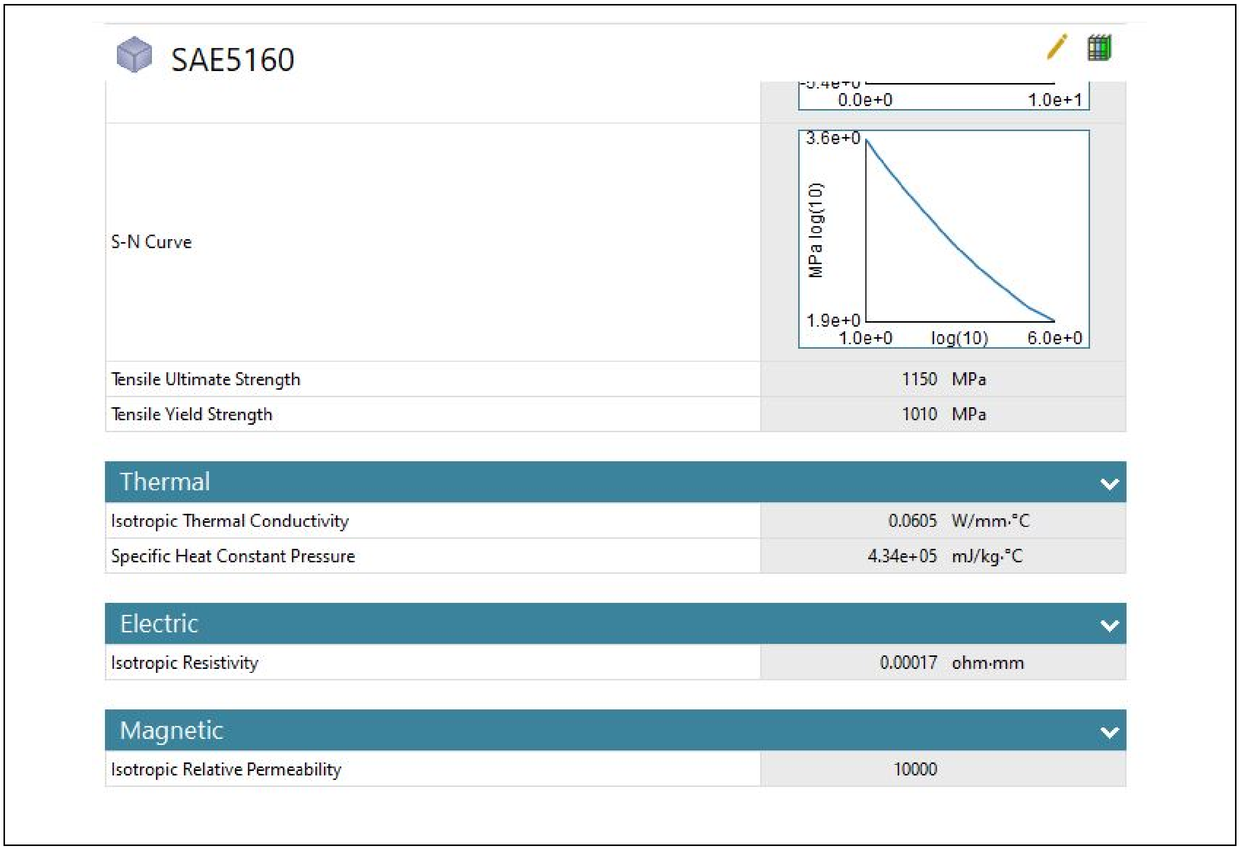


Fig 4.2 (B): Properties of SAE 5160 Steel, (Part-II)

Commercially available carbon fiber has high strength with respect to weight, high modulus and intermediate modulus. Carbon woven fiber has to be reinforced along with epoxy resin as a binder to make CFRP. For determining the properties of CFRP composite, the rule of mixture has been used which is elaborated in chapter 3 of the Thesis. Various properties of the CFRP are calculated which will be required for the analysis of CFRP material springs in ANSYS. Composite fiber properties are considered from "Mechanics of Composite Materials" book from Robert Jones.

Table 4.2 shows the properties calculated with the help of rule of mixture.

Table 4.2: Mechanical Properties of the CFRP

Properties	Metric
Density (kg/m3) Young's Modulus in X direction (E1)(GPa)	1800 23 GPa
Young's Modulus in Y direction (E2)	23 GPa
Young's Modulus in Z direction (E3)	23 GPa
Poisson ratio in XY direction	0.2
Poisson ratio in YZ direction	0.4
Poisson ratio in ZX direction	0.2
Shear Modulus in X direction (G12)(MPa)	9 G Pa
Shear Modulus in Y direction (G23)	8.2143G Pa
Shear Modulus in Z direction (G31)	9 GPa
Compressive yield strength	290 MPa
Tensile yield strength	300 MPa
Compressive ultimate strength	300 MPa
Tensile ultimate strength	600 MPa

Figure 4.3(A) and (B) shows the properties inputted in the ANSYS workbench for CFRP material.

Engineering Data: Material View

CFRP

Fatigue Data at zero mean stress comes from 1998 ASME BPV Code, Section 8, Div 2, Table 5-110.1

Density	1.8e-06	kg/mm^3
Structural		
Orthotropic Elasticity		
Young's Modulus X direction	2.3e+05	MPa
Young's Modulus Y direction	23000	MPa
Young's Modulus Z direction	23000	MPa
Poisson's Ratio XY	0.2	
Poisson's Ratio YZ	0.4	
Poisson's Ratio XZ	0.2	
Shear Modulus XY	9000	MPa
Shear Modulus YZ	8214.3	MPa
Shear Modulus XZ	9000	MPa
Isotropic Secant Coefficient of Thermal Expansion	1.2e-05	1/°C
Compressive Ultimate Strength	300	MPa
Compressive Yield Strength	285	MPa
Strain-Life Parameters		

Fig4.3 (A): Properties of CFRP (Part- I)

Engineering Data: Material View

CFRP

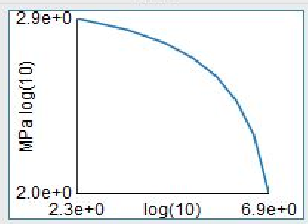
Strain-Life Parameters		
S-N Curve		
Tensile Ultimate Strength	600	MPa
Tensile Yield Strength	300	MPa
Thermal		
Isotropic Thermal Conductivity	0.0605	W/mm·°C
Specific Heat Constant Pressure	4.34e+05	mJ/kg·°C
Electric		
Isotropic Resistivity	0.00017	ohm·mm
Magnetic		
Isotropic Relative Permeability	10000	

Fig4.3 (B): Properties of CFRP (Part-II)

4.3.1.3 Meshing

Meshing is the crucial part of the FEA as better meshing reflects better results. Meshing is discretization of continuous geometry for solving the problem. More number of nodes and elements give better accuracy in results but sideways takes more computation time in analysis. It was observed that quadratic elements shows better results when compared with analytically calculated stresses and hence quadratic elements are selected in all the models and analysis is done. It is well know that meshing is an automated process but mesh quality can be improved by altering the underlying geometry or doing some changes at the corner meshing.

Mesh Size from 8.0 mm to 2mm was checked and finally 4 mm mesh size was considered for all cases as results were pretty accurate with this mesh size and computation time was also within limits. In view of that, number of nodes varies from 30000 to 100000, quadratic type elements varied from 8000 to 12000 in various models and due to that mesh convergence is obtained, so that Analysis results would not show any variation in results. Figure 4.5 shows the meshing of one of the model of CFRP leaf spring.

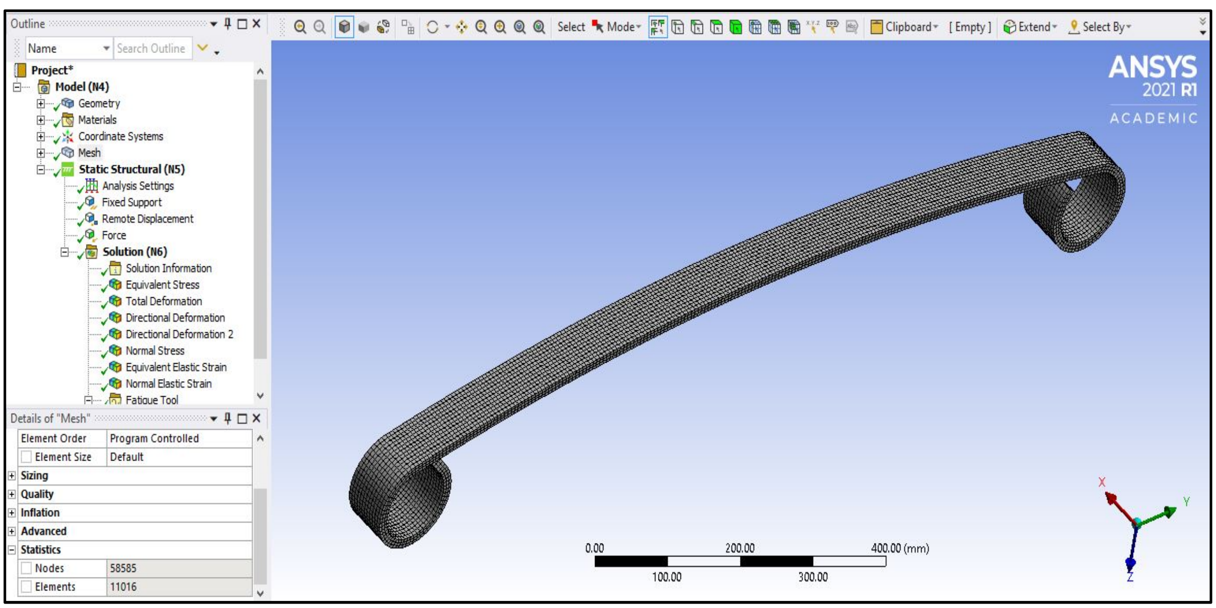


Fig 4.4: Meshing details of 12_65 CFRP Model

4.3.1.4 Boundary Condition and Loading

Boundary conditions are most important as we have to analyse the model considering real working condition. Boundary condition to Leaf spring is given per actual and real condition of leaf spring in trolley. Figure 4.6 shows applied loading and BC.

1. Left eye is taken as fixed Support.
2. Right Eye can rotate in principal axis and translate in transverse axis (remote displacement).
3. Applied force of 2500 N applied to top surface of the element. Value of load is decided as per actual loading condition and keeping factor of safety 2.

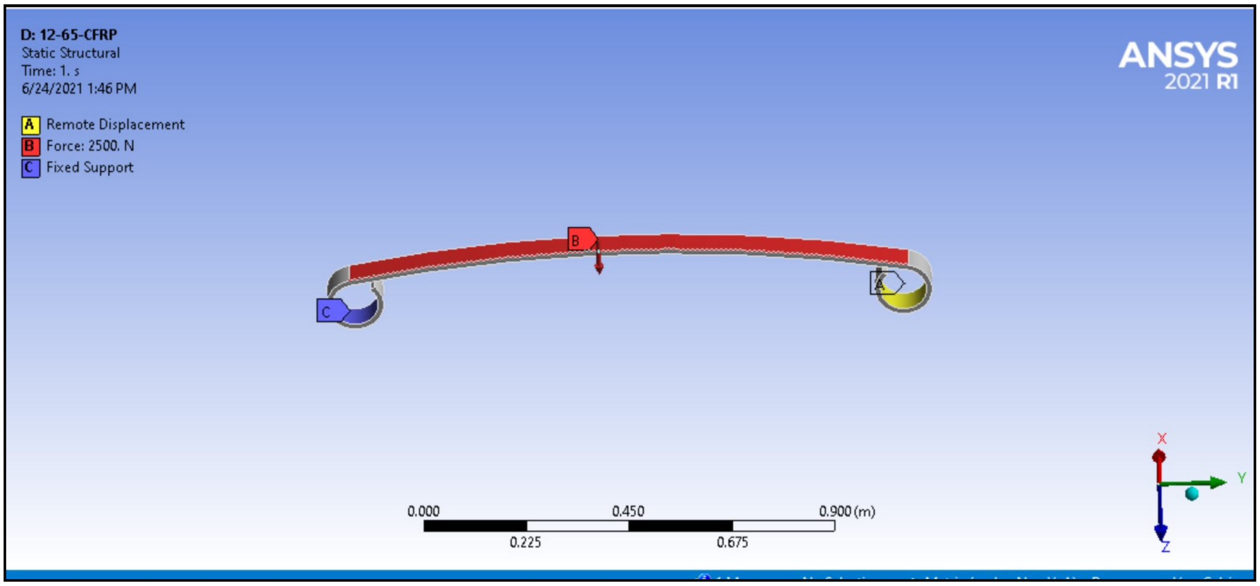


Fig. 4.5: Loading and Boundary Condition

4.3.2 Solution

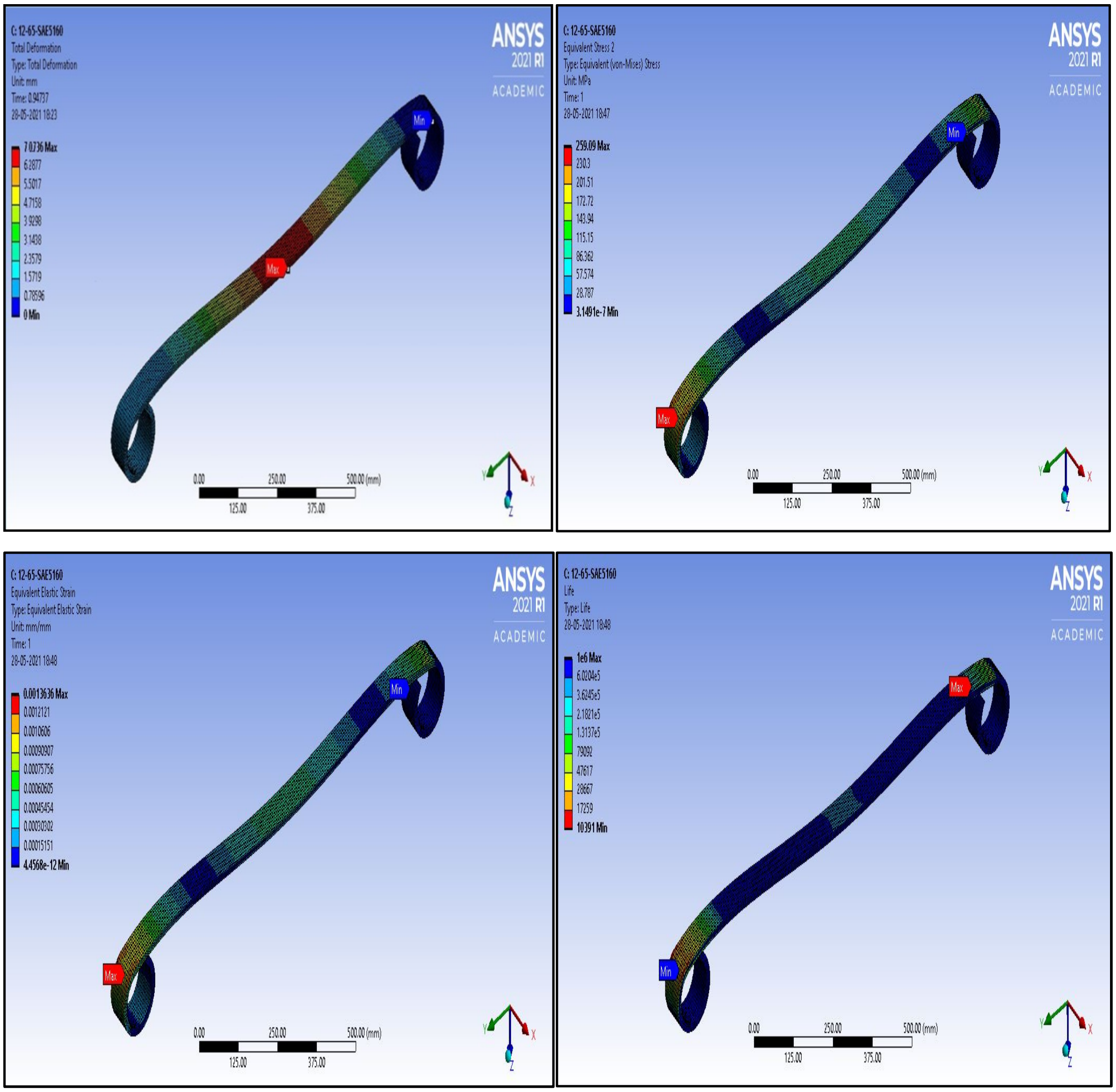
Solution happens in the background of the software and in this partial differential equations are converted into algebraic equations and that help it to represent equations in terms of matrices. Matrices of individual elements are assembled to make global matrices for complete model which will further solved for desired variable. Like in our particular model, we desire solution for equivalent Von-misses stress, strain, deformation and fatigue life.

4.3.3 Post processing

Once the solution part is successfully over, post processing of the results achieved is next step. Maximum stress induced, strains, deformation, fatigue life (minimum number of cycles before failure) are analyzed and concluded as per available data and information. Based on that, few modifications are required to improve the design.

In our analysis part, we got the result for all 10 models including 1 of SAE 5160 steel.

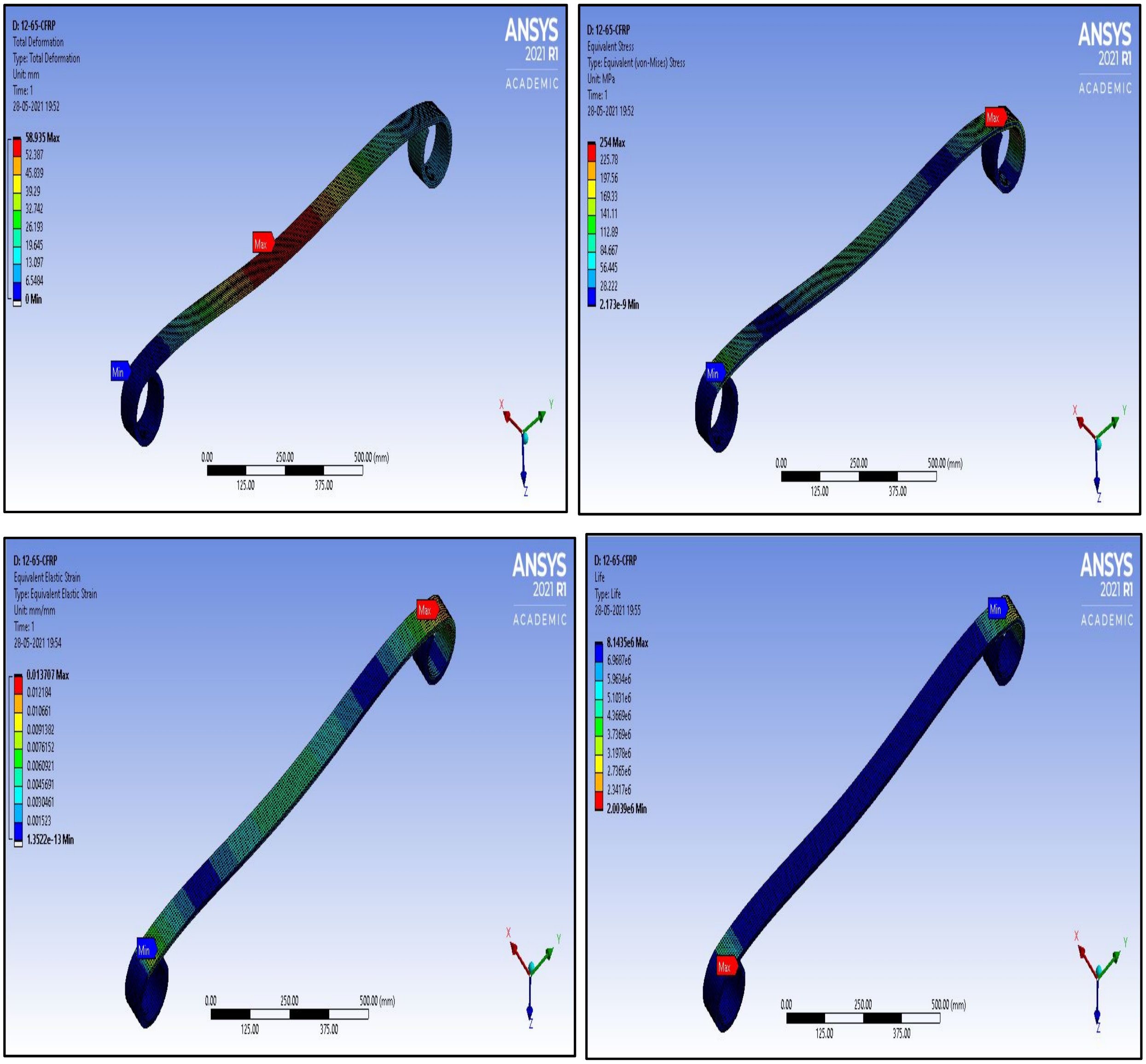
4.3.3.1 Result of Steel SAE5160 Leaf Spring Model



- Mass-11.1033 Kg
- Fatigue life-1.00e 006 cycles
- Equivalent Strain-0.00136
- Stress max-259 MPa
- Deformation-0.07 m

Fig. 4.6: Analysis of Steel SAE5160 Leaf Spring

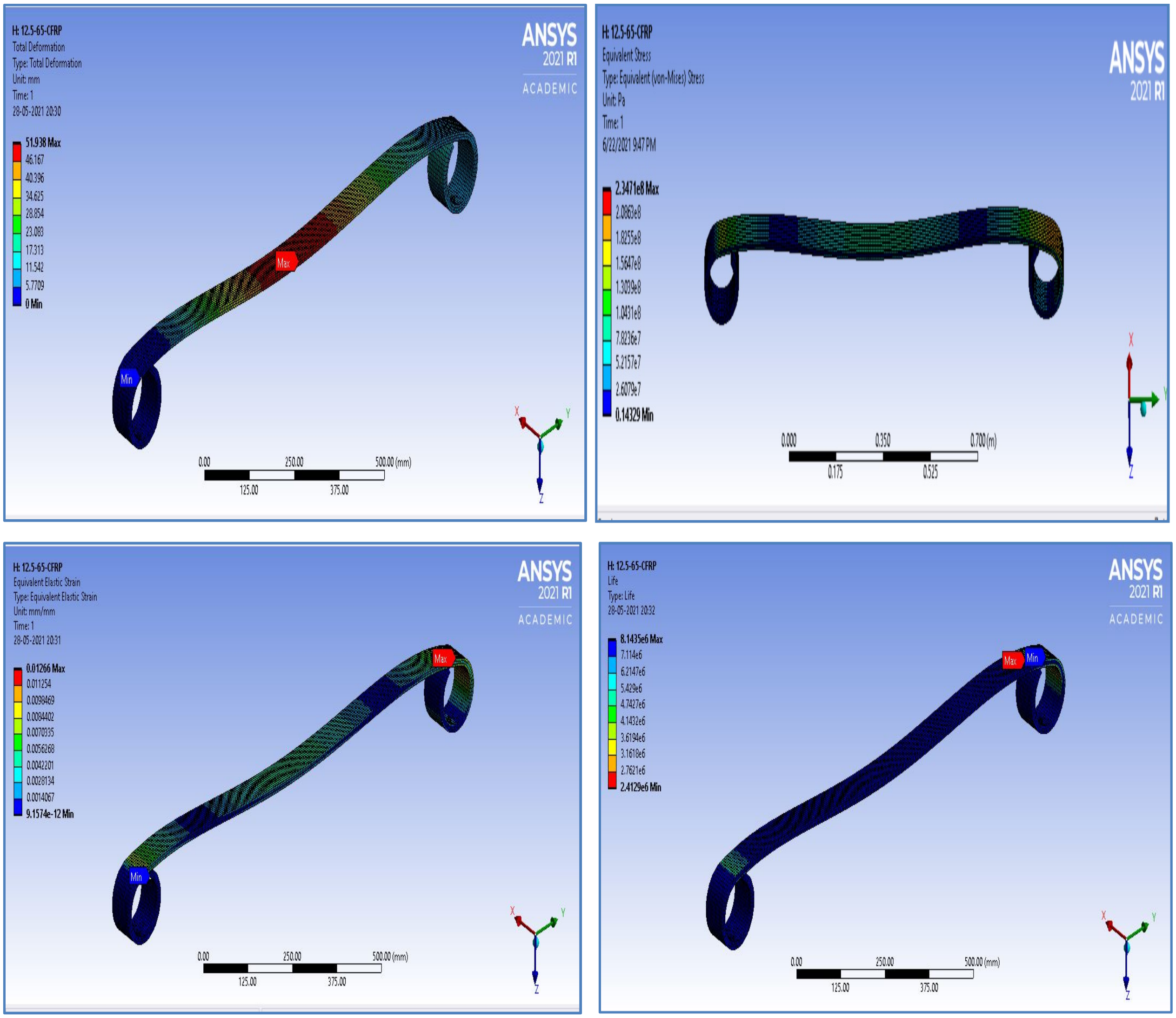
4.3.3.2 Result of CFRP 12_65 Model



- Mass-2.5623 Kg
- Fatigue life-2.0039e+006 cycles
- Equivalent Strain-0.001370
- Stress max-254 MPa
- Deformation-0.0585 m

Fig. 4.7: Analysis of CFRP 12_65 Model Leaf Spring

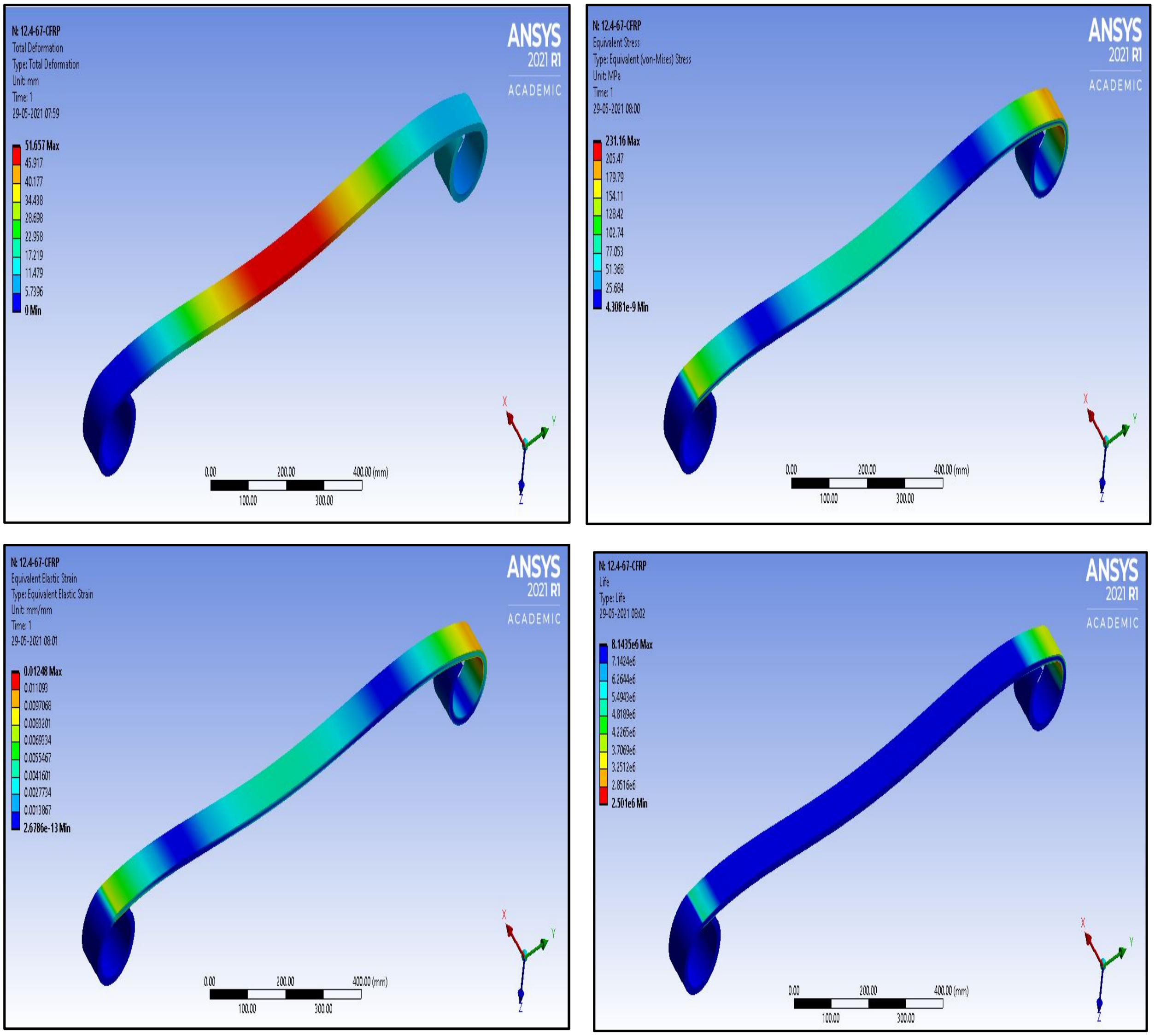
4.3.3.3 Result of CFRP 12.5_65 Model



- Mass-2.6634 Kg
- Fatigue life-2.4129e+006 cycles
- Equivalent Strain-0.01260
- Stress max-235 MPa
- Deformation-0.0519 m

Fig. 4.8: Analysis of CFRP 12.5_65 Model Leaf Spring

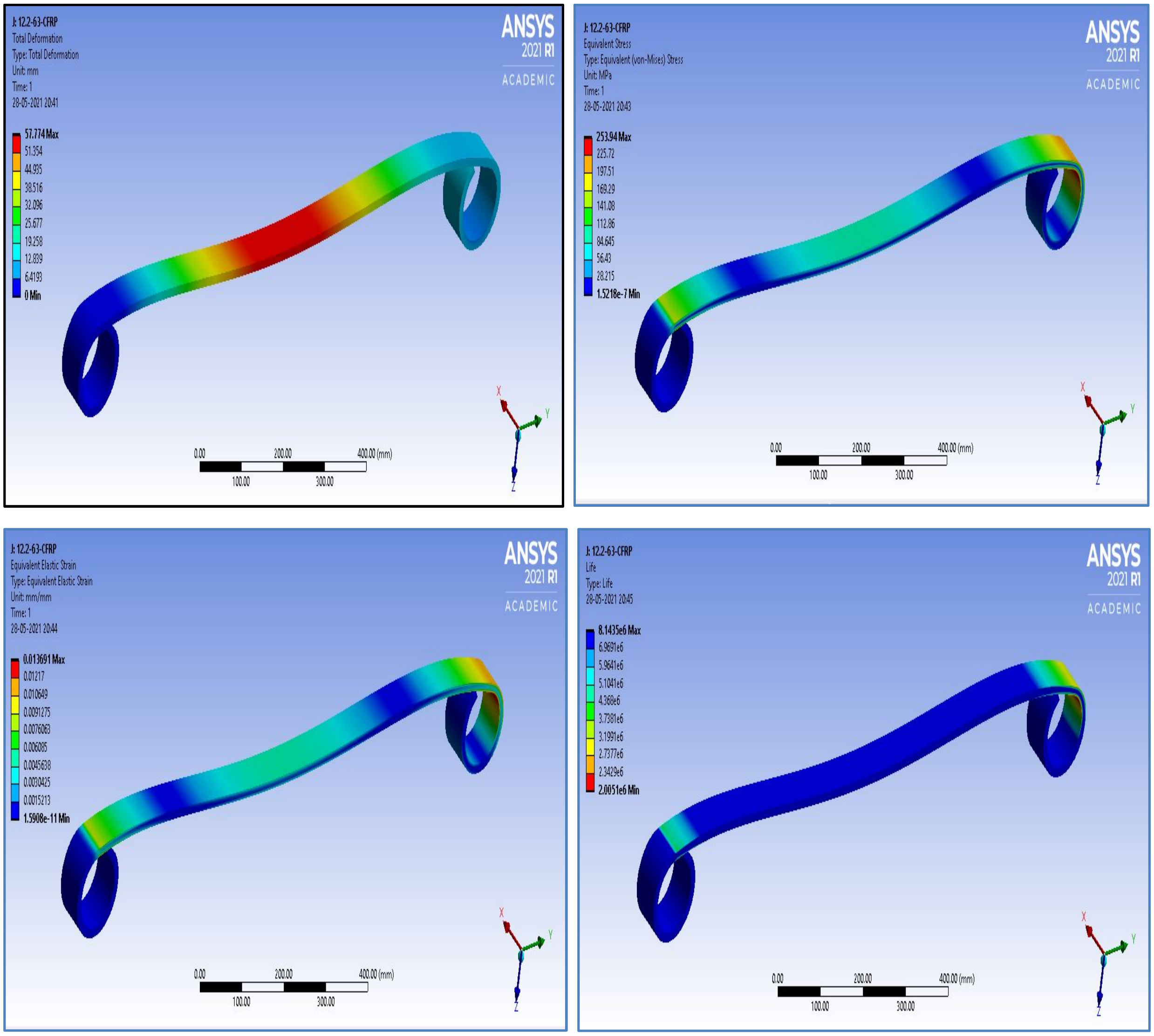
4.3.3.4 Result of CFRP 12.4_67 Model



- Mass-2.7242 Kg
- Fatigue life-2.501+006 cycles
- Equivalent Strain-0.01240
- Stress max-231 MPa
- Deformation-0.0516 m

Fig. 4.9: Analysis of CFRP 12.4_67 Model Leaf Spring

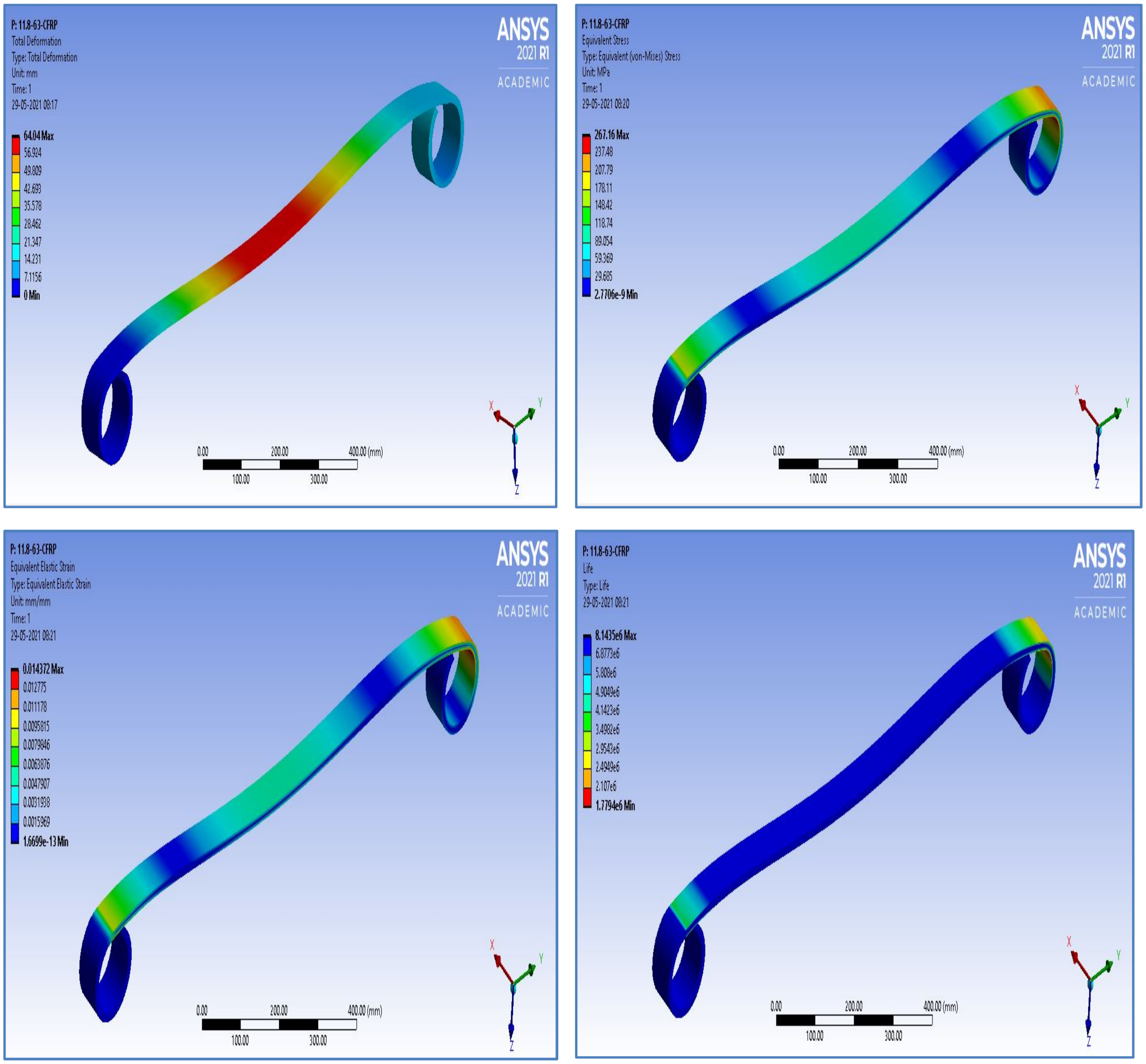
4.3.3.5 Result of CFRP 12.2_63 Model



- Mass-2.5218 Kg
- Fatigue life-2.0051e+006 cycles
- Equivalent Strain-0.01360
- Stress max-254 MPa
- Deformation-0.0577 m

Fig: 4.10:Analysis of CFRP 12.2_63 Model Leaf Spring

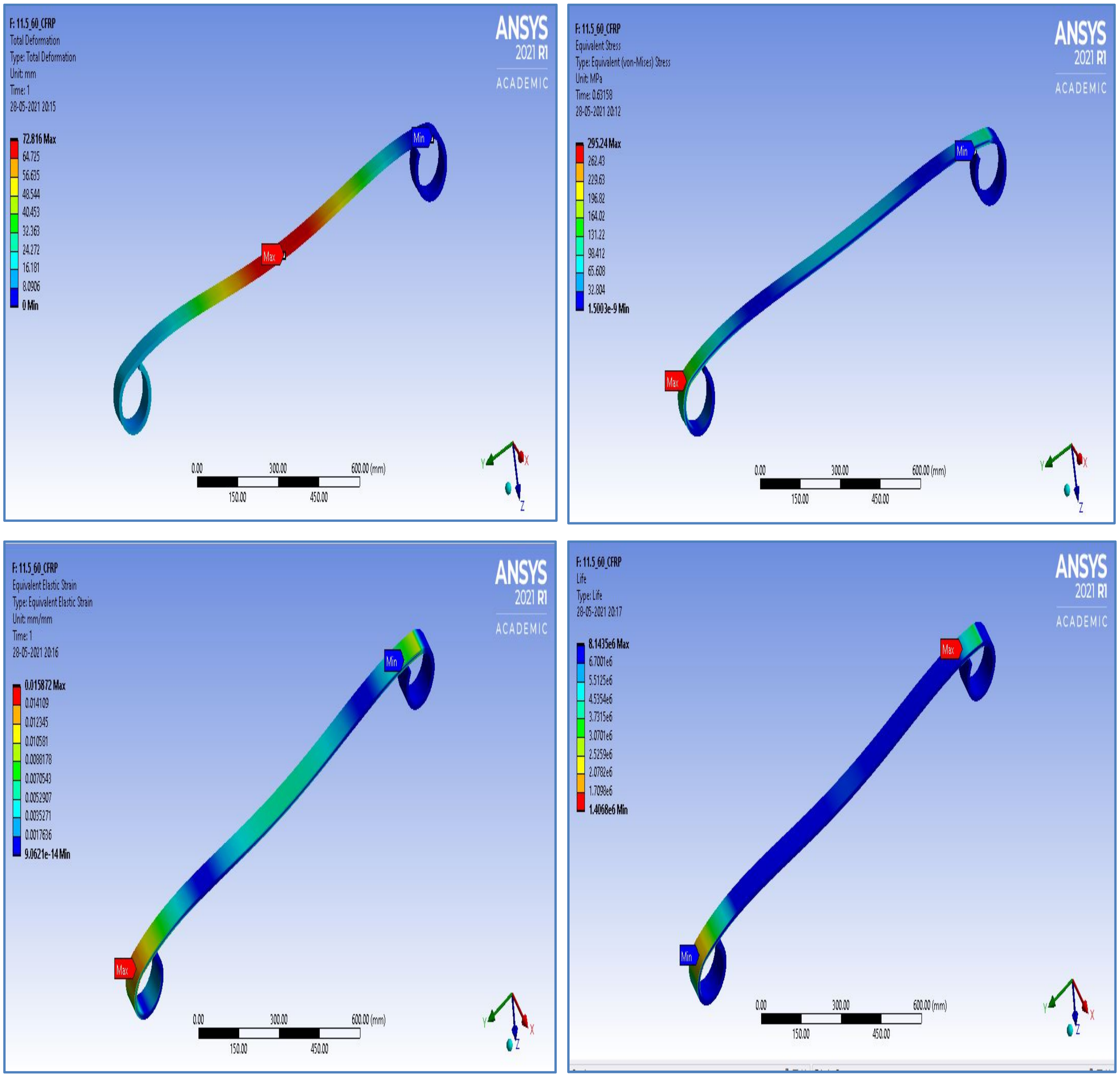
4.3.3.6 Result of CFRP 11.8_63 Model



- Mass-2.4420Kg
- Stress max-267 MPa
- Fatigue life-1.7794e+006 cycles
- Deformation-0.0640 m
- Equivalent Strain-0.01430

Fig: 4.11:Analysis of CFRP 11.8_63 Model Leaf Spring

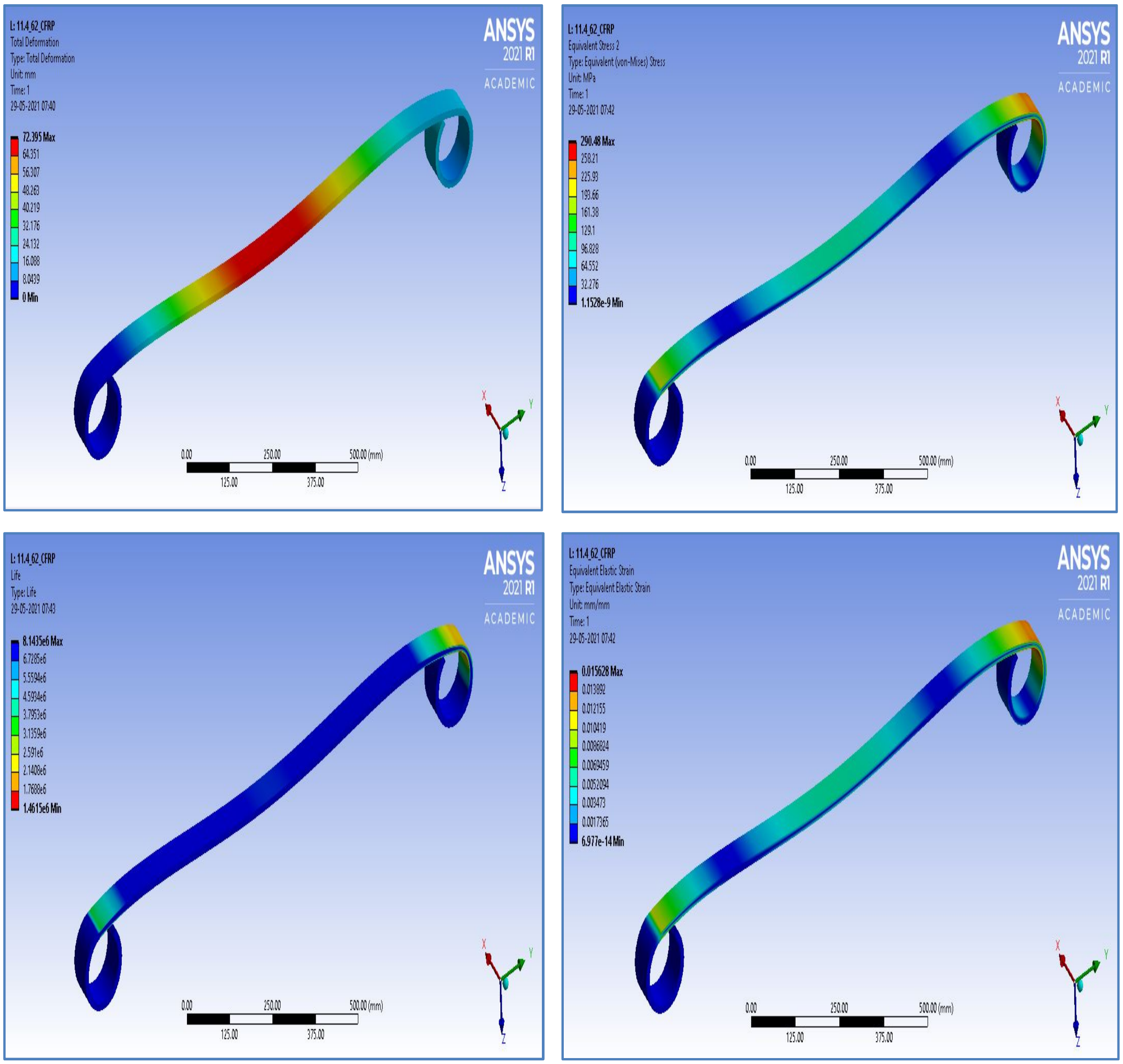
4.3.3.7 Result of CFRP 11.5_60 Model



- Mass-2.2666 Kg
- Fatigue life-1.4068+006 cycles
- Equivalent Strain-0.01580
- Stress max-295 MPa
- Deformation-0.0728 m

Fig: 4.12: Analysis of CFRP 11.5_60 Model Leaf Spring

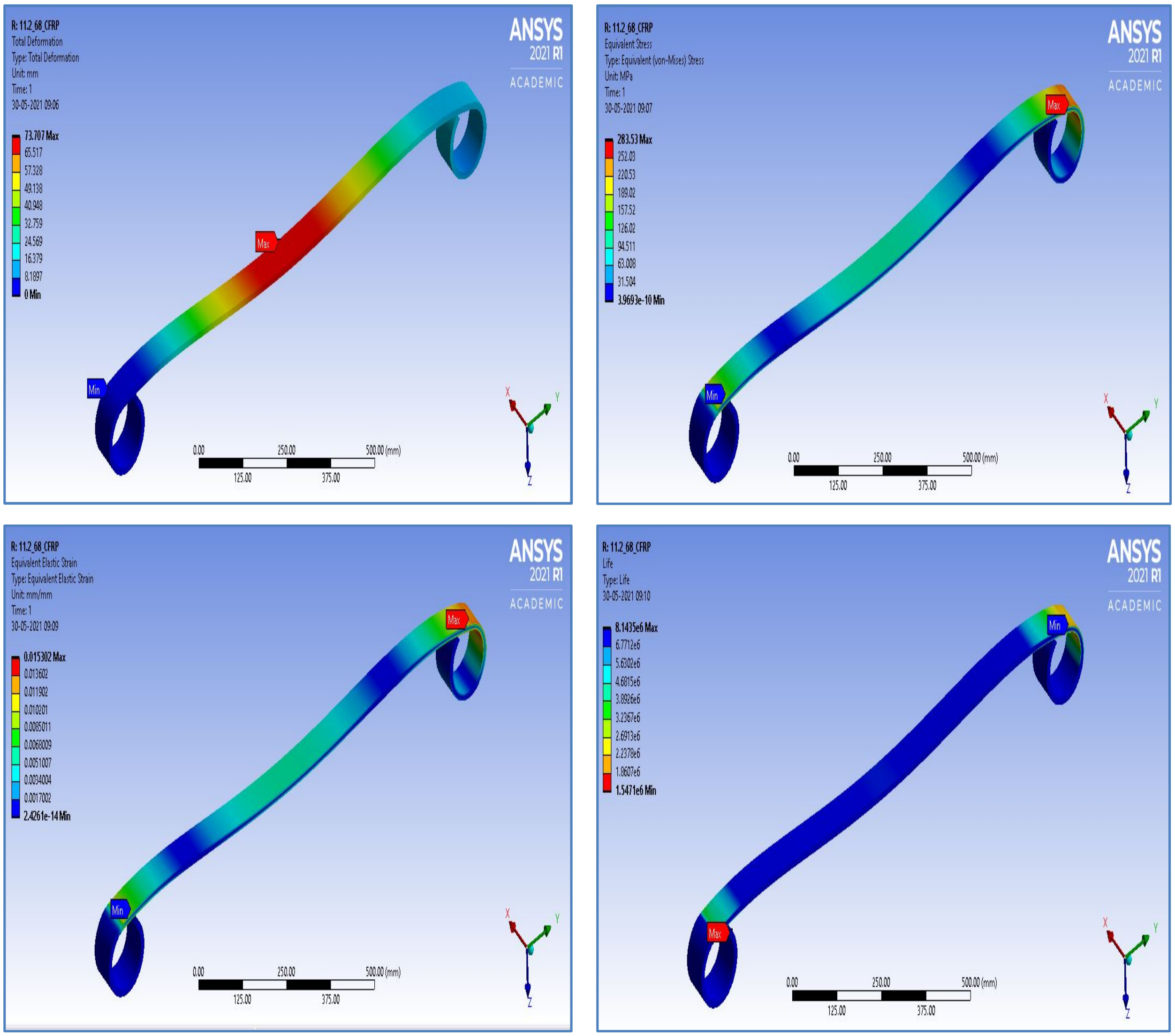
4.3.3.8 Result of CFRP 11.4_62 Model



- Mass-2.3246 Kg
- Stress max-290 MPa
- Fatigue life-1.4615e+006 cycles
- Deformation-0.0723 m
- Equivalent Strain-0.01560

Fig: 4.13: Analysis of CFRP 11.4_62 Model Leaf Spring

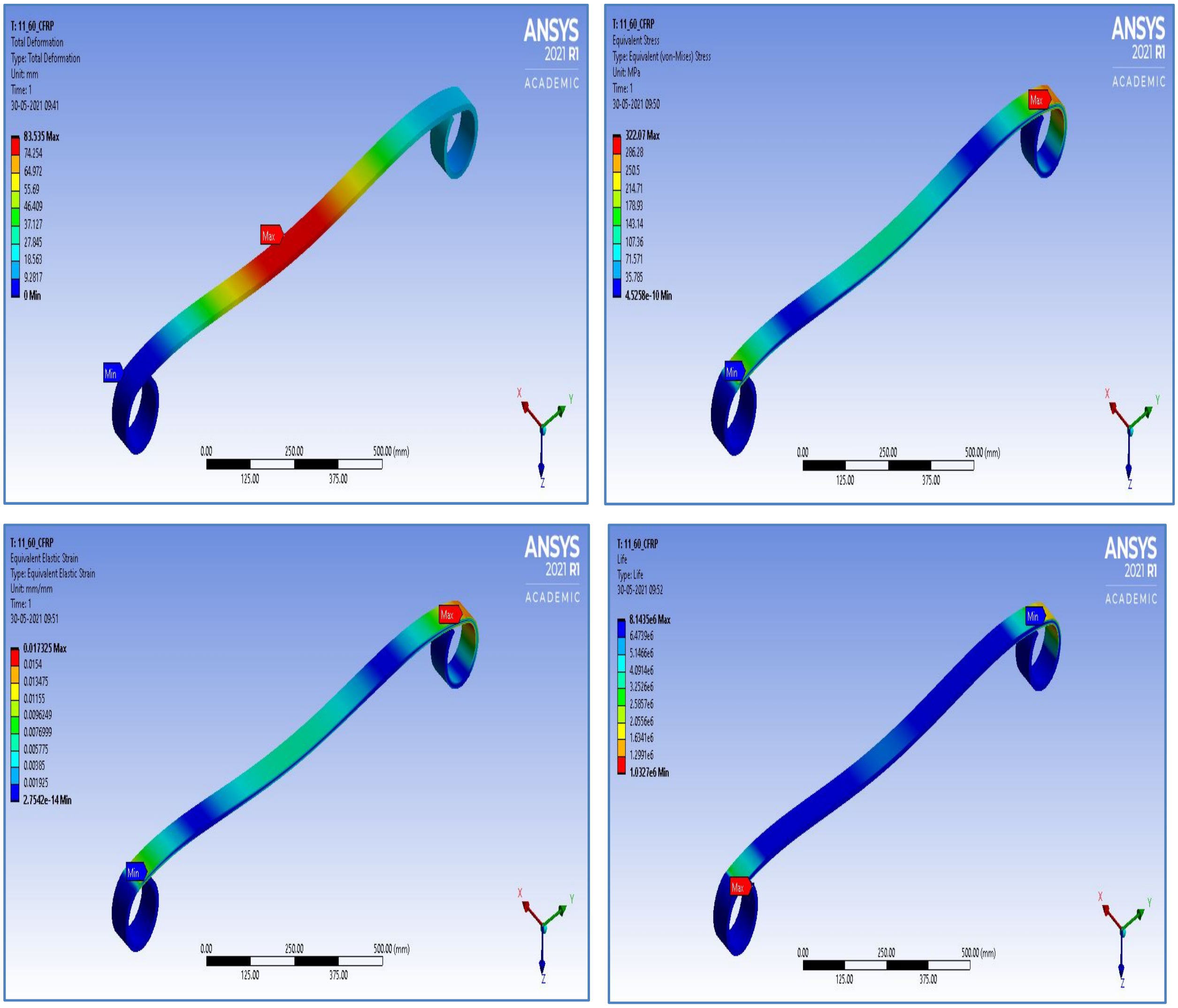
4.3.3.9 Result of CFRP 11.2_68 Model



- Mass-2.5018 Kg
- Fatigue life-1.5471e+006 cycles
- Equivalent Strain-0.01530
- Stress max-284 MPa
- Deformation-0.0737 m

Fig: 4.14: Analysis of CFRP 11.2_68 Model Leaf Spring

4.3.3.10 Result of CFRP 11_60 CFRP Model



- Mass-2.1681Kg
- Stress max-322 MPa
- Fatigue life-1.0327e+006 cycles
- Deformation-0.0835 m
- Equivalent Strain-0.01730

Fig: 4.15: Analysis of CFRP 11_60 Model Leaf Spring

4.3.4 Result Matrix of all Models :

There are 10 models for which FEM analysis is performed.

The table no. 4.3 shows the results obtained by using ANSYS WorkBench 2021 R1. The various parameters dealt under the study are stress max (Von-misses stress), fatigue life (minimum no. of cycles before failure), deformation, equvalent strain, masses of the spring.

Table 4.3: Results of various parameters in all models of Leaf Spring by ANSYS

Sl. No	Models	Material	Mass (Kg)	Stress max (MPa)	Fatigue life (min)	Deformation	Equivalent Strain max
1	12_65 SAE5160	SAE 5160	11.1033	259	1.00e+006 cycles	0.070 m	0.00136
2	12_65 CFRP	CFRP	2.5623	254	2.0039e+006 cycles	0.0585m	0.01370
3	12.5_65 CFRP	CFRP	2.6634	235	2.4129e+006 cycles	0.0519m	0.01260
4	12.4_67 CFRP	CFRP	2.7242	231	2.501e+006 cycles	0.0516m	0.01240
5	12.2_63 CFRP	CFRP	2.5218	254	2.0051e+006 cycles	0.0577m	0.01360
6	11.8_63 CFRP	CFRP	2.4420	267	1.7794e+006 cycles	0.0640m	0.01430
7	11.5_60 CFRP	CFRP	2.2666	295	1.4068e+006 cycles	0.0728m	0.01580
8	11.4_62 CFRP	CFRP	2.3246	290	1.4615e+006 cycles	0.0723m	0.01560
9	11.2_68 CFRP	CFRP	2.5018	284	1.5471e+006 cycles	0.0737m	0.01530
10	11_60 CFRP	CFRP	2.1681	322	1.0327e+006 cycles	0.0835m	0.01730

All these parameters values has been used in RSM (Design Expert software) for the optimization of the model of leaf spring which would best suits and can replace the steel leaf spring considering other factors also.

4.3.5 Validation of Model

It is necessary to validate the model before proceeding to optimization and there are different ways of valdating the model either by comparing the model results with experimental findings or comparing it with analytically calculated ones.

For vallidating with analytical model, we need to underdstand the design of multi leaf spring and has to derive the expression for maximum bending stress and deformation.

Design of Leaf Spring

Multi leaf or laminated spring consists of several flat parallel strips having identical width and thickness but varying length and placed one over another to improve load carrying capacity. Leaf spring works on the principle of cantilever beam and stresses developed in the leaf spring can be calculated with the same method as that of cantilever beam of varying thickness along the length. A complete structure of multi -leaf spring (fig. 4.16) along with all its sub-parts is shown below.

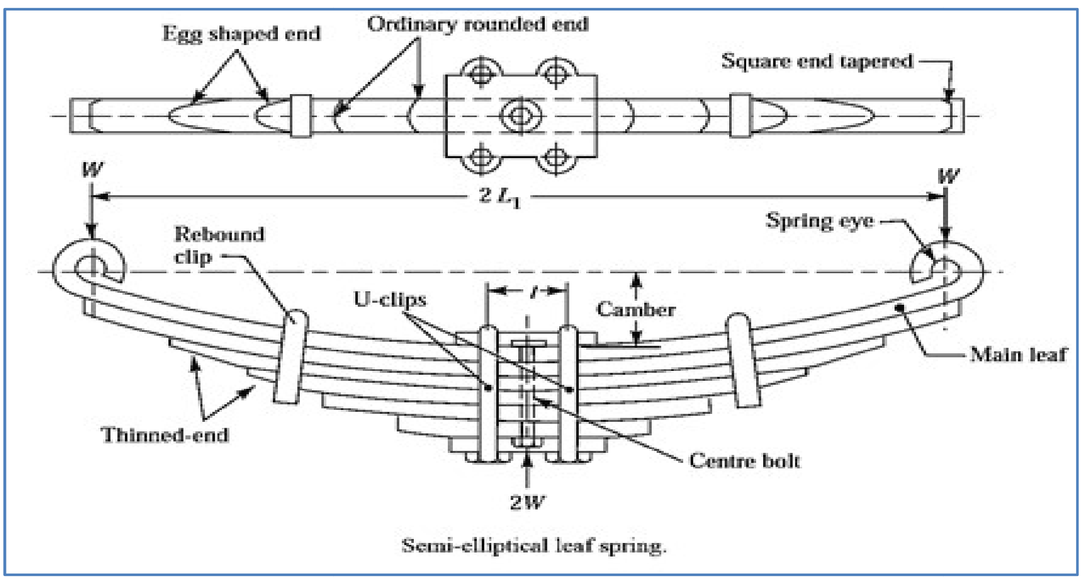


Fig. 4.16: Design of Multi-leaf Spring (Budynas and Nisbet, 2012)

Expression for maximum bending stress

As mentioned in above figure

t = Thickness of each plate

b = plates width

2L = span of Leaf spring (2L=1200 mm)

n = total number of plates

2W = load applied at leaf center (2500 Newton)

σ = Maximum bending stress

Bending moment at the center = (W) x L/2

Moment of Inertia:

$$I = bt^3/12 \qquad (4.1)$$

Bending stress can be calculated using formula

$$M/I = \sigma/y \qquad (4.2)$$

$$M = (\sigma/y) \times I$$

$$M = (2\,\sigma/t) \times bt^3/12$$

$$M = \sigma bt^2/ 6 \qquad (4.3)$$

Total resisting Moment:

$$n \times M$$

$$= \sigma nbt^2/ 6 \qquad (4.4)$$

Equating external and internal moments

$$WL/1 = \sigma nbt^2/ 6$$

$$\sigma = 6WL/ (nbt^2) \qquad (4.5)$$

For Single Leaf Spring:

$$\sigma = 6WL/(bt^2) \quad (4.6)$$

For Deflection in cantilever beam

$$\delta = W\ L3\ /\ (3\ E\ I) \quad (4.7)$$

E is Modulus of Elasticity of Material.

Based on above two expressions, maximum stress and deflection for all 10 models have been calculated and shown in table 4.4

Table 4.4: Analytical Model calculations

Sl No	Models	Material	Mass (Kg)	Analytical Model (stress in MPa)	Analytical model Deflection (mm)
1	12_65 SAE5160	SAE	11.1033	240	54
2	12_65 CFRP	CFRP	2.5623	240	50.16
3	12.5_65 CFRP	CFRP	2.6634	221.5	48.072
4	12.4_67 CFRP	CFRP	2.7242	218.4	44.1096
5	12.2_63 CFRP	CFRP	2.5218	239.9	49.248
6	11.8_63 CFRP	CFRP	2.4420	256.5	54.432
7	11.5_60 CFRP	CFRP	2.2666	283.5	61.7484
8	11.4_62 CFRP	CFRP	2.3246	279.24	61.344
9	11.2_68 CFRP	CFRP	2.5018	263.77	58.98
10	11_60 CFRP	CFRP	2.1681	309.07	75.06

When both analytically calculated stress and FEM stresses of all leaf spring models are compared, it is observed that there is difference of 3 to 7 percent. Similarly deformation i.e. deflections of all the leaf springs are compared and there was maximum 10-12 percent variation between the values of Analytical and FEM model. In view of this, it is observed that FEM modeling is successful one as it is showing results close to analytical values.

4.3.6 Summary

In this chapter, various 9 models of CFRP composite leaf spring are designed and analyzed through FEM. Various factor like deformation, Max. stresses (Von-Misses), equivalent strain, fatigue life (minimum no of cycle before failure) are examined. After getting result in post processing part of ANSYS, stress and deformation developed in FEM models are compared with Analytical model results and found pretty satisfactory.

Chapter : 5

OPTIMIZATION USING RSM

5.1 Introduction

This chapter describes about the use of RSM (RSM) in this research work to optimize various design parameters like width and thickness considering other parameters into considerations. RSM is world recognised statistical and mathematical tool which calculates the effect of various factors on the certain number of responses of interests. It is a tool which calculates and identifies the optimal responses by doing various numbers of experiments in short span of time. As conducting large number of experiments is a lengthy process, this methodology is very popular in researchers to get optimal solution in very short period of time. For modelling of RSM, we need to follow certain steps starting from selecting of independent variables and responses to putting experimental values of responses with respect to independent factors. RSM use various numerical tools, statistic techniques and graphs for creation of Mathematical Model and equations from the available data. For the creation of RSM model, Central composite design is selected which is commonly used to conduct large number of experiments within some range of factors.

In our study, we have used Design Expert @Software 10 for RSM modelling and optimization. It is mathematical and statistical software which is designed for performing design of experiments. RSM technique of Design Expert software is used in which it creates several matrices to examine various numbers of factors (maximum up to 50). Statistical Significance of selected factors can be examined by ANOVA (Analysis of Variance). Software also generates various graphs to study the inter-related relation of various factors, impact of factors on responses and etc.

5.2 RSM Optimization

RSM optimization is done via Design Expert software central composite module (design module) and in this modelling; we have considered the data collected from the results of FEM analysis. Table 5.1 describes about the build information of the model created in Design Expert software.

Table 5.1 RSM Build Information

File Version	11.1.2.0		
Study Type	Response Surface	**Subtype**	Randomized
Design Type	Central Composite	**Runs**	9
Design Model	Quadratic	**Blocks**	No Blocks

5.2.1. Selection of factors and responses

First Step of RSM is to select the important factors which are independent in nature and plays a significant role in designing of the component. In this case, width and thickness are considered as independent factors and their ranges are selected based on the actual requirement and constraints available. On the other hand, 4 responses are considered in our study which are maximum stress (von misses), deflection (deformation), mass of the leaf spring models and fatigue cycle (Minimum number of cycles before failure). All the data of independent factors and responses are taken from FEM analysis and then operated in the Design Expert software for creation of particular models for all responses. Table 5.1 depicts the whole information of the factors and responses matrices developed in RSM modeling.

Table 5.2 Details of Factors and Responses entered in Software

STD	Run	Factor 1 (thickness)	Factor 2 (width)	Response 1 (Stress Max)	Response 2 (Deflection)	Response 3 (Fatigue cycles)	Response 4 (Mass)
3	1	12	65	254	0.0585	2003900	2.5623
7	2	12.5	65	234.71	0.0519	2412900	2.6634
6	3	12.4	67	231.16	0.0516	2501000	2.7242
1	4	12.2	63	253.94	0.0577	2005100	2.5218
5	5	11.8	63	267.16	0.064	1779400	2.442
4	6	11.5	60	295.24	0.0728	1406800	2.2666
8	7	11.4	62	290.48	0.0723	1461500	2.3246
2	8	11.2	68	283.53	0.0737	1547100	2.5018
9	9	11	60	322.07	0.0835	1032700	2.1681

Table 5.3 Matrices shows maximum and minimum limit for both independent design parameters Coded high as well as coded low is automatically considered by the Design Expert software for the analysis work. Standard deviation and mean is also automatically calculated by this statistical software for further mathematical calculation. A factor considered here is thickness whereas width is considered as B factor.

Table 5.3 Matrices of Independent factors generated in RSM

Factor	**Name**	**Units**	**Type**	**Minimum**	**Maximum**	**Coded Low**	**Coded High**	**Mean**	**Std. Dev.**
A	thickness	mm	Numeric	11	12.5	-1 ↔ 11.00	+1 ↔ 13.00	11.78	0.5357
B	width	mm	Numeric	60	68	-1 ↔ 55.00	+1 ↔ 70.00	63.67	2.83

5.2.2 Analysis of Models

Analysis is the main part for modeling and optimization in Design Expert software. For Analysis we have to consider various important factors like ANOVA parameters which are P values, R squared values, adjustd R^2 and predicted R^2 value. And for all this, the design of experiments is focused on these particular factors. The regular R^2 can be artificially inflated by adding terms to the model even if that term value in not statistical significant. The adjusted R^2 value stabilizes when insignificant terms are incorporated in the model R^2 will decline when many insignificant terms are present in our model. In view of above, Adjusted R^2 value has to be within 0.2 range of predicted R^2 value to make our model significant. There are various ways of analysis which are

- Fit summary, Model, ANOVA (is like the calculator for analyzing data) are used to check their statistical significance.
- Diagnostic, model equations and model graphs gives an idea about the variation of responses.

Following steps are considered for all responses and P value, adjusted R^2 etc are checked for the significance of the model.

<u>Response 1: stress max</u>

<u>Fit Summary of Response (Stress max):</u>

It was observed that Linear Model suits best to stress maximum response as in this adjusted R^2 value and predicted R^2 value were close to each other. Also it was suggested by Design Expert software to go with linear Model for best results. Table 5.4 depicts about summary of fitness for model of stress maximum response.

Table 5.4: Fit Summary of Model for stress Max

Source	Sequential p-value	Lack of Fit p-value	Adjusted R²	Predicted R²	Remarks
Linear	3.22E-07		0.99086363	0.983304622	Suggested
2FI	0.351082896		0.990949316	0.929275681	
Quadratic	0.052018393		0.99789799	0.418205032	

<u>ANOVA for Linear Model (Stress max) :</u>

This is variance analysis for the stress maximum response Model. Table 5.5 depicts the model F value which is 434.81 for linear model and as per guidelines of Design Expert software model F value of 434.81 depicts statistic significance of the selected model. It is also observed that P value is lower than 0.05 which always indicates significance. There is 0.01% probability that the shown F value came because of some error, otherwise model is significant statistically.

Table: 5.5 ANOVA for (Stress Max. Response) Linear Model

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	7176.65	2	3588.33	434.81	< 0.0001	significant
A-thickness	4093.26	1	4093.26	496	< 0.0001	
B-width	573.43	1	573.43	69.48	0.0002	
Residual	49.52	6	8.25			
Cor Total	7226.17	8				

Based on the selection of model and after verifying significance of it, Design Expert software generates equations for the particular model like linear model for the stress max response.

Mathematical Equation of Stress Max Response (actual Factors)

Stress Max =1026.45160 - 46.41854*thickness -3.29042*width (5.1)

The above mentioned equation is in forms of actual factors which can be utilized to predict responses for specific values of factors. In this equation, all factors original units are maintained at particular level. Above mentioned equation was not utilized to decide the impact of factors as in this coefficient is scaled to consider and adjust the units of each factor.

Response 2: Displacement (Deformation)

Fit Summary of Response (Displacement):

It is observed that two models suits best for Displacement Response. One is linear model and another was quadratic one. For both models, adjusted R^2 value was in close range of predicted R^2 value but quadratic model is selected as we should select higher degree model for better calculation. Also it is recommended to select the higher order polynomial model when all statistical parameters are relevant and if that model is not biased. Table 5.6 depicts about the Fit summary of the model for displacement response.

Table 5.6 Fit Summary of Model for Displacement

Source	Sequential p-value	Lack of Fit p-value	Adjusted R^2	Predicted R^2	Remarks
Linear	< 0.0001		0.9884	0.9755	Suggested
2FI	0.4013		0.988	0.8951	
Quadratic	**0.0012**		**0.9998**	**0.9494**	**Suggested**
Cubic					Aliased

ANOVA for Quadratic model (Displacement Response): :

This is variance analysis for the displacement response model. Table 5.7 depicts the Model F value which is 6985.4 for quadratic model and as per guidelines of Design Expert software model F value of 6985.4 depicts statistic significance of the selected model. It is also observed that P value is lower than 0.05 which always indicates significance. There is 0.01% probability that the shown F value came because of some error, otherwise model is significant statistically.

Table 5.7 ANOVA for Response (Displacement) Quadratic Model

Sources	Sum of Squares	df	Mean Square	F_value	p_value	Remarks
Models	0.001	5	0.0002	6985.54	< 0.0001	significant
A-thickness	0.0001	1	0.0001	2020.87	< 0.0001	
B-width	8.05E-06	1	8.05E-06	287.07	0.0004	
AB	8.60E-07	1	8.60E-07	30.66	0.0116	
A^2	4.71E-06	1	4.71E-06	167.75	0.001	
B^2	1.01E-06	1	1.01E-06	35.86	0.0093	
Residual	8.41E-08	3	2.81E-08			
Cor Total	0.001	8				

Mathematical Equation of Displacment Response (actual Factors)

$$\textbf{Displacement} = +1.05015 - 0.107720*\text{thickness} - 0.006903*\text{width} - 0.000360*\text{thickness}*\text{width} + 0.004802*\text{thickness}^2 + 0.000080*\text{width}^2. \quad (5.2)$$

The above mentioned equation is in forms of actual factors which can be utilized to predict responses for specific values of factors. In this equation, all factors original units are maintained at particular level. Above mentioned equation was not utilized to decide the impact of factors as in this coefficient is scaled to consider and adjust the units of each factor.

Response 3: Fatigue life

Fit Summary of Response (Fatigue life):

It was observed that linear model suits best to fatigue cycle response as in this predicted R^2 value 0.9688 is in close range with 0.9905 value of adjusted R^2, also it is recommended to select that model in which all statistical parameters are relevant and model is not aliased but here cubic model is aliased. Table 5.8 depicts about the fit summary of the model for stress Maximum response.

Table 5.8 Fit Summary of Model for Fatigue life

Source	Sequential p-value	Lack of Fit p-value	Adjusted R²	Predicted R²	Remarks
Linear	< 0.0001		0.9905	0.9688	Suggested
2FI	0.0573		0.9949	0.9824	
Quadratic	0.7322		0.993	0.0913	
Cubic					Aliased

ANOVA for Linear model (Fatigue life):

This is variance analysis for the fatigue cycle response model. Table 5.9 depicts the model F value which is 419.15 for linear model and as per guidelines of Design Expert software model F value of 419.15 depicts statistic significance of the selected model. It is also observed that P value is lower than 0.05 which always indicates significance. There is 0.01% probability that the shown F value came because of some error, otherwise model is significant statistically

Table 5.9 ANOVA for Response (Fatigue life) Linear Model

Source	Sum of Squares	df	Mean Square	F-value	p-value	Remarks
Model	1.86E+12	2	9.30E+11	419.15	< 0.0001	significant
A-thickness	1.09E+12	1	1.09E+12	490.54	< 0.0001	
B-width	1.34E+11	1	1.34E+11	60.33	0.0002	
Residual	1.33E+10	6	2.22E+09			

Mathematical Equation of Fatigue life Response (actual Factors)

Fatigue life = 1904000 + 756800 * thickness + 377000 * width (5.3)

The above mentioned equation is in forms of actual factors which can be utilized to predict responses for specific values of factors. In this equation, all factors original units are maintained at particular level. Above mentioned equation was not utilized to decide the impact of factors as in this coefficient is scaled to consider and adjust the units of each factor.

Response 4: Mass

Fit Summary of Mass Response:

It is observed that two models suits best for this Response. One is 2F1 model and another is quadratic one. For both models, Adjusted R^2 value was in close range of predicted R^2 value but quadratic model is selected as we should select higher degree model for better calculation. Also it is recommended to select the higher order polynomial model when all statistical parameters are relevant and if that model is not biased. Table 5.10 depicts about the Fit summary of the model for Displacement response.

Table 5.10 Fit Summary of Model for Mass

Source	Sequential p-value	Lack of Fit p-value	Adjusted R^2	Predicted R^2	Remarks
Linear	< 0.0001		0.9995	0.9971	
2FI	0.0038		0.9999	0.9991	Suggested
Quadratic	**0.0306**		**1**	**0.9983**	**Suggested**
Cubic					Aliased

ANOVA for Quadratic model (Mass response)

This is variance Analysis table for the Fatigue cycle response Model. Table 5.11 depicts the Model F value which is 97615.75 for quadratic

Table 5.11 ANOVA for Response (Mass) Quadratic Model

Source	Sum of Squares	df	Mean Square	F-value	p-value	Remarks
Model	0.2683	5	0.0537	97615.75	< 0.0001	significant
A-thickness	0.0097	1	0.0097	17600.26	< 0.0001	
B-width	0.0093	1	0.0093	16837.82	< 0.0001	
AB	0.0001	1	0.0001	166.39	0.001	
A^2	7.73E-06	1	7.73E-06	14.05	0.0331	
B^2	3.85E-06	1	3.85E-06	7	0.0773	
Residual	1.65E-06	3	5.50E-07			
Cor Total	0.2683	8				

Model and as per guidelines of Design Expert software Model F value 97615.75 depicts statistic significance of the selected model. It is also observed that P value is lower than 0.05 which always indicates significance. There is 0.01% probability that the shown F value came because of some error, otherwise model is significant statistically.

Mathematical Equation of Mass (in actual Factors)

$$\mathbf{Mass = -1.11125 + 0.111256 * thickness + 0.015213 * width + 0.003718 * thickness * width - 0.006154 * thickness^2 - 0.000157 * width^2} \quad (5.4)$$

The above mentioned equation is in forms of actual factors which can be utilized to predict responses for specific values of factors. In this equation, all factors original units are maintained at particular level. Above mentioned equation was not utilized to decide the impact of factors as in this coefficient is scaled to consider and adjust the units of each factor.

Figure 5.1 shows the summary of all the responses and their models considered in our study in RSM.

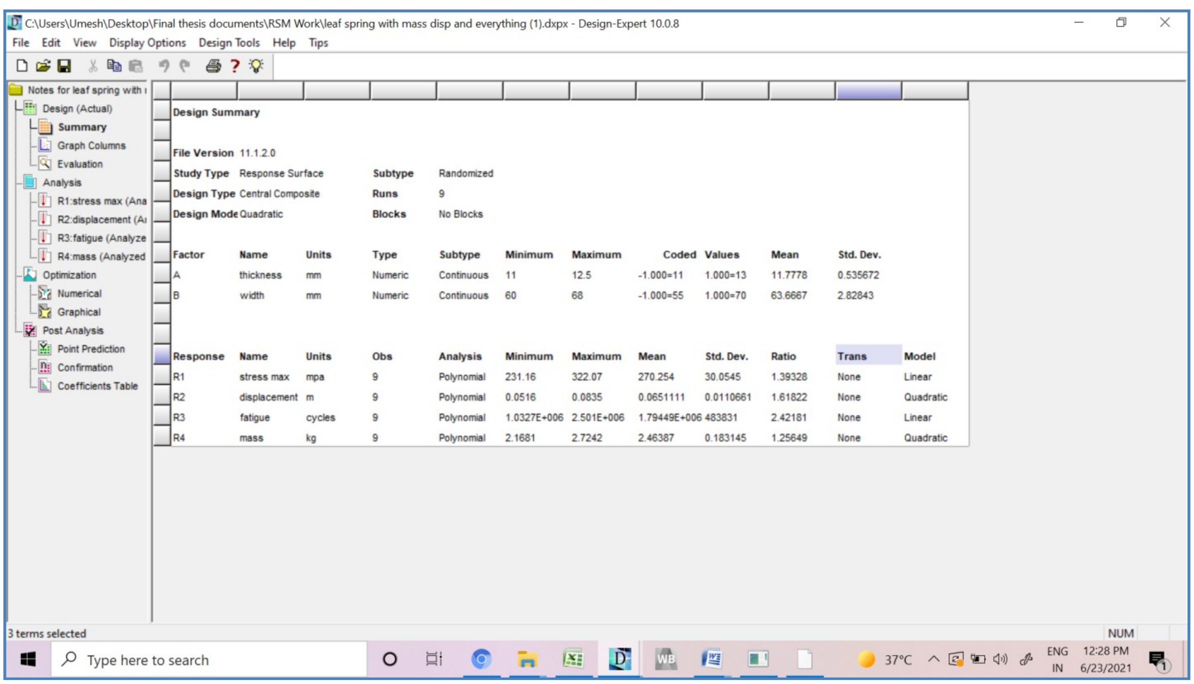


Fig.5.1 Detail summary of all responses models

5.2.3 Optimization

In this part of RSM, optimization can be reached either through numerical optimization or graphical optimization. For numerical optimization, one needs to set goals for each response and then run the software to get the optimum solutions for conditions/factors. Similarly in graphical optimization it is need to fix minimum and maximum limit of each response to create overlay of graph which shows area of operability.

In this study numerical optimization technique is selected to get the optimized solution and several constraints and ranges are identified and incorporated in RSM software before running it for optimization. Table 5.11 describes about the constraints.

Constraints

- Thickness should be minimized within the range of 11 to 13. And weight-age along with importance is given to this factor for minimizing.
- Width should be minimized within range from 55 to 70.
- Displacement/Deflection should be less for the particular loading condition.
- Fatigue life should be maximum and proper importance factor of 1.4 is given to this response.
- Stress max induced in the leaf spring should be minimized within range of permissible stress limit.
- Mass should be minimized with-in the range

Table 5.12: Constraints selected for optimization

Parameter	Motive	Lower Lt.	Higher Lt.	Lower Wt	Higher wt.	Imp.
Thickness	minimize	11	13	1	1.3	3
Width	minimize	55	70	1	1	3
Stress max	minimize	231.16	285	1	1.2	3
displacement	is in range	0.05	0.08	1	1	3
Fatigue Cycles	maximize	1032700	2501000	1.3	1	4
Mass	minimize	2.1681	2.7242	1	1.2	3

Starting Points

After identification of constraints, RSM software runs the solution and in our study, 109 different designs are checked and evaluated for different results. Details of those 109 points are shown in table 5.13. For all these starting points, calculation is being done as per the mathematical models derived in initial phase of this chapter and keeping the constraints in mind, Final optimized result is selected.

Table 5.13: Starting points of Experiments

Sl. No	Thickness	Width
1	12.5	65
2	11.8	63
3	12.2	63
4	11.5	60
5	12	65
6	11	60
7	12.4	67
8	11.2	68
9	11.4	62
10	11.33182721	60.0827046
11	11.04837461	62.3552376
12	11.8495269	62.16433389
13	11.00049659	58.45550933
14	12.83528059	60.60037296
15	11.37362227	61.17359319
16	11.9083207	64.45856335
17	11.69557078	63.84500823
18	12.25952812	56.64441398
19	11.84954478	57.48695219
20	11.94284016	65.99379268
21	12.19681112	61.21417043
22	12.09612739	67.58880305
23	11.30033784	65.35232119
24	12.58007631	62.9786752
25	12.1719737	69.48790766
26	11.52700979	64.80279522
27	11.13334579	57.39374765
28	12.5123545	60.14396563

29	12.96430497	64.24301619
30	11.14184556	68.61364441
31	12.52113916	69.59844362
32	12.76834304	59.86504556
33	11.8833377	64.0899861
34	11.36360075	66.84864313
35	12.11423406	57.0689594
36	11.0100027	62.28179453
37	12.12460874	58.00952136
38	12.04716579	68.04072594
39	11.35309302	67.15929205
40	11.22213546	69.82436573
41	12.73425564	65.59097992
42	12.30752529	66.3254768
43	12.70654465	56.64309419
44	11.600118	58.36809022
45	11.70696277	62.55226588
46	12.75704794	63.56834707
47	12.97864432	56.14750815
48	11.33530759	55.29478023
49	11.64890017	67.0281791
50	11.27522121	68.78153226
51	11.97771577	57.66031559
52	12.30200272	67.12644404
53	12.68648422	69.75599972
54	11.81942745	62.88693288
55	11.10020128	60.71676713
56	12.03091265	64.34892745
57	12.60290138	57.39604666
58	12.16716274	55.96325517
59	11.12126244	66.91131504
60	11.31288579	63.33793302
61	12.99920296	63.35852123
62	11.92202512	65.60786761
63	12.78867314	68.36588861
64	12.50802885	60.54462639
65	12.33522996	62.62403515
66	12.10415121	60.1486765
67	12.6730509	67.02982229
68	11.02717043	67.23937682
69	11.25499207	62.85274774

70	12.21631173	64.3227615
71	12.39292457	59.8721449
72	11.09283761	61.33511666
73	12.13479628	59.99445847
74	11.24412435	60.49409413
75	12.45740191	57.24191494
76	11.71194815	55.52835872
77	12.08762139	62.22774195
78	12.79359794	68.26811865
79	11.26648474	63.48918764
80	12.54114129	68.47197621
81	12.6653552	58.15447607
82	11.34038281	67.18174127
83	12.40668038	64.0219829
84	11.67180267	63.01599673
85	11.98179539	56.87402464
86	12.20564171	67.1180408
87	11.04868029	69.47985442
88	12.33377058	62.38110802
89	12.84683499	61.67821927
90	12.01185732	55.05459041
91	12.94757579	69.81953902
92	12.80448188	61.13157498
93	11.01577743	64.61472902
94	11.7568682	67.90483851
95	12.95505485	65.98683684
96	12.82673758	61.78454666
97	12.05024979	55.68082268
98	12.09452357	55.44015949
99	11.83906038	63.4149781
100	11.25578097	64.41567923
101	12.93054098	65.10060732
102	11.64535519	67.07583004
103	12.66568157	68.16677324
104	11.42070309	60.3355339
105	11.9127565	58.35131956
106	12.35319658	63.48625926
107	12.86296409	68.31105234
108	12.05246788	62.74203636
109	11.06567711	59.85299554

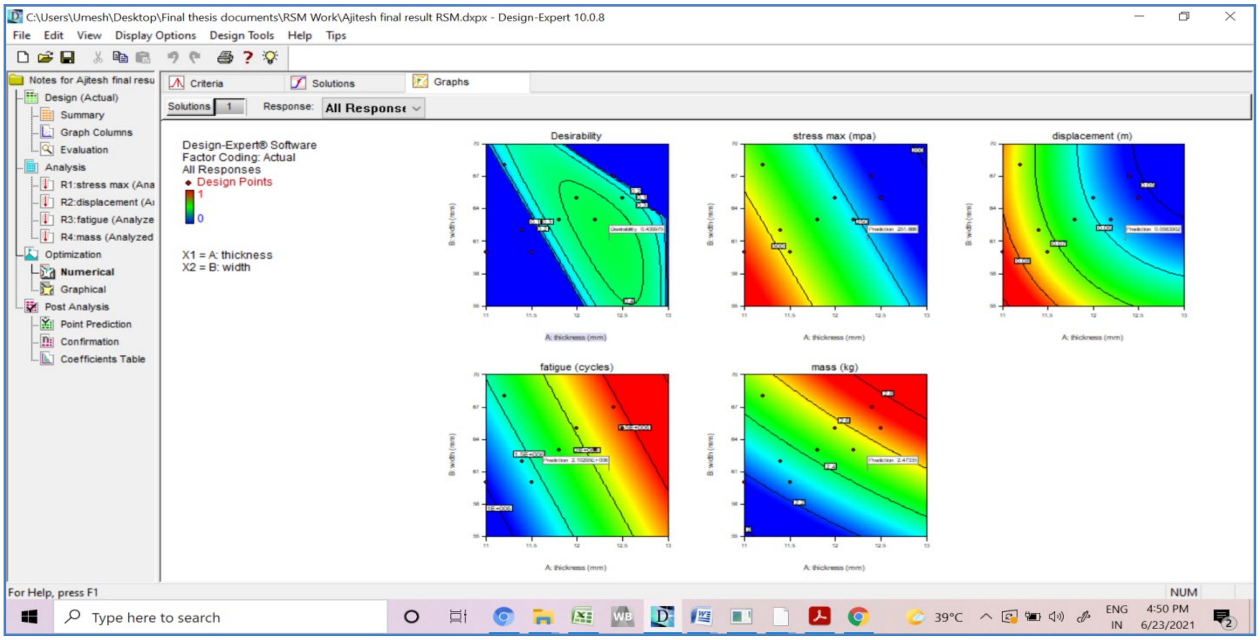


Fig 5.2 Graphical representation of optimization for all responses

Figure 5.2 shows the graphical presentation of optimization of responses keeping constraints into the consideration. In this particular figure, all responses i.e. stress max, mass, displacement, fatigue cycle graphs are shown. Graphs are divided into various regions on the basis of various constraints decided before running the solution and the design which suits best in all the graphs will be the solution of optimization part.

Optimization Result:

After examining the responses for all 109 starting points, RSM software has selected one optimized solution which is shown in Table 5.14. It is understood that Mass of optimized leaf spring is 2.473 Kg along with 12.35 thickness and 61.1mm width.

Table 5.14: Optimized Design with Responses

Number	Thickness(mm)	Width(mm)	stress max (MPa)	Deflection (m)	Fatigue life cycles	Mass (kg)
1	**12.35535875**	**61.10708396**	**251.8660698**	**0.058390177**	**2102951**	**2.47335**

Chapter 6

RESULTS AND DISCUSSION

This chapter describes about the results which we got during our research and how these results influenced this whole study. Firstly as described in chapter 3, all models (9 CFRP and 1 steel SAE 5160) were designed and analyzed in FEM software i.e. ANSYS workbench 2021 R1. Various Boundary conditions have been applied in the geometry to simulate the design as per actual working conditions. Meshing convergence is done to get accurate results. Loading is also applied considering actual weight of the trolley and goods that can be transported from one end to another. Factor of safety 2 was considered while calculating the load. Various parameters are analyzed in post processing of ANSYS like stress max, strain, deformation, fatigue life, equivalent strain etc. Fatigue life analysis is done using Goodman's theory approach of ANSYS. Various parameters are verified using Analytical Model (discussed in chapter 4) which shows that boundary conditions, meshing etc are done properly and modeling part is done accurately.

Optimization part (Discusses in chapter 5) is done on RSM software "Design Expert" where again statistical models are developed using data from ANSYS. In RSM, various graphs and mathematical equations are developed which will be further discussed in this chapter. Our result and Discussion part mainly concentrate over 4 parameters which are identified in chapter 5 to optimize for better design of CFRP composite leaf spring.. In view of all, results and discussions are subdivided into various parts like:

6.1 ANSYS Results verses Analytical model calculation

Various leaf spring Models are designed and analyzed in ANSYS software to get various results like stress maximum (Von-misses stress), Deformation, equivalent strain, Fatigue life etc. Subsequently Analytical Stress calculations are done for all the leaf spring models in chapter 4. Both Stresses are compared for each leaf spring model and it is observed that both values are close to each other. Fig 6.1 shows 3-7 percent variation in the stresses value of both ANSYS and Analytical model. Deformation parameter is also checked for both the models and there was 10-12 percent variation which may be because of different approaches and various assumptions taken during development of both the models (like Leaf is semi-elliptical shape but considered as straight cantilever beam while developing Analytical model). Also as FEM is a statistical tools which calculates approximate values, it is absolutely clear that the ANSYS model is perfectly developed.

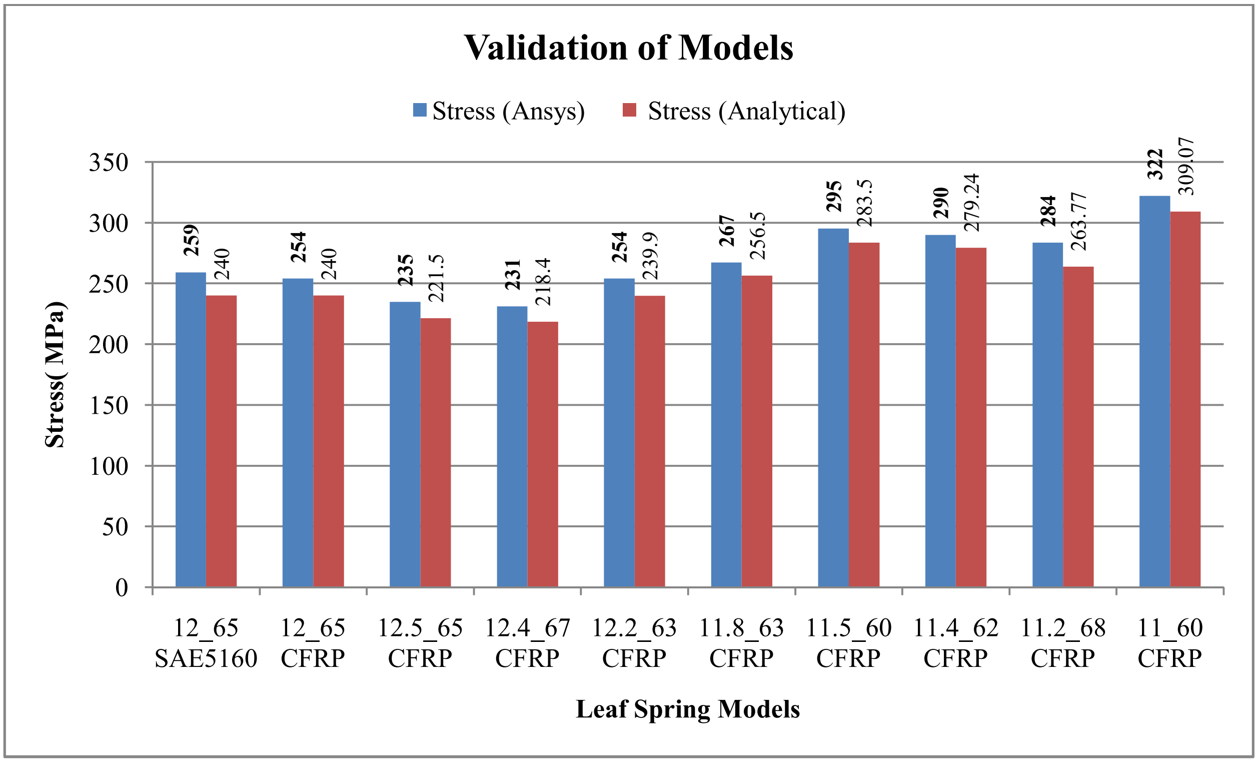


Fig 6.1: Bar-graph representation of Analytical stress and Von Misses stress (ANSYS).

In the Figure 6.1, blue bars shows the value of Von-misses stress developed in ANSYS where as brown bars shows Analytical stresses calculated in chapter 4. Von-misses stresses are more than the Analytical stresses as FEM considers other factors also like stress concentrations due to edge effects, variable cross-sections, geometry shape and structure. However both the models are in close relation with each other value vise.

6.2 Deformation

Deformation in all the leaf springs are compared and it is found that deformation in CFRP is less as compared to steel leaf spring for the same dimension which convey that CFRP composite is stiffer and harder than that of steel and can replace it very well but the ride quality will be on stiffer side although difference in deformation is not so much. For the same dimension, Steel spring shows 70.236 mm as compare to 58.5 mm in CFRP leaf spring model. When analyzed, it is understood that the reason of more deformation in Steel Spring is its lower young modulus as compare to that of CFRP (23 GPa). When CFRP leaf spring models compared, CFRP 12.4_67 showed minimum deformation whereas 11_60 CFRP leaf spring had maximum deformation of 83.5 mm. Figure 6.2 represents all leaf models deformations.

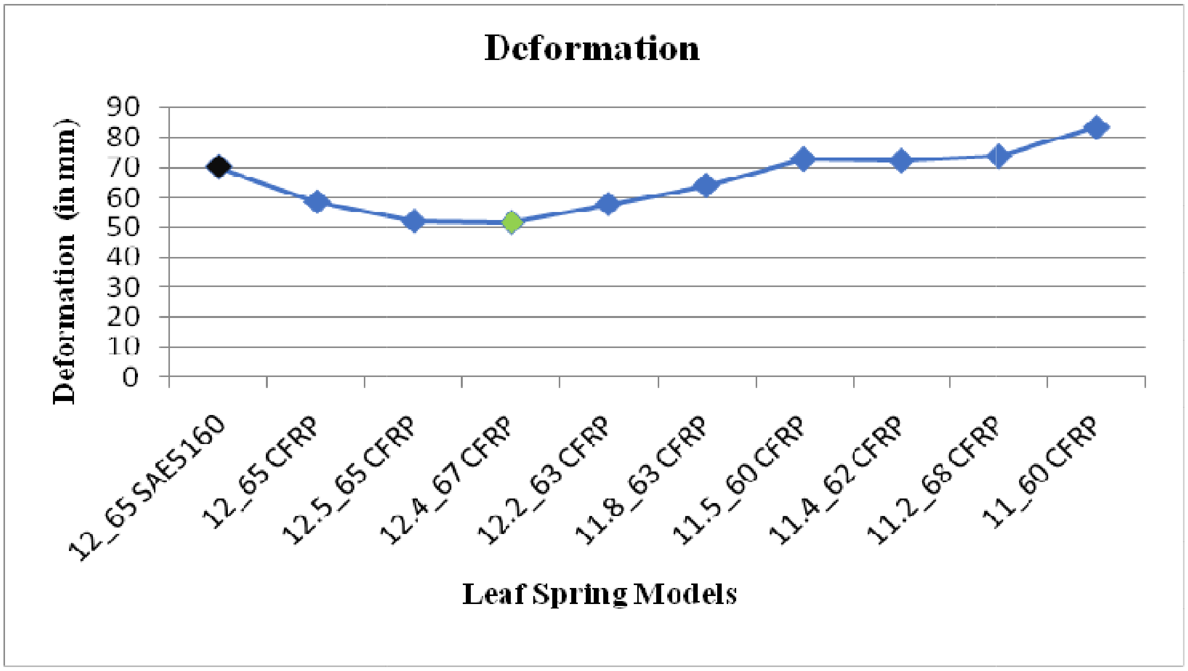


Fig 6.2: Deformation in all leaf spring Models

6.3 Stress Maximum

Stress developed in CFRP composite material is less than the stresses in chromium steel for the same geometry for eg CFRP 12_65 leaf spring develops 254 MPa stress as compared to 259 MPa in case of steel SA 5160 leaf spring. After analyzing, it is also understood that the model 11_60 CFRP develops maximum stress. All models can replace the steel leaf spring of electric trolley (except last one which develops 322 MPa being very high comparatively). All the data have been used to develop the model in RSM "DESIGN EXPERT" software for optimization work. Figure 6.3 shows the value of maximum stresses in all the leaf spring models. Model with green boundary is the safest model to be used in terms of developed stresses whereas black bar graph shows the stresses developed in Steel Leaf spring.

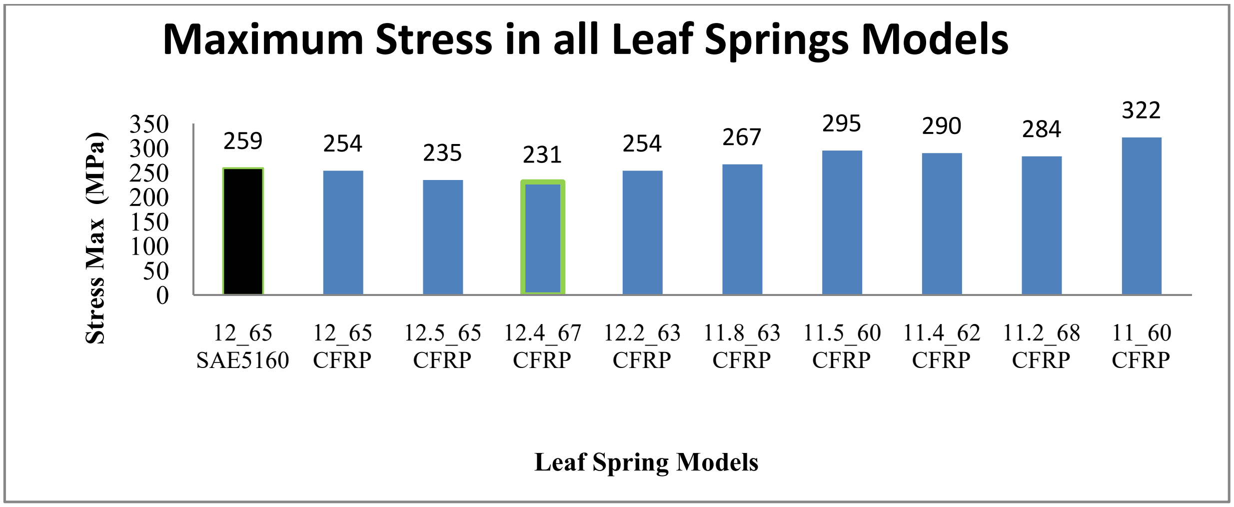


Fig 6.3: Max Stress induced in all Leaf Spring Models.

6.4 Fatigue life

Fatigue life is number of cycle before failure. Most of the leaf spring fails under fatigue failure due to cyclic loading condition when vehicle runs on roads. For simulation of real condition, a cyclic load of fully reversed type is applied and Goodman's theory of Mean Stress is used to get the fatigue life of all the models. When compared, it is understood that Fatigue life cycles of CFRP are way better than that of SAE 5160 spring which shows that Composites performs better as compare to steels in compressive loading. Figure 6.3 shows the comparison of fatigue life of all the models with steel one. Model 12.4_67 CFRP spring have almost 2.5 times the life SAE5160 spring.

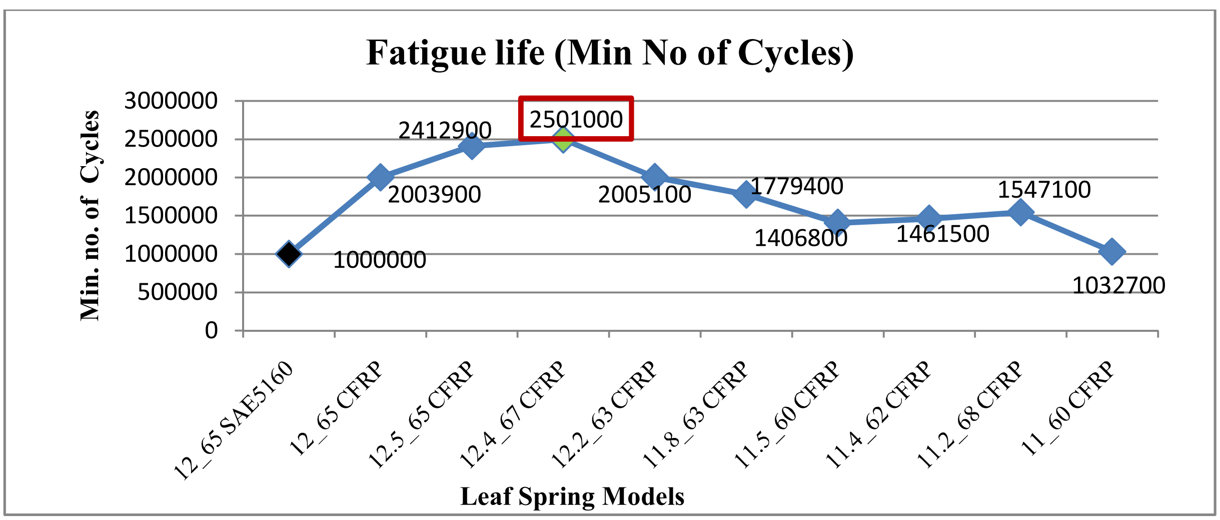


Fig 6.4: Fatigue life of all Leaf Spring Models.

6.5 Mass

Masses of all the considered leaf spring are compared through bar graphs and being low density materials all CFRP leaf springs model weighs around 20-30 percent of existing steel leaf spring. Also it is calculated that overall weight of vehicle reduced by around 8-11 percent if we changes the steel leaf spring with the CFRP one.

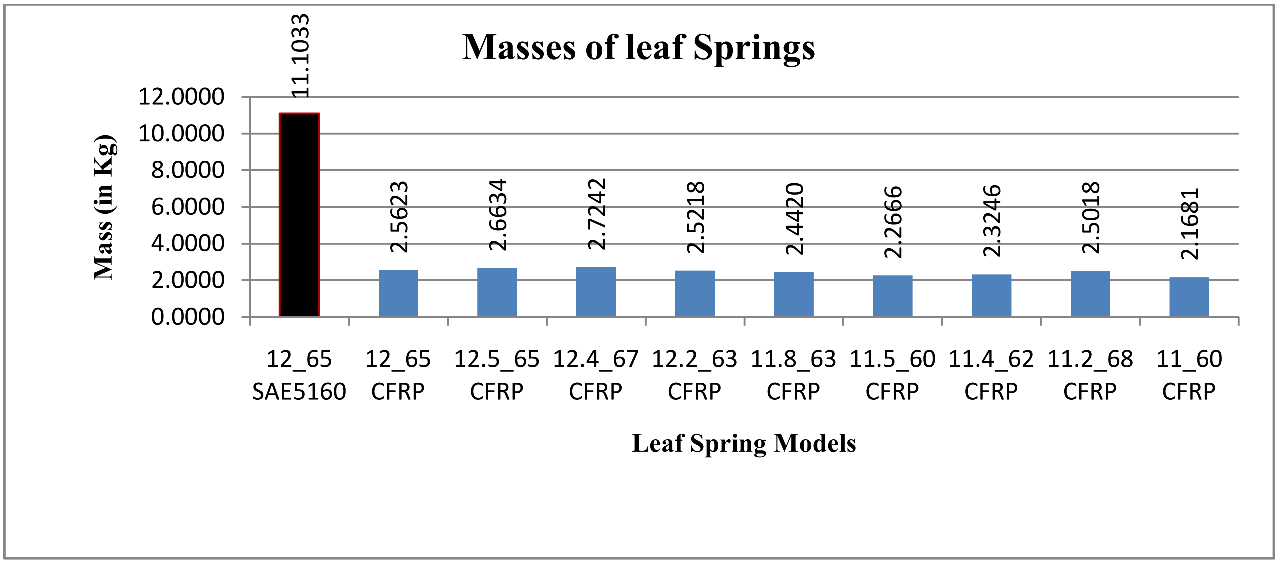


Fig 6.5: Mass of all Leaf Spring Models.

6.6: Comparison of Optimized leaf with SAE 5160 leaf

In chapter 5, RSM is utilized to optimize design parameters of CFRP leaf spring which can replace the steel leaf spring considering other parameters also in considerations. The basic motive was to replace the material without compromising with other factors in decreasing the weight of the spring. Various models along with mathematical equations and statistical techniques are used to optimize the design factors. Finally best optimum solution achieved is represented in Table 5.13 of chapter 5 and various graphs and bar representations (shown in Figure 6.6) are done to evaluate the results.

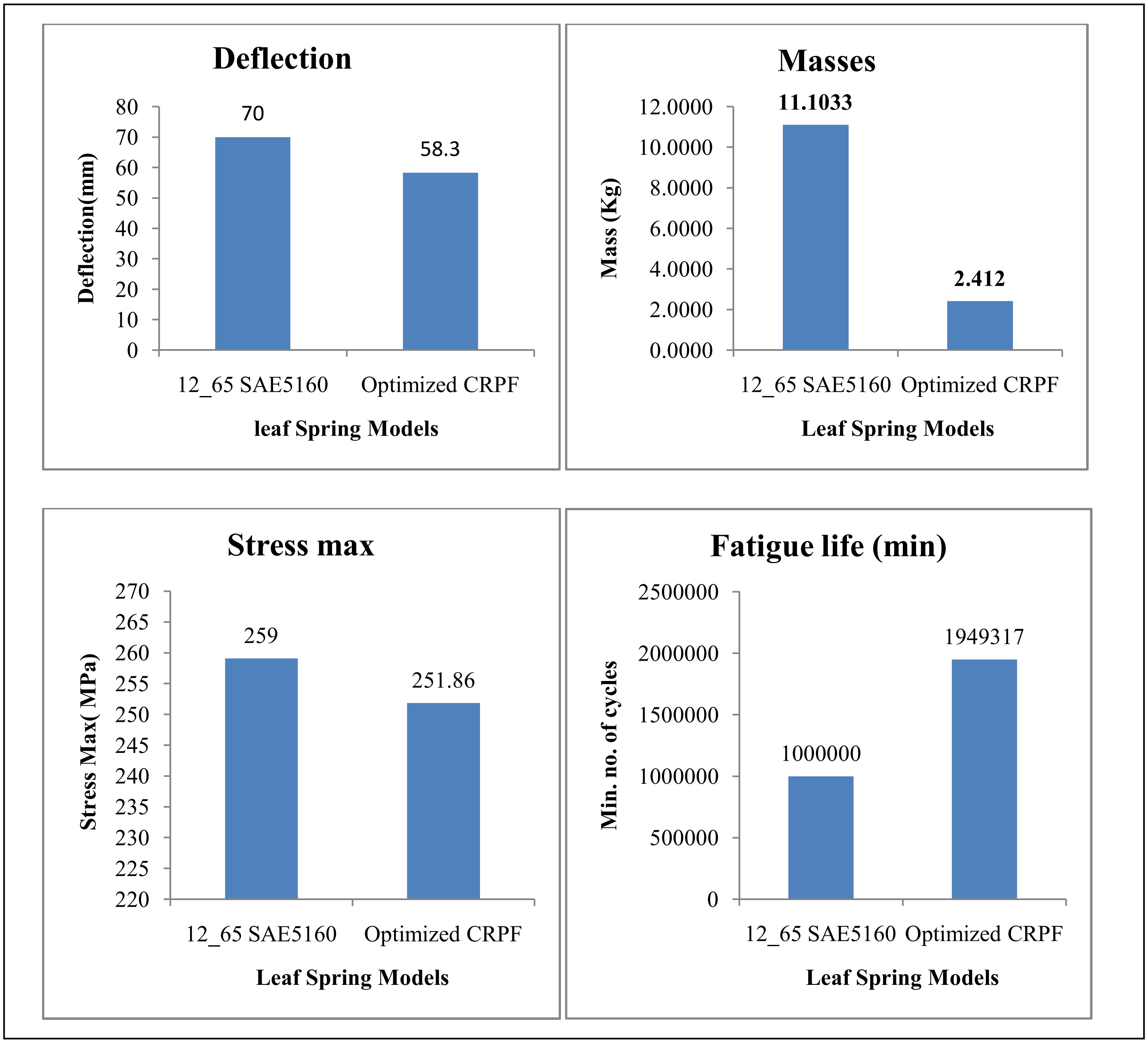


Fig 6.6: Comparison of Optimized Leaf Spring with Steel Leaf Spring.

- It is found that CFRP with 12.35 thickness and 61.10 mm perform best considering all parameters like stress life, mass, fatigue life etc into consideration.
- Deformation will be 58.4 mm which is 16 percent lesser than that of steel leaf spring.
- There is huge saving of weight of leaf spring. Optimized design CFRP leaf spring is 2.473 kg as compared to 11.10 kg of existing steel leaf spring which means new spring will be 4.48 times lighter than existing spring. If we consider Leaf spring weight to be 15

percent of the trolley weight, it has decreased around 8-9 percent of trolley weight which definitely improves the efficiency and working time of electric trolley.

- Fatigue life of optimized CFRP spring is 2102951 cycle before failure which is almost double than the fatigue life of SAE 5160 existing spring.
- Stress in CFRP leaf spring is 251 MPa as compare to 259 MPa stress of SAE leaf spring that makes it more reliable alternative.

Chapter 7

CONCLUSIONS AND FUTURE SCOPE

7.1 Conclusions

Modeling and optimization of trolley leaf spring of CFRP material is conducted in this research work to replace the existing leaf spring which concluded some points that are as follows.

- SAE 5160 leaf spring can be replaced by CFRP leaf spring as it shows less deformation, higher fatigue life, lower stresses as compared to SAE 5160 steel and weighs 4.5 times lighter than existing leaf spring which overall reduces weight of electric trolley by 8-9 percent.
- Theoretical validation of FEM model is done successfully.3-7 percent variation in stresses can be accepted due to several factors being ignored during analytical modeling like taking assumption of pure bending etc.
- It is observed that RSM is a good optimization tool which easily optimized multiple factors at the same time. In this study, design parameters (width and thickness) are optimized considering multi responses parameters i.e. stress, fatigue life, mass and deformation into the consideration.
- CFRP materials perform better in fatigue loading and have almost double fatigue life than steels.

7.2 Future Scope

Leaf Spring is an area that has an immense scope of research work. In last two decade, a tremendous work pertaining to the automotive industry has been done but still there are scope of further researches and improvements in this field which are as follows.

- Complex design of leaf spring can be studied along with more design parameters for further improved design.
- Experimental study can also be conducted in future.
- New materials can be explored which will perform better than the existing ones.
- Fresh innovative designs of leaf springs can be developed for better ride quality.
- More advanced modeling and optimization softwares can be used in future for precised outcomes.

APPENDIX

(Calculation of composite properties in MATLAB)

```
clc;
clear all;
%%%vol. fraction of  carbon fiber%%%
vf=0.7;
%%% vol.  fraction of epoxy  matrix%%%
vm=0.3;
%%%density of fiber in kg/m3 %%%
df=1.95*1000;
%%%density of matrix%%%
dm=1.45*1000;
%%%youngs modulus of fiber in GPa %%%
ef=230;
%%%youngs modulus of matrix in GPa%%%
em=10.5;
%%%possions ratio of fiber%%%
pf=0.4;
%%%poisson ratio of matrix%%%
pm=0.3;
%%%longitudual tensile stregthGPa%%%
s1T=0.300;
%%%longitudual compressive strength GPa%%%
s1C=0.280;
%%% transverse tensile stress %%%
s2T=0.094;
%%% transverse compressive stress in GPa%%%
s2C=0.072;
%%% shear modulus %%%
g=9.0;
```

```
%%% density of composite%%%
dc=(df*vf)+(dm*vm)
%%% calculation of E1%%%
e1=(e1f*vf)+(e1m*vm)
%%% calculation of e2%%%
e2=(e2f*em)/((Vmatrix*e2f)+(vf*em))
e3=e2
%%% determination of poission ratio in 12 direction %%%
p12=(pm*vm)+(pf*vf)
%%% determination of poission ratio in 21 direction %%%
p21=(e2*p12)/e1
%%% determination of poisson ratio in 23 direction%%%
p23= p12*((1-p21)/(1-p12))
%%% shear modulus fiber in GPa %%%
gf²=ef²/(2*(1+pf))
%%%shear mod. of matrix in GPa %%%
gm=em²/(2*(1+pm))
%%% shear modulus of composite in 12 direction in GPa%%%
g12=(gm*gf)/((vm*gf)+(vf*gm))
%%% shear modulus in 23 direction %%%
g23=e2/(2*(1+p23))
%%% tensile stress in x direction %%%
sigma1t=(vf*s1T)
A=(sqrt(vf)-vf)
B=(em/ef)
C=gm/g12
D=gm/g23
%%%tensile stress in y direction %%%
sigma2t=s2T*(1-(A*(1-B)))
%%% tensile stress in z direction %%%
sigma3t=sigma2t
```

```
%%% comp. stres in x axis %%%
sigma1c=-(vf*s1C)
%%% comp. stress in y axis %%%
sigma2c=-s2C*(1-(A*(1-B)))
%%% comp. stress in z direction %%%
sigma3c=-sigma2c
%%%shear stress G12%%%
G1=g*(1-(A*(1-C)))
%%%shear stress G23 %%%
G2=g*(1-(A*(1-D)))
%%% shear stress 31 %%%
G3=G1
%%% tensile strain in x axis %%%
epsilon1t=sigma1t/e1
%%% tensile strain in y axis %%
epsilom2t = s igma2t/ e1
%%% tensile strain in z axis %%%
epsilon3t=epsilon2t
%%% comp. strain in x axis %%%
epsilon1c=-signa1c/c1
%% comp. strain in y axis %%%
epsilon2c=-sigma2c/e2
%% comp. strain in z axis %%%
epsilon3c=-epsilon2c
%%%shear strain G12%%%
epsilong1=G1/e1
%%%shear strain G23 %%%
epsilong2=G2/e2
%%% shear strain 31 %%%
epsilong3=epsilong1
```

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