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Finite Element Analysis and Mechanical Properties of Carbon Fiber Reinforced Polymer

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ABSTRACT: *Human understanding of materials keeps increasing at an accelerating rate and this accounts for the wide range of synthetic and naturally occurring materials which have been used across different fields for industrial, domestic and other applications. This study investigates the mechanical behavior of Carbon Fiber Reinforced Polymer (CFRP) materials through computational modeling using SolidWorks for component design and MATLAB for simulation and analysis. The aim is to explore the advantages of CFRP as a potential alternative material for structural applications, considering its lightweight properties and enhanced performance. For the models developed, the maximum stress values observed for Cast Alloy Steel were 121.1* N/mm^2 *(MPa) for the connecting rod and 95.9* N/mm^2 *(MPa) for the cam shaft, whereas CFRP exhibited slightly lower values of 113.1* N/mm^2 *(MPa) and 87.8* N/mm^2 *(MPa) respectively. The maximum stress values for Aluminum Alloy in the propeller were 162.1* N/mm^2 *(MPa), while CFRP showed a slightly lower value of 161.4* N/mm^2 *(MPa). These results from the computational analysis of CFRP materials showcases their superior mechanical characteristics when compared to Alloy Steel and Aluminum, also providing valuable insights into the potential benefits of CFRP as a lightweight and high-performance material, supporting its consideration as an alternative option in structural engineering applications.*

KEYWORDS: Carbon Fibre Reinforced Polymer (CFRP), MATLAB, SolidWorks, Finite Element Analysis, Computer Aided Design (CAD), modelling.

INTRODUCTION

In today's world, there is a growing need for cost effective and environmentally friendly materials in manufacturing industries (Devendra Reddy et al., 2021). As a result, composite materials have gained popularity as an alternative to traditional materials due to their cost-effectiveness and exceptional properties. Composite materials are materials made from two or more different components, each with distinct physical and chemical properties, that are combined to produce a material with superior properties compared to the individual components. Composite materials can be designed to be lightweight, strong, durable, and resistant to corrosion, making them ideal for use in a wide range of applications. They currently enjoy widespread acceptance and have steadily penetrated new markets. They have become a major component of the construction materials industry, being constantly applied in everything from everyday items to specialized and niche products. As such, composites are not only a viable alternative to traditional ferrous and non-ferrous materials, but they are also valuable in addressing technical challenges across a diverse range of industries (Barbero, 2017).

One of the common versatile composite materials available is Carbon Fiber Reinforced Polymer (CFRP). CFRP consists of a polymer matrix reinforced with carbon fibers. It has excellent mechanical properties such as high strength-to-weight ratio, fatigue resistance, and stiffness. This makes it suitable for various industries like aerospace, civil engineering, automotive, and sports (Park & Kim, 2015). In comparison with traditional materials like steel and aluminum, Carbon Fiber Reinforced Polymer (CFRP) due to its higher strength-to-weight ratio, is ideal for lightweight structures that require high strength. This property has led to the increased use of CFRP in the aerospace industry, where weight reduction is critical to improving fuel efficiency and performance (Craig Jr & Taleff, 2020). In addition to its high strength-to-weight ratio, CFRP also exhibits high stiffness, a measure of a material's resistance to deformation under load, and high stiffness is essential for structures like aircraft wings, sporting tools, and automobile bodies that require high rigidity and stability to work optimally (Liu et al., 2022).

In engineering, there is constant need to optimally utilized manufacturing materials. Hence, to ensure maximum use of CFRP, and to avoid deviating from actual theoretical results caused by the complex characteristics of composite materials, a finite element analysis is normally done. Finite Element Analysis (FEA) is a numerical technique used to analyze the behavior of complex structures subjected to different loading conditions by dividing them into smaller, more manageable elements and analyzing each element separately. FEA allows engineers to simulate and optimize the performance of structures before they are physically built, saving time and costs in the design and manufacturing process. Vital to note, is that, FEA is also a more economic and easy means of validating a design compared to physical testing and provides a method to integrate validation into the first design phase, making it possible to spot design problems at the early stage of the design process, thus reducing the danger of failures. When very simple modifications are made to an FEA model, it becomes possible to simulate a good variety of structural tests, which when compared to laboratory testing is limited in scope. Finite Element Analysis breaks down the structure of a material into smaller parts to analyze them. By doing this, the behaviour of the complete structure of the material can be determined. Hence, Finite Element Analysis under different loading conditions allows difficult complex structures that are looking impossible to solve to be analyzed using analytical methods. The different loading conditions includes static, impact and dynamic loading. Today, the use of FEA on CFRP has led to notable advances in the design and analysis of lightweight structures. FEA can be used to predict the mechanical properties of CFRP structures, which can then be optimized for specific applications (Liu et al., 2022). However, predicting and optimizing the mechanical properties of CFRP structures is still challenging due to the various factors that influence the mechanical properties of CFRP. Several of these factors includes, the orientation and content of carbon fibers, the type of polymer matrix, and the manufacturing process (Barbero, 2023). Therefore, to accurately use FEA for predictions, the material characterization is essential, leaving the focus of researchers on improving the accuracy of material characterization of CFRP using different kinds of techniques like microscopy, mechanical testing, and X-ray diffraction (Azhagiri et al., 2023). Also, although Finite Element Analysis (FEA) is a numerical technique that can be used to simulate the behavior of structures under different loading conditions, the accuracy of FEA predictions is highly dependent on the accuracy of material characterization.
Hence, the purpose of this study is to conduct a comprehensive finite element analysis of the mechanical properties of carbon fiber reinforced polymer, so as to develop a finite element model of a

CFRP structure that accurately represents the microstructure and mechanical properties of the material. In addition, the mechanical properties of the CFRP structure under static loading analyzed, and the design of the Carbon Fiber Reinforced Polymer structure optimized for improved mechanical properties.

This study is significant as it contributes to the general understanding of the behavior of Carbon Fiber Reinforced Polymer structures and the application of FEA in the design and analysis of lightweight structures. Also, an accurate prediction of the mechanical properties of CFRP structures using FEA can lead to the development of more efficient and lighter structures relevant in different industries.

LITERATURE

Carbon fiber reinforced polymer (CFRP) are composite materials with the potential to reduce structural weight and improve durability in civil engineering (as well as other industries), and this is due to its high strength, light weight, and excellent corrosion resistance (Duarte A.P.C., et, al; 2017; J. Guo & P. Chen, 2017). However, because of the unidirectional arrangement of carbon fibers in the matrix, there are poor results in transverse mechanical performance of CFRP materials (Z. Fang., et, al; 2013; A. Riccio., et, al; 2017). This can be a major cause for concern when the materials are subjected to transverse loads such as those generated by vehicles or deviators (Reinoso., et, al; 2017). The impact of transverse loads can create a combined tension-bending condition in the materials, making it critical to investigate the mechanical performance of CFRP under various loading conditions.

Therefore, the primary objective of this literature review is to evaluate previous research that has examined the mechanical properties of CFRP using Finite Element Analysis (FEA). By analyzing the available literature, this review aims to provide a foundation for an overview of Carbon Fiber Reinforced Polymer (CFRP), the reaction of CFRP under loadings, finite element analysis of the mechanical properties of CFRP, advancements in FEA and future research directions of CFRP & FEA.

OVERVIEW OF CARBON FIBER REINFORCED POLYMER (CFRP)

Composite materials have been employed for centuries in various engineering applications, with over 50,000 material types developed over time (M. Ashby & D. Jones, 2012) These materials ranges from very old available materials like copper, brass, cast iron, etc., to recently developed materials like steel, ceramics, etc. Composites materials involves the combination of two or more constituents, like a matrix and reinforcement, that differ in physical form and chemical composition. A three dimensional region with specific characteristics between these two constituents is called an interphase region (Mitchell, 2004). Carbon Fiber Reinforced Polymer (CFRP) as a composite material is composed of carbon fibers embedded in a polymer matrix, typically an epoxy resin, although other materials like polyester and vinyl ester can be used. The carbon fibers used in reinforcing polymer are usually made from polyacrylonitrile (PAN) or pitch, which after reinforcements processing, causes CFRP to develop its high strength, stiffness, and light weight, while also being resistant to fatigue, corrosion, and impact. However, it is relatively brittle and can be damaged by impact or sharp objects. The mechanical properties of CFRP are largely determined by the properties of its constituent materials and the manufacturing process. The carbon fibers, as the reinforcing element, contains high tensile strength and stiffness, while the polymer matrix, which serves to bind the fibers together, can be made from various materials, including epoxy, polyester, and vinyl ester resins. The choice of polymer matrix affects the mechanical properties of the composite, such as its stiffness, roughness and strength (P. Khalili, & X. Zhao, 2018). The manufacturing process of CFRP is done in multiple steps. First, carbon fiber is prepared for manufacturing, followed by the polymer matrix application, and curing. There are different types of techniques for manufacturing CFRP, with the most common ones being; hand lay-up, resin transfer molding (RTM), and automated fiber placement (AFP). Trying to decide the exact method to use, depends on factors like, the desired properties of the composite, the production volume, and the cost. (De Baere, & Van Paepegem, 2018).

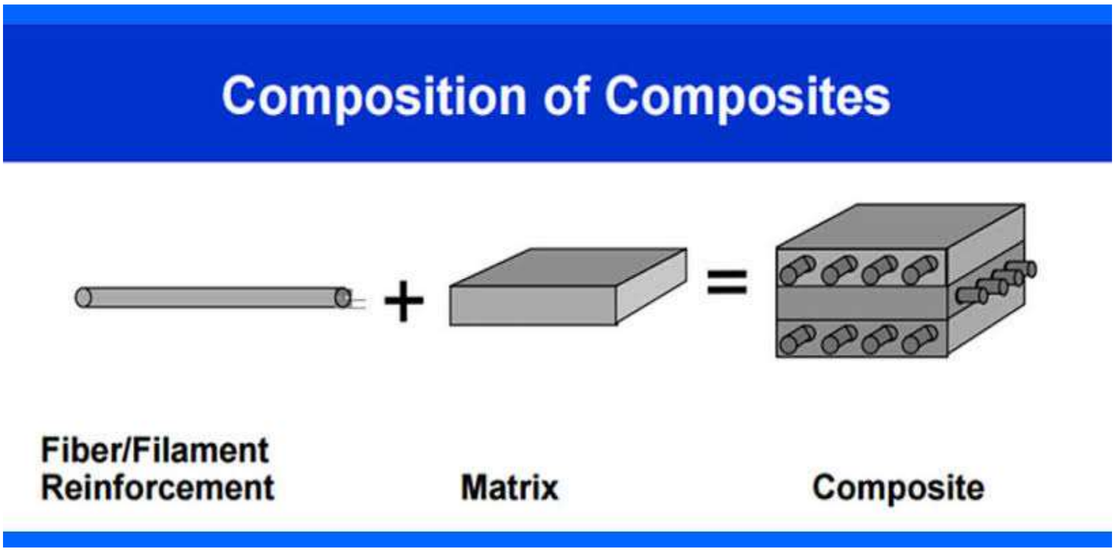

Figure 1. Combination of Matrix and Reinforcements to form Composites

Furthermore, Carbon Fiber Reinforced **Polymer** has found numerous applications in different industries, some of which are aerospace, automotive, construction, etc. In the aerospace industry, CFRP is used to manufacture aircraft parts such as wings, fuselages, and tail sections, resulting in lower emissions and improved fuel efficiency (Wang., et, al; 2020). In the automotive industry, CFRP is utilized to manufacture high-performance components such as body panels, chassis, and suspension systems, which are vital to generating an improved fuel efficiency, better handling, and crash safety. In the construction industry, CFRP is used to reinforce concrete structures such as tunnels, bridges, and buildings, increasing their strength and durability.

In addition, CFRP has a list of benefits that makes it advantageous over other materials for usage. Some of these advantages are vast. For example, CFRP has a higher strength-to-weight ratio than steel and aluminum, making it ideal for applications where weight reduction is critical. It is also corrosion-resistant material and has a longer lifespan than steel and other metals. Additionally, due to the properties of CFRP, the composite can be tailored to meet specific requirements, like stiffness, toughness and strength (P. Khalili, & X. Zhao, 2018).

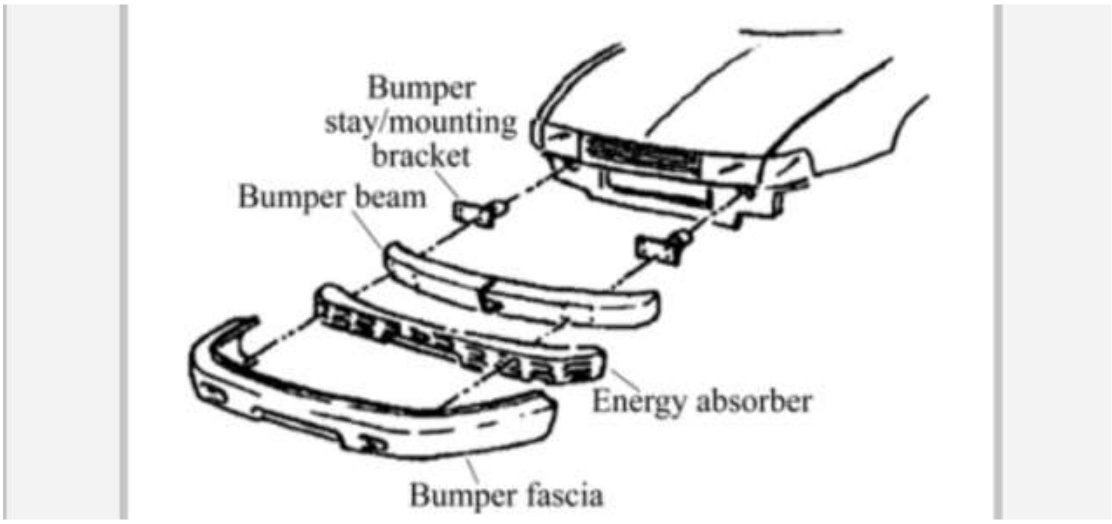

Figure 2. Automotive bumper parts with potential application of Carbon Fiber Reinforced Polymer Composite.

Historical Background of Finite Element Analysis (FEA)

Finite Element Analysis (FEA) is a valuable computational tool for analyzing and predicting the behavior of mechanical structures subjected to different loading conditions. It is a numerical method in mechanical engineering used for analyzing complex structures that cannot be otherwise solved manually, hence has been widely accepted. Today, FEA has significantly contributed to the design and optimization of mechanical components by giving room for engineers to evaluate the functionality, optimum performance and reliability of their designs before manufacturing (Bathe, 2014).

Looking at the history of finite element analysis, studies have shown that, the roots of FEA dates back to as early as 1950s when researchers initiated the development of numerical methods for solving partial differential equations. At its inception, FEA was limited to only linear problems and simple geometries. But as time went on, especially with the advancements in computing power and sophisticated algorithms, the analytical tool evolved to handle more complex problems and non-linear material behaviors. Currently, FEA is an essential tool in modern mechanical engineering design and analysis (Zienkiewicz, 2013). Today, there are different finite element analytical methods for designs used by mechanical engineers, some of them include; the Finite Difference Method (FDM), Boundary Element Method (BEM), and Finite Element Method (FEM). The FEM is the most frequently used method, which is applied to discretize the structure into smaller elements afterwards solving the governing equations for each element. BEM is ideal for solving problems with infinite domains, while FDM is suitable for problems with regular geometries (Reddy, 2017).

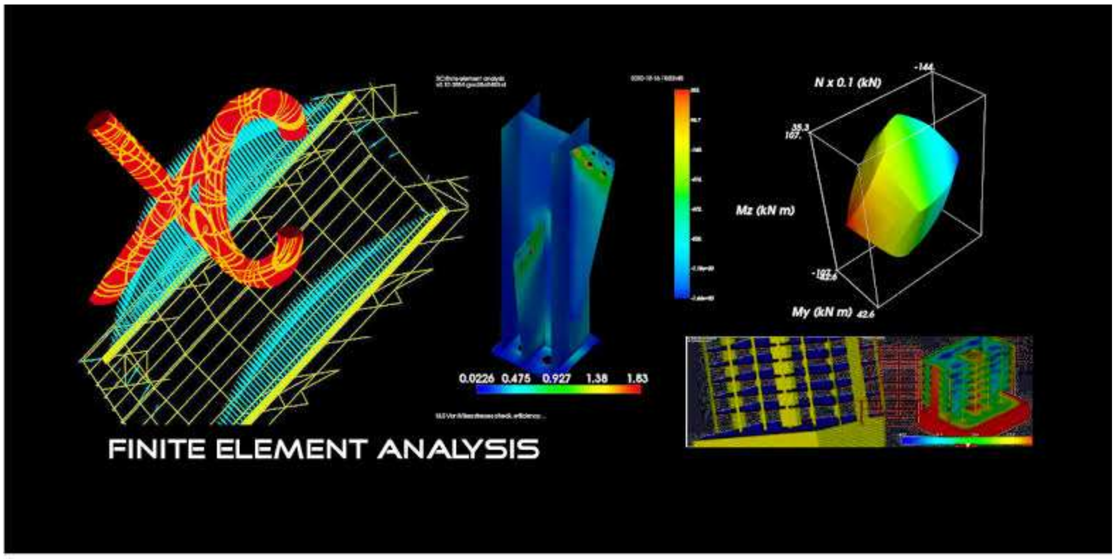

Figure 3. Finite Element Analysis and Simulation of a Mechanical Component

APPLICATIONS AND TECHNIQUES USED IN FINITE ELEMENT ANALYSIS

FEA is a powerful computational tool that has been widely used for various applications. The basic concept behind the operation of FEA is dividing a complex structure into simpler elements, and solving each element independently before combining the results to obtain the overall behavior of the structure. FEA employs different kinds of elements for its operation, depending on what it is needed for. Some examples of these elements are; Linear elements which are used for modeling structures with small deformations, Nonlinear elements used for modeling structures with large deformations or contact interactions, Shell elements for thin structures such as aircraft wings and ship hulls, and Solid elements, which model thick structures like machine parts and buildings. Also, FEA has been utilized in diverse fields for different analysis ranging from structural analysis, fluid flow analysis, vibration analysis, heat transfer analysis, and fatigue analysis (Wikipedia, 2023).

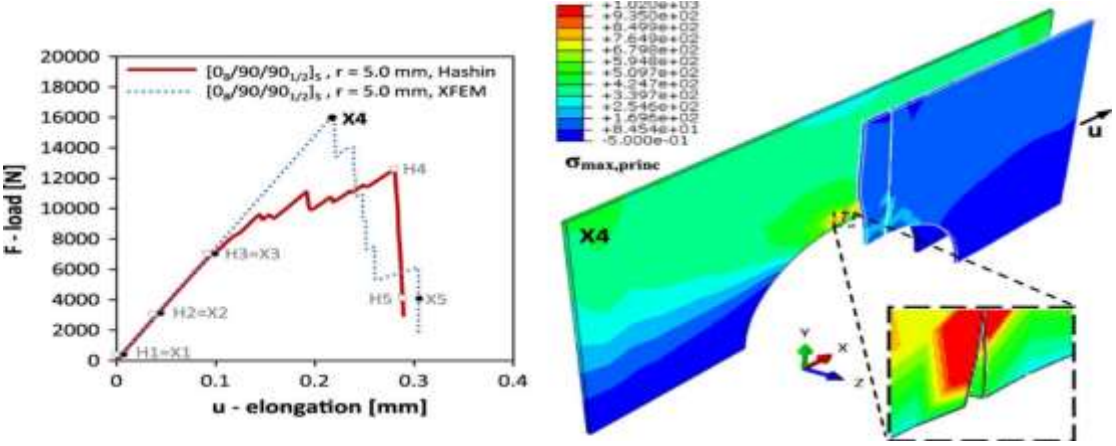

Figure 4. Application of FEA on a graphical abstract showing the readings of Elongation to Load on a Carbon Fiber Reinforced Polymer.

PREVIOUS STUDIES CONDUCTED IN DETERMINING THE MECHANICAL PROPERTIES OF CARBON FIBER REINFORCED POLYMER (CFRP) USING FEA

Accurate determination of CFRP's mechanical properties is crucial for designing reliable and efficient structures. For this reason, a number of studies have been conducted to investigate the mechanical properties of CFRP using finite element analysis (FEA). One of the earliest studies was conducted by Hashin and Rotem (1974). In their research, they proposed a micromechanics-based model to predict the strength and stiffness of CFRP. The key assumption in their model was that the fibers and matrix in CFRP are perfectly bonded. This assumption implies that there is no debonding or sliding between the fibers and the matrix, resulting in an ideal load transfer between the two phases. The model considered the CFRP as a homogeneous material and incorporated the mechanical properties of the individual constituents, namely the fibers and the matrix, to predict the overall behavior of the composite (Zhang et al., 2019).

In addition, studies conducted in the 1980s investigated the effects of fiber orientation on the mechanical properties of carbon fiber reinforced polymer (CFRP). These studies showed that the strength and stiffness of CFRP are significantly affected by the fiber orientation. For instance, CFRP with unidirectional fiber orientation has the highest strength and stiffness, while CFRP with random fiber orientation has the lowest strength and stiffness. The orientation of the fibers affects the way the load is distributed within the material, which in turn affects its mechanical properties (Subhedar et al., 2020). Furthermore, studies conducted in the 1990s investigated the effects of fiber volume fraction on the mechanical properties of CFRP. These studies showed that the strength and stiffness of CFRP increase with increasing fiber volume fraction, but the increase is not linear. The composites with higher fiber volume fraction and longer fiber length are more sensitive to strain rate, with the elastic modulus stress at 65% strain, and energy absorption capability increase with fiber volume fraction and fiber length. The stiffness of composites improves with the addition of milled glass fiber into polyurea, and the energy dissipative capability also increases. However, the transverse strength of composites decreases with increasing fiber volume (Kim et al., 2019).

In the 2000s, previous studies investigated the effects of matrix properties on the mechanical properties of CFRP. These studies showed that the mechanical properties of CFRP are significantly affected by the matrix properties. For example, CFRP with a high-modulus matrix has the highest strength and stiffness, while CFRP with a low-modulus matrix has the lowest strength and stiffness. In 2018, Yuan et al in particular, calculated macroscale behavior like temperature and residual stress in laminates using macroscopic FEA, and based on the macroscale results obtained, investigated the microscopic residual stress distribution in the heterogeneous fiber/resin structure using microscopic FEA (Yuan et al., 2018). Similarly, Saito et al. in 2020 performed microscopic FEA to characterize the macroscopic viscoelastic properties depending on the cure conversion and temperature, while predicting the process-induced saddle-shaped deformation of asymmetric cross-ply laminates using macroscopic FEA (Saito et al., 2020). These previously conducted investigations done in determining the mechanical properties of CFRP generally provided valuable insights into the behavior of these composites under different loading conditions in a bid to understand the effects of fiber orientation, fiber volume fraction, stacking sequence, and matrix properties. Thus, these studies have contributed to the development of accurate finite element analysis of material models and design guidelines for CFRP structures.

CHALLENGES OF MODELING CFRP USING FINITE ELEMENT ANALYSIS (FEA)

Trying to model the composite material CFRP using FEA comes with quite a few challenges. One of these is accounting for the effects of manufacturing defects on the mechanical properties of the composite. This is revealed when Haolong., et, al, investigated the impact of voids on the tensile properties of CFRP composites using FEA and observed that the presence of voids significantly reduced the tensile strength and modulus of the composite material. The occurrence of these phenomenon was attributed by the researchers to the stress concentration around the voids, which led to premature failure of the CFRP composite (Haolong., et, al; 2017). Another challenge experienced when modeling CFRP composites using FEA is obtaining accurate material property data. Dipak & Ramesh showed this when they conducted a study on the effect of material properties on the mechanical properties of CFRP composites using FEA and found that the mechanical properties of the composite were highly sensitive to the material properties used in the model. The authors therefore emphasized the need for precise material property data to enhance the accuracy of FEA predictions (Dipak, K & Ramesh, N, 2019). Hence, it can be expressly stated that, interfacial bonding between carbon fibers and the polymer matrix significantly influences the mechanical properties of CFRP, and while modeling CFRP comes with various challenges, FEA remains a widely used tool for investigating the mechanical properties of CFRP composites. But the orientation of carbon fibers, fiber volume fraction, and interfacial bonding being crucial factors must be considered.

ADVANCEMENTS IN FEA AND FUTURE RESEARCH DIRECTIONS

Over the past few decades, various failure criteria such as the maximum stress and Puck criteria, have been proposed to analyze the mechanical performance of carbon fiber reinforced polymer materials. These criteria enable the assessments of the damage state of CFRP composites under specific stress levels possible, which can be further utilized to predict the failure behavior of CFRP components. Hence, incorporating conventional failure criteria in finite element analysis could be a potential solution to unveil the mesoscopic damage evolution process of CFRP materials under combined tension and bending (Duarte A.P.C., et, al; 2017).

Furthermore, with advances in FEA, modeling the mechanical behavior of CFRP materials has become more accurate and efficient. This is observed in the development of multi-scale modeling techniques to address the complex microstructure of CFRP and enhance the precision of FEA simulations. One of these multi-scale technique is the cohesive zone model (CZM), which can represent the interface between the carbon fibers and the polymer matrix as a distinct material entity with its own mechanical properties. CZM has been successfully used to model delamination and crack propagation in CFRP laminates (J. Guo & P. Chen, 2017).

METHODOLOGY

This section presents the research design for investigating the mechanical properties of carbon fibre reinforced polymer (CFRP) and optimizing the design of CFRP structures. Here, the materials, steps, methodologies, and tools employed to address the research questions and achieve the research objectives are discussed. To comprehensively investigate the mechanical properties of CFRP and optimize the design of CFRP structures, series of research questions were used as guide in the investigation. One of the primary research questions is focused on determining the mechanical properties of CFRP. This involves a detailed examination of the material's behaviour under various loading conditions. By conducting finite element analysis (FEA), we aim to assess properties such as strength and failure characteristics of CFRP.

Additionally, the research seeks to address the question of design optimization for CFRP structures. Through FEA simulations and subsequent analysis, we aim to identify design modifications that can enhance the mechanical properties of CFRP structures. This includes exploring geometry, material composition, and structural configurations to achieve superior performance. Figure 5 is a graphical representation of the research design for the study. It is noteworthy to state however that due to the intricacies of the study preference has been given to top level activities presented in the diagram.

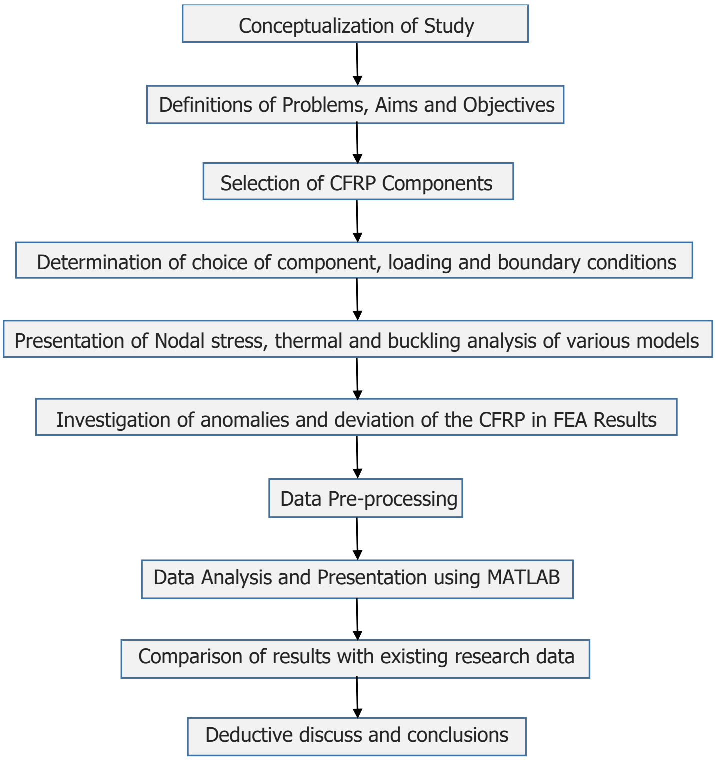

Figure 5. Research design work flow for determining the mechanical properties of CFRP using FEA.

MATERIALS

This section describes the materials and instruments utilized in the investigation of the mechanical properties and design optimization of carbon fibre reinforced polymer (CFRP) structures. The selection of appropriate materials and dimensions is crucial to ensure accurate representation of the structures under investigation. The following materials and instruments were employed in the research process:

MEASURING TOOLS

Various measuring tools were used to acquire precise dimensions and specifications of existing structures made from everyday objects. These tools include callipers, micrometres, meter rule and measuring tapes. By obtaining the accurate dimensions of automotive parts, propeller wings, and other relevant structures, we can create realistic models for analysis and design optimization.

INDUSTRY-BASED DIMENSIONS

In the case of complicated designs like the aircraft wings, industry sourced dimensions and specifications of the CFRP structures investigated utilized. These standards provide guidelines for the design and manufacturing of CFRP components in different applications. By adhering to these dimensions, the models are deemed to be accurate representation of real-world CFRP structures.

SOLIDWORKS

SolidWorks, a computer-aided design (CAD) software, was utilized to create 3D models of the CFRP structures. By incorporating the measured dimensions and industry-based specifications into SolidWorks, accurate representation of the geometries and configurations of the structures under investigation were obtained.

MATLAB

MATLAB, a powerful numerical computing environment, was employed for finite element analysis (FEA) simulations of the CFRP structures. Using the 3D models generated in SolidWorks, MATLAB allowed for the simulation of the mechanical behaviour of the structures and the analysis of their response under different loading conditions. MATLAB's capabilities facilitated the extraction and interpretation of relevant mechanical properties from the simulation results.

The use of measuring tools and industry-based dimensions ensured that the models closely resembled existing CFRP structures in various applications. By incorporating these dimensions into SolidWorks, accurate 3D models that reflected the real-world geometries and configurations were created. These models were then subjected to FEA simulations in MATLAB, leading to a thorough analysis of the mechanical properties and optimization of the CFRP structures. It is important to acknowledge that while physical CFRP samples were not used in this study, the dimensions and specifications of real-world structures made from CFRP were taken into consideration. This approach allowed for the investigation and design optimization of CFRP structures based on industry standards and practical applications.

COMPONENT SELECTION AND GEOMETRY

The component selection process is aimed at identifying suitable components for the study that meet industry standards and define their geometric properties to create accurate models for subsequent analysis and design optimization. To ensure relevance to real-world applications, various components from different industries were considered. automotive parts, turbine blades, and other CFRP structures served as the basis for component selection. These components were chosen due to their wide range of shapes, sizes, and complexities, providing a comprehensive representation of CFRP structures. The geometry of each selected component was carefully examined and measured using the aforementioned measuring tools. Calipers, micrometers, and industry recommended parameters were employed to capture accurate dimensions and intricate details. This meticulous process ensured that the geometric characteristics of the components were faithfully replicated in the 3D models created in SolidWorks.
By accurately selecting and defining the geometry of the components, the subsequent analysis and optimization steps can be conducted with a high level of confidence. The resulting models will closely resemble real-world CFRP structures, enabling accurate assessments of their mechanical properties and performance.

MATERIAL PROPERTIES

The material properties of CFRP, including its stiffness, strength, and failure characteristics, were derived from experimental data available in the literature. These data sources provided valuable insights into the behaviour of CFRP under various loading conditions.In addition to the available data, relevant mechanical principles and formulas were employed to characterize the material properties of CFRP. The principles of elasticity and composite material mechanics, industry standards and specifications were also referenced to ensure the selection of appropriate material properties. These standards provide guidelines for the mechanical properties of CFRP based on its composition, fiber orientation, and manufacturing processes. By considering these standards, the material properties used in the analysis were aligned with accepted industry practices. Table 1 shows the strength, weaknesses, opportunities and threats (SWOT) analysis of four common CFRP materials. It captures the benefits and challenges associated with the use of any of the material so appropriate selection can be done.

Table 1. SWOT analysis of common Carbon Fibre Materials.

Carbon Fibre Material	Strengths	Weaknesses	Opportunities	Threats
Carbon AS4C (3000 Filaments)	- High tensile strength and modulus of elasticity - Excellent fatigue resistance	- Limited availability - High cost	- Proven performance in aerospace and other industries - Potential for further research and development	- Potential competition from other carbon fibre materials - Potential supply chain issues
Thornel Mat VMA	- High strength-to-weight ratio - Good impact resistance	- Limited availability - Limited documentation and research - Low water absorption	- Potential for specialized applications - Good dimensional stability	- Limited supplier options - Potential procurement challenges
Thor Mel VCB-20 Carbon Cloth	- Versatile and flexible material - Ease of handling and conformability	- Lower mechanical properties compared to others - Limited information available	- Suitable for applications requiring flexibility and ease of fabrication - Not as strong as other materials	- Potential limitations in structural applications - Can be difficult to bond
Zoltek Panex 33	- High strength-to-weight ratio - Wide availability	- Moderate impact resistance - Wide availability	- Wide availability and established reputation	- Potential competition from lower-cost alternatives

MATERIAL CHOICE

The choice of material plays a crucial role in determining the mechanical behaviour and overall performance of the of CFRP structures. After careful consideration of available options, the Carbon AS4C (3000 Filaments) material has been selected as the primary material for modeling and simulation. The decision is based on several key factors and considerations.

1. Strength and Stiffness: One of the primary reasons for choosing Carbon AS4C is its high strength and stiffness properties. CFRP materials, including Carbon AS4C, are known for their exceptional mechanical strength and rigidity. With a tensile strength of 4900 MPa, significantly higher

than other carbon fibers, Carbon AS4C offers superior strength characteristics. This makes it a suitable choice for applications where strength is critical, particularly in load-bearing structures. Additionally, Carbon AS4C exhibits a modulus of elasticity of 230 GPa, which is also significantly higher than other carbon fibers. This high stiffness makes it well-suited for applications where rigidity and dimensional stability are essential, such as in high-performance aircraft.

2. Lightweight: Another advantageous feature of Carbon AS4C is its lightweight nature. With a density of 1.78 g/cm^3, Carbon AS4C offers a favorable weight-to-strength ratio. This lightweight property is particularly beneficial in industries such as aerospace and defense, where weight reduction is crucial for enhancing fuel efficiency, maneuverability, and overall performance. By utilizing Carbon AS4C, the study aims to explore the potential of CFRP structures to deliver lightweight solutions without compromising on strength and structural integrity.
3. Suitability for CFRP Structures: CFRP materials, such as Carbon AS4C, are specifically designed and engineered for applications involving composite structures. The carbon fiber reinforcement in CFRP provides excellent tensile and compressive strength, making it suitable for various engineering applications. Carbon AS4C, with its exceptional strength and stiffness characteristics, aligns well with the requirements of CFRP structures. By using Carbon AS4C in the modeling and analysis, the study aims to capture and analyze the behaviour of CFRP structures accurately.
4. Industry Acceptance: Carbon AS4C is a widely recognized and accepted carbon fiber material in various industries, including aerospace, automotive, and sporting goods. The extensive use of Carbon AS4C in these industries signifies its reliability, performance, and established track record. By utilizing Carbon AS4C in the study, the findings and conclusions can be more easily compared and validated against existing research and industry standards. This enhances the credibility and applicability of the study's results to real-world scenarios.
5. Cost Considerations: It is important to acknowledge that Carbon AS4C is associated with a relatively higher cost compared to other materials. However, considering the specific aims and objectives of this study, where the focus is on exploring the mechanical properties and optimizing the design of CFRP structures, the enhanced performance and capabilities offered by Carbon AS4C outweigh the cost implications. The study recognizes that the cost factor might limit the widespread application of Carbon AS4C in all scenarios, but for the purpose of this research, it provides valuable insights into the mechanical behaviour of CFRP structures.

Table 2. SWOT analysis of common Carbon Fiber Materials

Property	Value	Units
Elastic Modulus	231	N/m^2
Poisson's Ratio	0.34	N/A
Shear Modulus	130	N/m^2
Mass Density	1780	Kg/m^3
Tensile Strength	4900	N/m^2
Yield Strength	3400	N/m^2
Thermal Expansion Coefficient	12.5	$\mu m/(m \cdot K)$
Thermal Conductivity	17	$W/(m \cdot K)$
Specific Heat	710	$J/(kg \cdot K)$

Sourced: Analysis of mechanical properties of natural fiber composites with FEA (K. Balasubramanian, N. Rajeswari, & K. Vaidheeswaran)

The identified material properties, along with the relevant formulas and mechanical principles, such as Young's modulus, Poisson's ratio, and ultimate strength, will be incorporated into the FEA simulations conducted in MATLAB. In Table 2, the properties of the CFRP material chosen are tabulated. By accurately representing the mechanical behaviour of CFRP, the simulations provided valuable insights into the structural performance and allowed for the subsequent optimization of CFRP structures.

BOUNDARY CONDITIONS

Boundary conditions define the external constraints applied to the structures, which play a significant role in simulating their real-world behaviour. The selection of appropriate boundary conditions depends on the specific application and loading scenarios under consideration. For instance, in the case of an automotive part such as a connecting rod, the boundary conditions would reflect the forces and constraints experienced during its intended use. Similarly, for a propeller blade, the boundary conditions would simulate the aerodynamic loads and structural constraints encountered in operation.

The determination of boundary conditions involved the application of mechanical principles and relevant formulas to replicate the expected loading and constraints on the CFRP structures. This included considerations of static and dynamic loads, moments, and constraints at specific locations. The boundary conditions were established based on a combination of engineering judgment, existing guidelines, and available experimental data. By aligning the boundary conditions with the intended application and loading scenarios, the FEA simulations could provide valuable insights into the mechanical response and performance of the CFRP structures.

MESH GENERATION

Mesh generation plays a crucial role in accurately representing the geometry and behaviour of the structures during the analysis process. Using the SolidWorks software, the geometric models of the CFRP structures were divided into a mesh of finite-sized elements. The meshing process involved subdividing the components into smaller regions or elements, such as tetrahedra or hexahedra, to create a discretized representation of the structure.

The mesh was automatically generated with the SolidWorks mesh generation algorithm that considers the structural complexity and the desired level of accuracy of the user. The size and distribution of the elements were determined to capture the key features of the geometry and ensure sufficient resolution for accurate analysis. By employing an appropriate mesh, the FEA simulations in MATLAB could effectively analyze the mechanical response and provide insights into the behaviour of the CFRP structures under different loading conditions. The mesh's quality and refinement played a crucial role in obtaining reliable results, such as stress distribution, deformation patterns, and failure modes.

LOADING CONDITIONS

Loading conditions represent the external forces and loads applied to the structures, simulating real-world operating conditions. The selection of loading conditions depends on the specific application and the intended use of the CFRP structures. For example, in the case of a cam shaft, the loading conditions would represent the forces and moments experienced during its typical usage scenarios. Similarly, for a propeller blade, the loading conditions would simulate the aerodynamic forces and dynamic loads encountered in operation.

The loading conditions were established based on a combination of engineering analysis, available experimental data, and industry standards. They were chosen to represent the most critical and relevant loading scenarios for the specific application under investigation. By applying appropriate loading conditions, the FEA simulations in MATLAB could analyze the response of the CFRP structures to different types and magnitudes of loads. This analysis provided insights into the structural behavior, stress distribution, deformation patterns, and failure modes, facilitating the subsequent optimization of the CFRP structures.

MODEL SETUP AND FINITE ELEMENT ANALYSIS (FEA) PROCEDURE

To conduct the analysis of the CFRP structures, a comprehensive model setup and FEA procedure were established. This section outlines the steps involved in setting up the model and performing the FEA simulations using the SolidWorks software and MATLAB.

The 3D models of the CFRP structures, created based on the selected components and their geometric properties, were imported into the SolidWorks environment. Within SolidWorks, the necessary material properties, boundary conditions, and loading conditions were applied to the models. This ensured that the simulated structures closely represented the real-world CFRP structures. Following the model setup in SolidWorks, the FEA simulations were performed using the Finite Element Method (FEM) implemented in MATLAB. The FEA procedure involved the discretization of the structures into finite-sized elements, which were interconnected at nodes to form a mesh. The governing equations of elasticity and the FEM were employed to solve the system of equations representing the mechanical behaviour of the CFRP structures.

DATA EXTRACTION AND ANALYSIS

Once the FEA simulations were completed, the resulting data, including stress, strain, displacement, and other relevant parameters, were extracted from the numerical models. These data were analyzed to understand the structural response, identify critical areas, and evaluate the performance of the CFRP structures.

POST-PROCESSING OF FEA RESULTS

Using specialized software tools, such as MATLAB's post-processing capabilities or dedicated FEA post-processors, the raw data from the FEA simulations were processed and transformed into meaningful information. This involved visualizing the stress distribution, deformation patterns, and other relevant mechanical quantities through contour plots, displacement plots, and other graphical representations.

EXTRACTION OF MECHANICAL PROPERTIES

By analyzing the stress-strain relationships obtained from the FEA simulations, mechanical properties such as modulus of elasticity, ultimate strength, and failure criteria were determined. These properties provide valuable insights into the structural integrity and performance of the CFRP structures. The mechanical properties of CFRP were evaluated using a variety of methods, including tensile testing, compressive testing, shear testing, flexural testing, impact testing, and fatigue testing. The simulated data from the FEA served as a basis for comparison and validation against experimental results, enabling a comprehensive understanding of the CFRP's mechanical behavior.

MATLAB SIMULATION

By utilizing MATLAB, the FEA simulations were conducted to predict the structural response of the CFRP structures. The software provided a flexible and efficient platform for implementing the FEM and solving the governing equations. Furthermore, MATLAB's extensive range of functions enabled the analysis of the simulation results and the extraction of valuable insights.

RESULTS

FINITE ELEMENT ANALYSIS RESULTS

The following results were obtained from the analysis carried out using Solid works software on a variation of models designed with the techniques in the methodology section. In view of the aim and objectives of this study, results describing the physical properties, stress, displacement, strain characteristics and thermal behaviour of the model variations are represented and discussed.

Table 3. Physical properties of the designed models and their variations

SN	Model	Material	Type of analysis/Loading	Model Properties
1	Connecting Rod	CFRP	Static - Compressive Loading (1000N)	Mass: 0.035227 kg Volume: 1.97904e-05 m3 Density: 1,780 kg/ m3 Weight: 0.345225 N
		Alloy Steel	Static - Compressive Loading (1000N)	Mass: 0.14447 kg Volume: 1.97904e-05 m3 Density: 7,300 kg/ m3 Weight: 1.41581 N
2	Propeller Blades	CFRP	Pressure 200 MPa	Mass: 0.00271675 kg Volume: 1.52626e-06 m3 Density: 1,780 kg/ m3 Weight: 0.0266241 N
		Aluminium	Pressure 200 MPa	Mass: 0.00412091 kg Volume: 1.52626e-06 m3 Density: 2,700 kg/ m3 Weight: 0.0403849 N
3	I-Beam	CFRP	Buckling (1000N)	Mass: 54.0112 kg Volume: 0.0303434 m3 Density: 1,780 kg/ m3 Weight: 529.31 N
		Alloy Steel	Buckling (1000N)	Mass: 238.438 kg Volume: 0.0303434 m3 Density: 7,858 kg/ m3 Weight: 2,336.69 N
4	Cam Shaft	CFRP	Static stress analysis, Torsional (1000N)	Mass: 1.29432 kg Volume: 0.000727149 m3 Density: 1,780 kg/ m3 Weight: 12.6844 N
		Alloy Steel	Static stress analysis, Torsional (1000N)	Mass: 5.30819 kg Volume: 0.000727149 m3 Density: 7,300 kg/ m3 Weight: 52.0202 N

The Finite Element Analysis (FEA) results obtained from the SolidWorks software for the designed models are presented in Table 3. The models were created using industry standard dimensions and real-world data to ensure their relevance and accuracy. Table 3 provides an overview of the physical properties of the designed models and their variations. The models include a Connecting Rod, Propeller Blades, I-Beam, and Cam Shaft, with each made from different materials such as CFRP and Alloy Steel. The analysis conducted on these models involved different types of loading conditions, including static compressive loading, pressure, and buckling.

The properties of each model, such as mass, volume, density, and weight, are specified in the table. The mass and volume values are given in kilograms (kg) and cubic meters (m^3), respectively. The density of each material is also provided in kilograms per cubic meter (kg/m^3), while the weight is given in Newtons (N). These properties are crucial in understanding the physical characteristics of the models and their behaviour under various conditions. It is important to note that the material properties assigned to the models, such as CFRP and Alloy Steel, are supported by extensive experimental and literature data already covered in the literature review section of this study. This ensures the reliability and validity of the models' behaviour and performance in real-world applications.

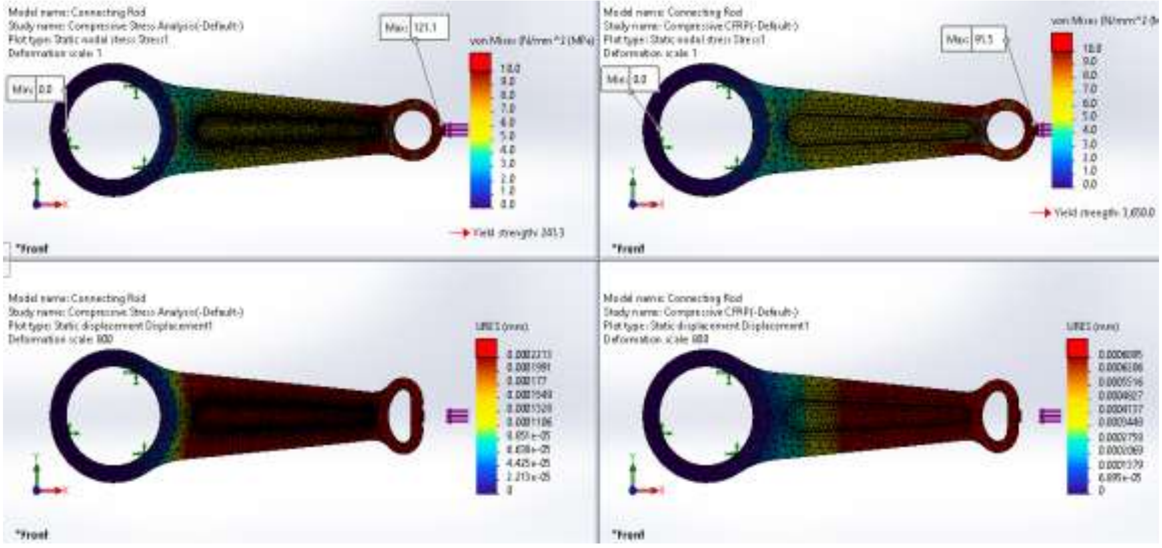

Figure 6. Stress distribution in the CFRP and steel alloy connecting rod model subjected to static compressive loading.

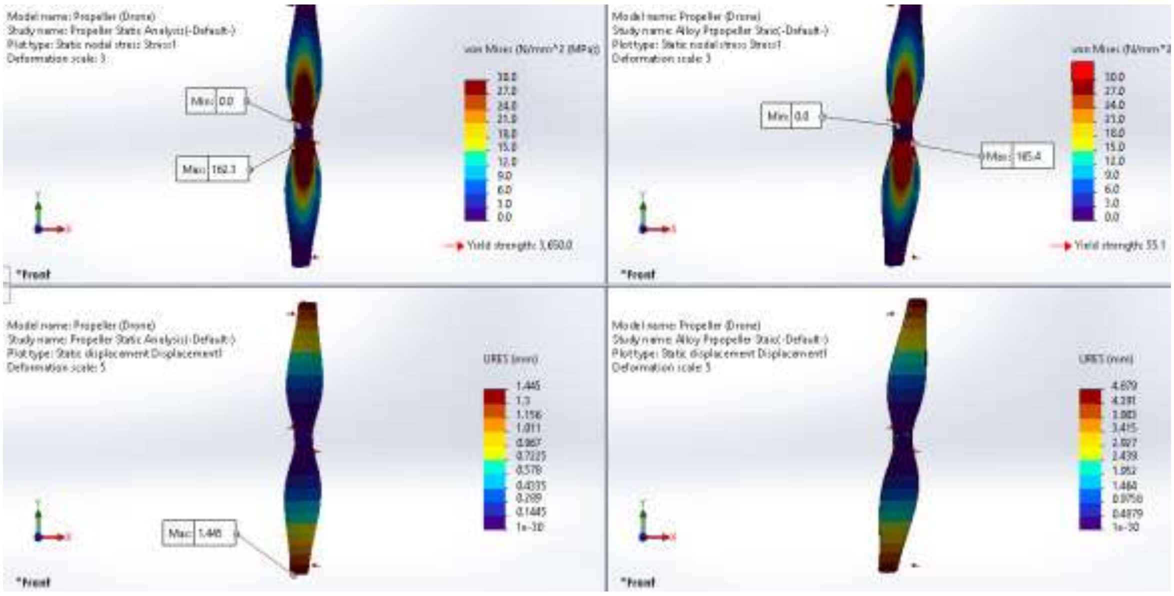

Figure 7. Stress distribution in the CFRP and aluminium propeller blades model subjected to static compressive loading.

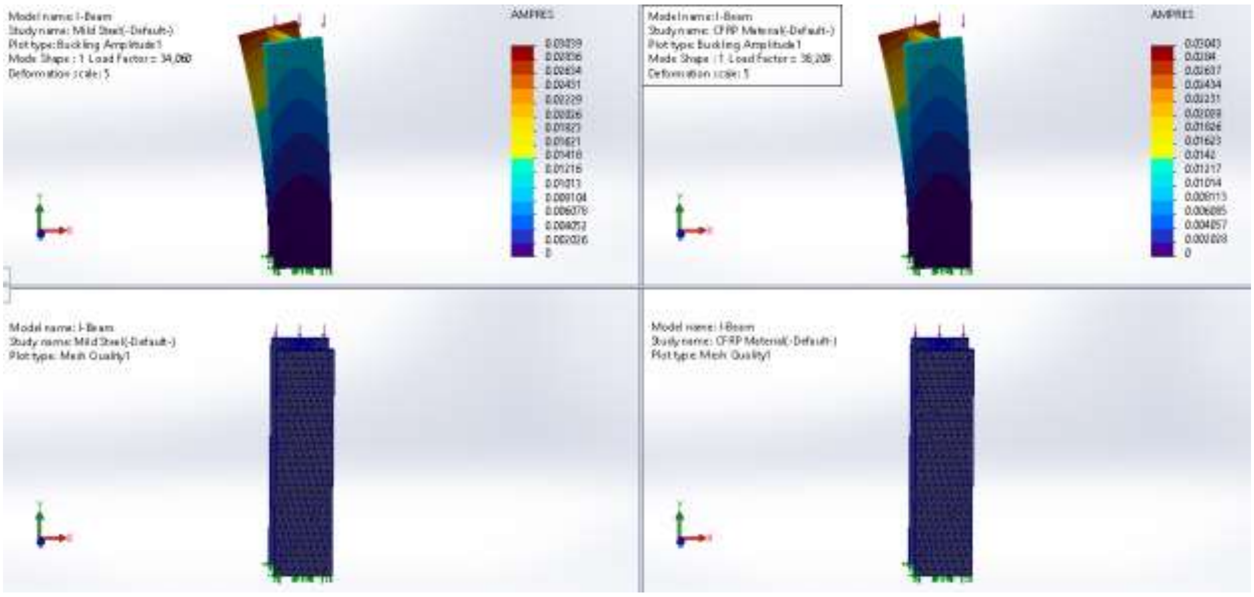

Figure 8. Stress distribution in the CFRP and steel alloy I-Beam model subjected to buckling loading.

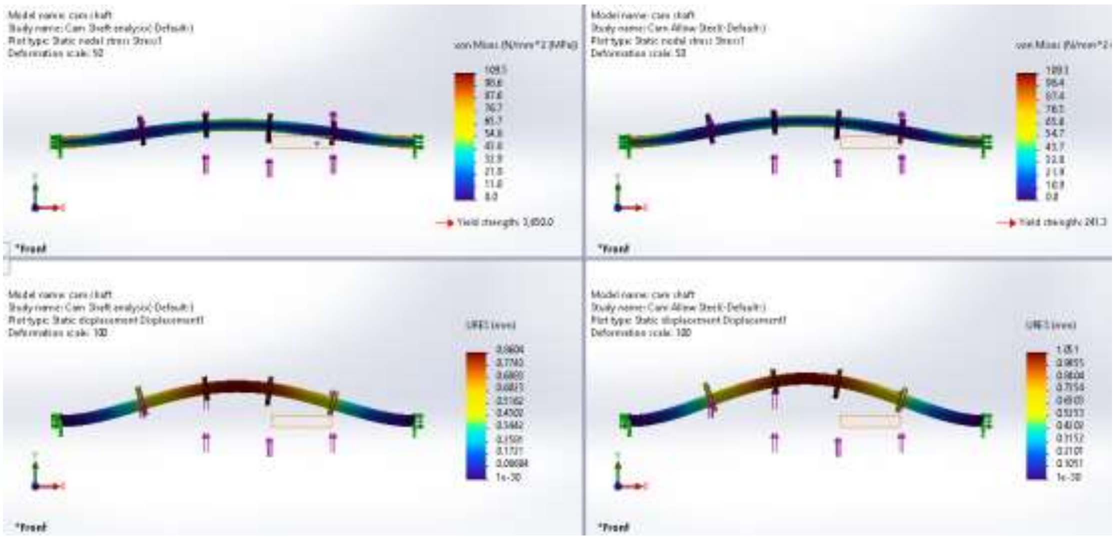

Figure 9. Stress distribution in the CFRP and steel alloy Cam Shaft model subjected to static and torsional loading.

The FEA results for CFRP, as compared to other materials, are presented in Figures 6 to 8, showcasing the stress and deformation characteristics under different loading conditions. Figure 6 illustrates the stress distribution in the CFRP Connecting Rod model subjected to static compressive loading. The colour contour plot highlights the areas of high stress concentration, allowing for a visual understanding of the load-bearing capacity and potential failure zones. By comparing the stress distribution of CFRP with other materials used in the Connecting Rod, valuable insights can be gained regarding the material's performance and its suitability for the given application.

Similarly, Figure 7 presents the stress distribution in the CFRP and Aluminium Propeller Blades models subjected to pressure loading. The contour plot reveals the stress patterns and enables a comparative analysis between CFRP and other materials. Understanding the stress distribution is crucial for optimizing the design and ensuring that the material can withstand the applied pressure without failure or excessive deformation. In Figure 8, the stress distribution in the CFRP I-Beam model under buckling conditions is depicted. The FEA results highlight the regions of high stress concentration, indicating potential areas of failure or deformation. By comparing the stress distribution of CFRP with that of Alloy Steel, valuable insights can be gained into the structural behaviour and load-carrying capacity of the different materials.

Lastly, Figure 9 presents the stress distribution in the CFRP Cam Shaft model subjected to static stress analysis and torsional loading. The contour plot provides a visual representation of the stress distribution along the camshaft, allowing for an assessment of its structural integrity and potential failure points. Comparing the stress distribution of CFRP with Alloy Steel provides insights into the material's performance in terms of torsional loading and stress resistance. The stress and deformation distribution obtained from the FEA results offer valuable information about the mechanical behaviour and load-carrying capacity of the CFRP models. By comparing these results with those of other materials, the advantages and limitations of CFRP can be identified in terms of stress concentration, deformation, and overall structural performance.

FAILURE MODES AND DAMAGE PREDICTION

The failure modes and damage prediction for the analysed models are essential in assessing the structural integrity and potential failure mechanisms of CFRP structures. The Max von Mises stress criterion has been utilized in this study as the critical failure point, representing the stress at which the stress-strain curve discontinues. The analysis involves examining the failure characteristics of CFRP structures under various loading and boundary conditions.

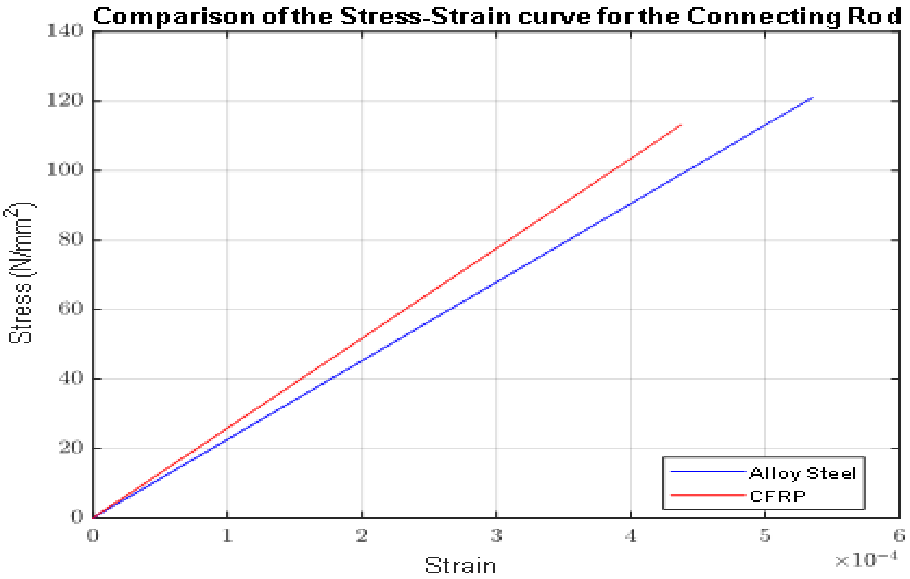

Figure 10. Stress-Strain Curves for the CFRP and Alloy Steel Connecting rod models

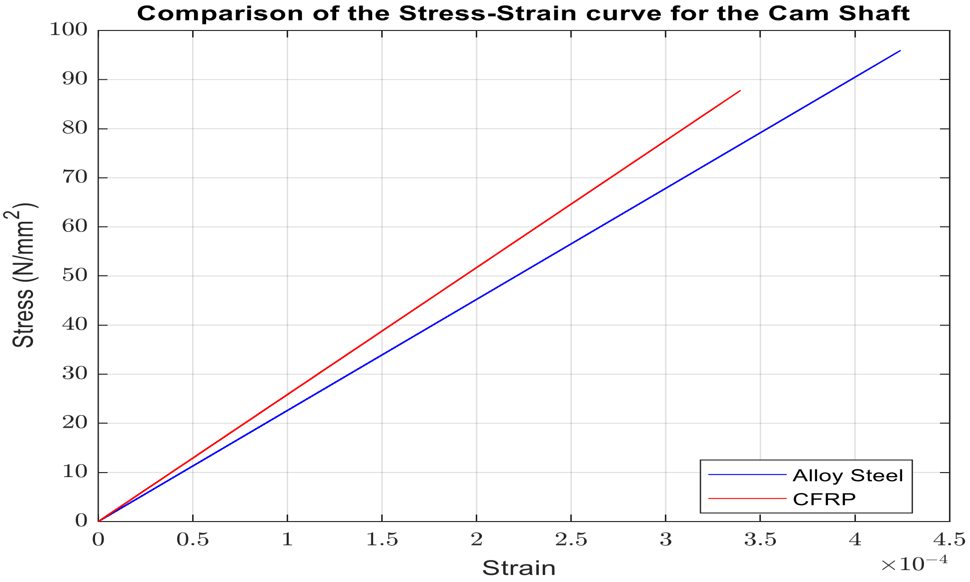

Figure 11. Stress-Strain Curves for the CFRP and Alloy Steel cam shaft models

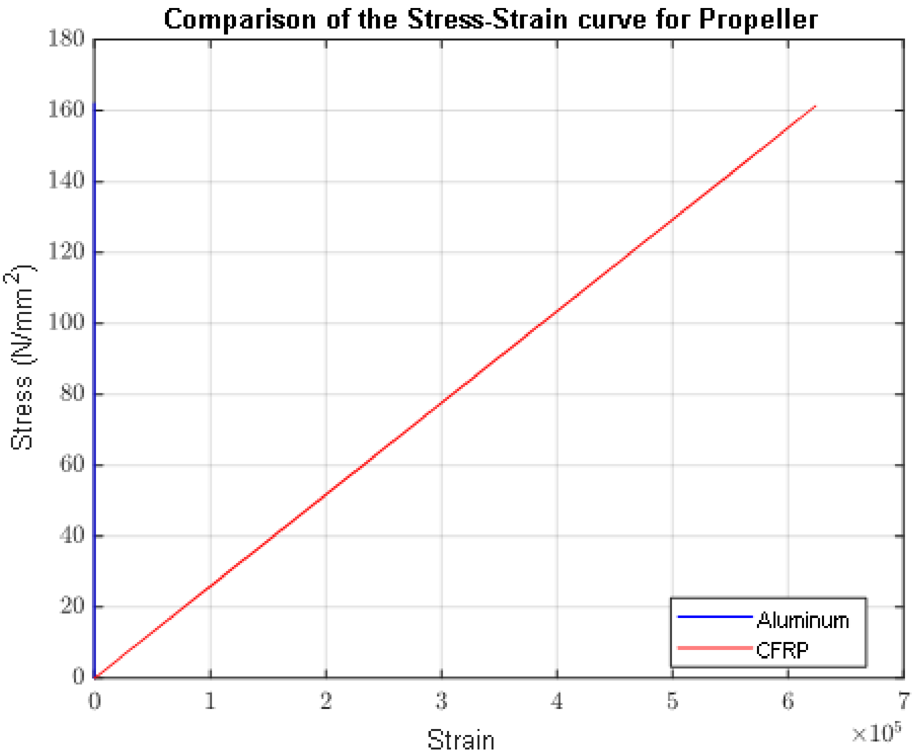

Figure 12. Stress-Strain Curves for the CFRP and aluminium propeller models

Figure 10 showcases the stress-strain curves for the Connecting Rod model, comparing the mechanical behaviour of CFRP with Alloy Steel. The red line represents the stress-strain curve for CFRP, while the blue line represents Alloy Steel. The stress is plotted on the ordinate axis, while the strain is plotted on the abscissa axis. Similarly, Figure 11 presents the stress-strain curves for the Cam Shaft model, comparing CFRP with Alloy Steel. The red line represents the stress-strain curve for CFRP, while the blue line represents Alloy Steel.

In Figure 12, the stress-strain curves for the Propeller models are displayed, comparing CFRP with Aluminium. The red line represents the stress-strain curve for CFRP, while the blue line represents Aluminium. These curves provide insights into the material's behaviour under loading and help in predicting failure modes and damage mechanisms.

NODAL ANALYSIS

The results of the nodal analysis for stresses, strains, and deformation are presented in in this section. Comparison is made for the different materials used in the models.

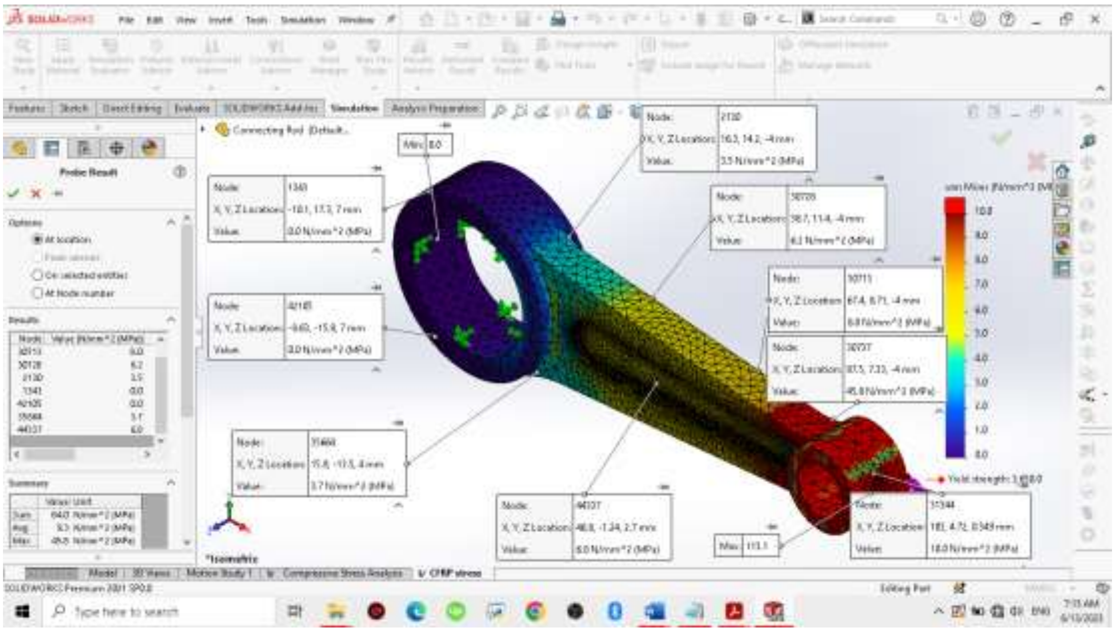

Figure 13. Nodal capture of connecting rod for stress, strain and deformation characteristics.

NODAL TEST AND ANALYSIS

The nodal stress, strain and deformation data were exported from SolidWorks in '.csv' format and imported as vector variables in MATLAB for further analysis. A plot of the nodal elements with respect to the Cartesian coordinates of the models was plot against the stress and strain values obtained from the FEA of each model. The results are presented in Figure 14 to 18.

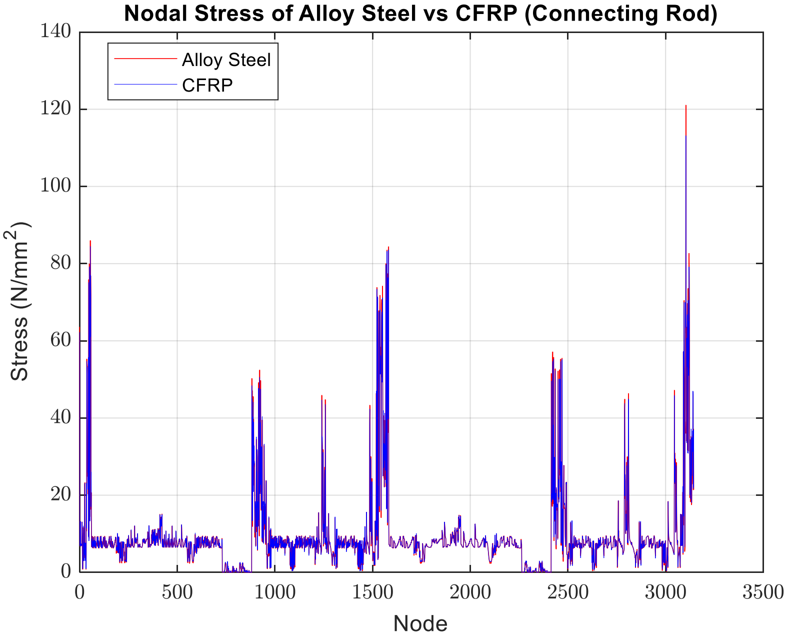

Figure 14. Nodal Stress for Connecting rod model.

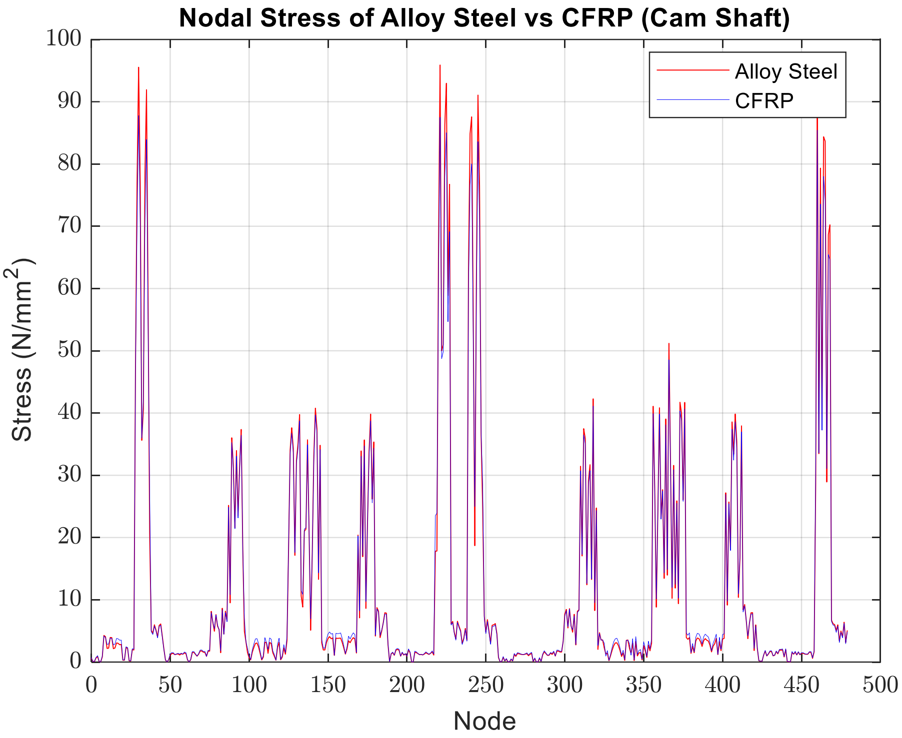

Figure 15. **Nodal Stress for Cam shaft model.**

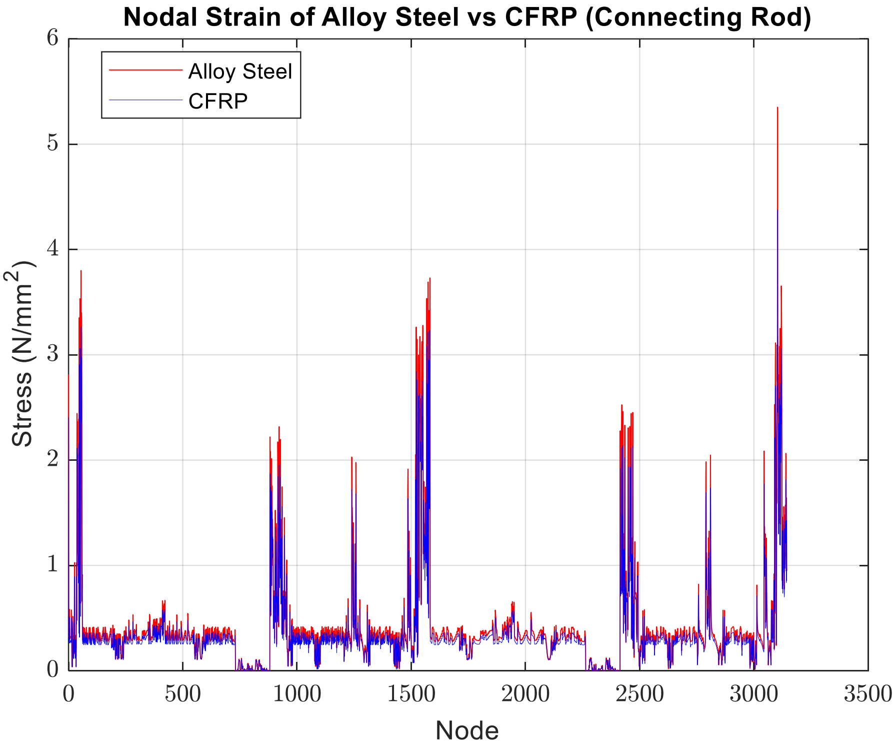

Figure 16. **Nodal Stress for Cam sha Nodal Strain for Connecting rod model**

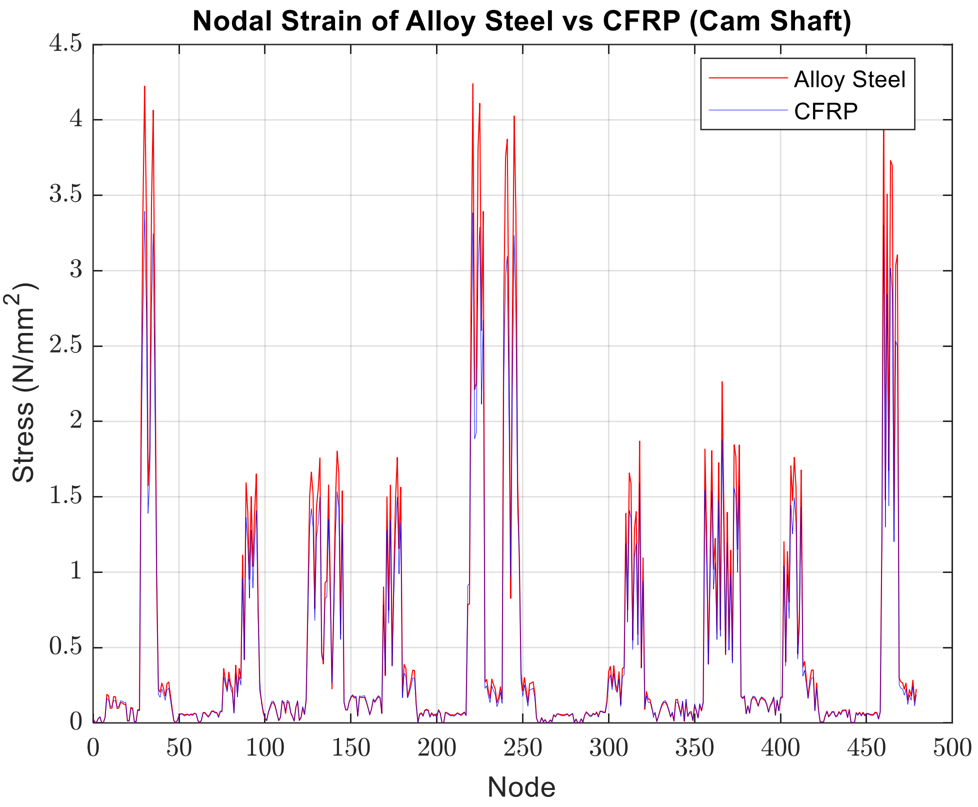

Figure 17. **Nodal Strain for Cam shaft model**

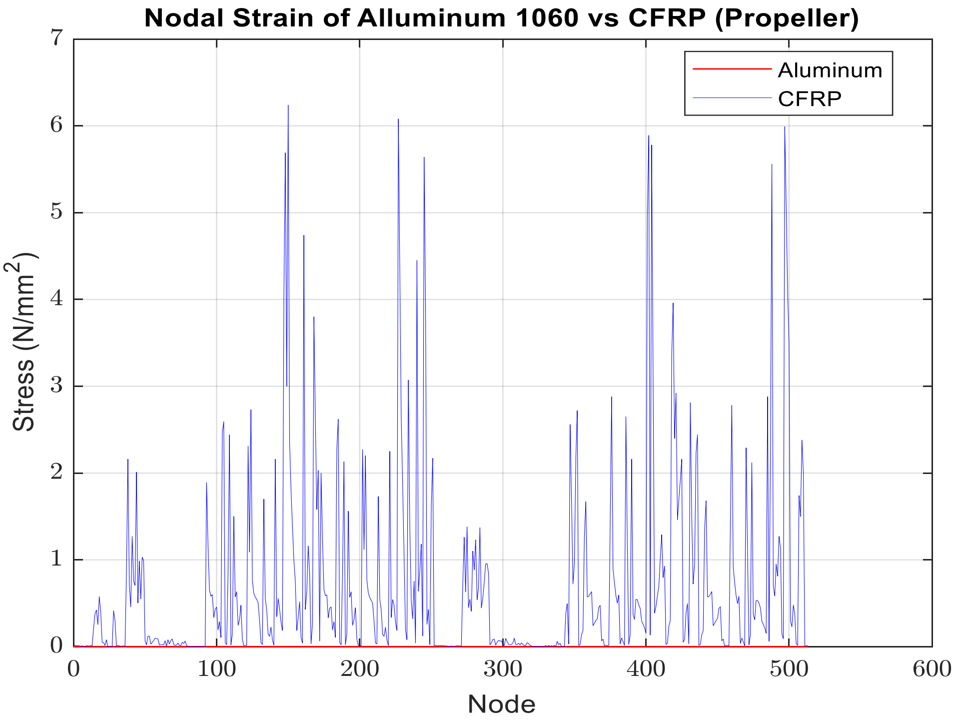

Figure 18. **Nodal Strain for Propeller model**

Figures 14 and 15 present the nodal stress plots for the connecting rod and the cam shaft, respectively. In these plots, the blue line represents the CFRP material, while the red lines depict the stress distribution for the Aluminium and alloy steel counterparts. The stress values are plotted on the ordinate axis, while the nodes are represented on the abscissa axis. These plots provide a visual representation of the stress distribution within the components, allowing for a detailed analysis of the areas experiencing the highest stress concentrations.

Moving on to the nodal strain plots, Figure 16 displays the nodal strain distribution for the connecting rod. Similarly, Figure 17 represents the nodal strain distribution for the cam shaft. The strain values are plotted on the ordinate axis, and the nodes are depicted on the abscissa axis. Lastly, Figure 18 showcases the nodal strain plot for the propeller. Similar to the previous plots, the blue line represents CFRP, while the red lines correspond to the strain distribution for aluminium and alloy steel.

STATISTICAL ANALYSIS OF RESULTS

Statistical analysis allows shows useful insights into the distribution and variation of the stress, strain, and deformation within the models. Table 4 presents the statistical analysis results of stress, strain, and deformation for the different models. For the connecting rod, both CFRP and alloy steel materials were analysed. The maximum, minimum, mean, and root mean square (RMS) values of stress, strain, and deformation are provided. Similarly, for the cam shaft, the statistical analysis is performed for CFRP and alloy steel materials. The propeller blades were analysed for CFRP and Aluminium materials.

Table 4. Statistical Analysis of Stress, Strain, and Deformation in the Models.

Design	**Material**	**Nodes**	**Stress (N/mm^2 (MPa))**				**Strain**				**Deformation (mm)**			
			Max	Min	Mean	RMS	Max	Min	Mean	RMS	Max	Min	Mean	RMS
Connecting rod	Cast Alloy steel	30881	121.1	0.0	9.3	14.4	0.0005352	4.495e-09	4.129e-05	6.344e-05	0.008554	1e-30	0.001642	0.0025
	CFRP	30881	113.1	0.0	9.4	14.3	0.0004376	6.104e-09	3.62e-05	5.515e-05	0.006978	1e-30	0.001342	0.0020
Cam shaft	Cast Alloy steel	2744	95.9	0.0	11.7	22.8	0.000424	7.708e-08	5.184e-05	0.0001006	0.9953	1e-30	0.6816	0.7441
	CFRP	2744	87.8	0.0	11.5	21.5	0.0003394	8.485e-08	4.461e-05	8.33e-05	0.8151	1e-30	0.5578	0.609
Propeller	Aluminium Alloy	1345	162.1	0.0	18.2	34.	0.002084	2.607e-08	0.0002333	0.000437	4.851	1e-30	1.712	2.471
	CFRP	1345	161.4	0.0	18.1	34.0	6.243e+05	8.188	7.007e+04	1.313e+05	1.445e+09	1e-30	5.097e+08	7.356e+08

DISCUSSION

MODEL PROPERTIES

The physical properties of the designed models and their variations are presented in Table 3. These properties provide important insights into the characteristics of the models and play a significant role in their performance. For the Connecting Rod, both CFRP and Alloy Steel materials were considered. The CFRP connecting rod has a lower mass, volume, and density compared to the Alloy Steel connecting rod. This indicates that the CFRP connecting rod is lighter and has a lower material density, potentially offering advantages in terms of weight reduction and improved fuel efficiency. However, it is important to consider the trade-offs between weight reduction and strength when selecting the material for the connecting rod application.

Similarly, in the case of the Propeller Blades, the CFRP material exhibits lower mass, volume, and density compared to Aluminium. Again, this suggests that CFRP offers the potential for weight reduction in the propeller blades, which can be advantageous in terms of improving the overall performance and efficiency of the system. In the analysis of the I-Beam, both CFRP and Alloy Steel materials were subjected to buckling loading. It is observed that the CFRP I-Beam has a significantly lower mass, volume, and density compared to the Alloy Steel I-Beam. This indicates that CFRP can offer weight reduction benefits while maintaining structural integrity under buckling loads. For the Cam Shaft, which underwent static stress analysis and torsional loading, the CFRP material exhibits lower mass, volume, and density compared to Alloy Steel. The lower mass of the CFRP cam shaft indicates potential benefits in terms of reducing inertia and improving the response time of the system.

STRESS AND DEFORMATION CONTOURS

In Figure 5 to 8, the stress, strain and deformation contours are presented aside by side for the different materials. Figure 5 shows the stress contours for the Alloy Steel and CFRP connecting rod at the top left and bottom respectively. From the meshed diagram, the high stress region (red) in the Alloy steel spreads farther away from the point of application of the force towards the bushing support. In the CFRP connecting rod however, the stress seems to be more contained as seen in the containment of the red region close to the area where the force was applied. The displacement contours (bottom left and right) also show that the allow steel material will tend to deform more as evident in the dark red colour spanning for more than 3/4 of the rod length. The CFRP model however does not experience such high deformations as the allow steel under the same loading.

In Figure 6, the stress, strain, and deformation contours are presented for the Propeller made of Aluminium and CFRP materials. The stress contour plot clearly shows that the induced stress is higher in the Aluminium propeller compared to the CFRP propeller. The red regions representing high stress are more extensive and widespread in the Aluminium propeller, indicating a higher stress concentration throughout the structure.

Additionally, the stress contours reveal interesting differences at the blade connection. In the CFRP propeller, the stress is more contained and localized near the blade connection, as seen by the smaller extent of the red region. This suggests that the CFRP material effectively distributes and absorbs the applied load, resulting in a more uniform stress distribution and lower stress concentration at critical regions. The strain contour plot provides insights into the deformation characteristics of the propeller. The colour gradients in the Aluminium propeller indicate very high deformations, with dark red regions spanning a significant portion of the blade sections. This indicates that the Aluminium propeller experiences substantial deformations under the applied loading.

Comparing the stress contours, the red colours representing high stress levels appear darker in the Aluminium propeller compared to the CFRP propeller. This observation suggests that the Aluminium material experiences higher stress magnitudes, potentially indicating a higher risk of structural failure or reduced structural integrity.

NODAL STRESS, STRAIN AND DEFORMATION

In the nodal stress and strain figures, it is consistently observed that the red line representing the Aluminium or Alloy Steel material is higher than the blue line representing CFRP across all the models and configurations. This indicates that the Aluminium or Alloy Steel materials experience higher stress and strain levels compared to CFRP under the given loading conditions.

Notably, in the propeller nodal strain figure (Figure 17), the graph of the Aluminium material shows a straight line, suggesting that all the nodes have surpassed their plastic deformation limit. This indicates a critical failure mode where the propeller material has exceeded its elastic limit and undergone permanent deformation. In contrast, the CFRP graph shows a more gradual and limited increase in strain, indicating that CFRP exhibits better resistance to plastic deformation and maintains its structural integrity under the applied loading. The consistently higher stress and strain values in the red (Aluminium or Alloy Steel) graphs compared to the blue (CFRP) graphs emphasize the differences in mechanical behaviour and performance between these materials. The higher stress and strain levels in the red graphs suggest that the Aluminium and Alloy Steel materials may be more susceptible to failure and exhibit reduced structural resilience compared to CFRP.

STATISTICAL ANALYSIS

Table 4 presents the results of the statistical analysis conducted on the stress, strain, and deformation data obtained from the models. This analysis provides valuable insights into the distribution and characteristics of these parameters, allowing us to better understand the behaviour of the materials and their response to different loading conditions. In the case of the Connecting Rod, both the Cast Alloy Steel and CFRP materials were analysed. The maximum stress observed in the Cast Alloy Steel connecting rod was 121.1 N/mm^2 (MPa), while for CFRP, it was slightly lower at 113.1 N/mm^2 (MPa). The minimum stress was 0.0 N/mm^2 (MPa) for both materials. The statistical analysis also provides information on the mean and RMS (root mean square) values of stress, strain, and deformation for each material.

In the case of the Cam Shaft, both Cast Alloy Steel and CFRP materials were examined. The maximum stress observed in the Cast Alloy Steel cam shaft was 95.9 N/mm^2 (MPa), while for CFRP, it was slightly lower at 87.8 N/mm^2 (MPa). Again, the minimum stress was 0.0 N/mm^2 (MPa) for both materials. The statistical analysis also provides information on the mean and RMS values of stress, strain, and deformation. For the Propeller, the analysis considered Aluminium Alloy and CFRP materials. The maximum stress observed in the Aluminium Alloy propeller was 162.1 N/mm^2 (MPa), while for CFRP, it was slightly lower at 161.4 N/mm^2 (MPa). The minimum stress was 0.0 N/mm^2 (MPa) for both materials. Additionally, the statistical analysis provides insights into the mean and RMS values of stress, strain, and deformation for each material.

IMPLICATION TO RESEARCH AND PRACTICE

Based on the discussed findings, here are six key observations:

1. The physical properties of the designed models highlight the differences between materials. CFRP exhibits lower mass, volume, and density compared to Alloy Steel or Aluminium, indicating potential weight reduction benefits and improved performance in terms of fuel efficiency and response time.
2. The stress contours reveal that Alloy Steel tends to experience higher stress concentrations spreading farther away from the point of force application, while CFRP demonstrates more contained stress regions near the application area. Displacement contours show that Alloy Steel undergoes higher deformations compared to CFRP.
3. The stress contour plot of the Propeller shows higher induced stress in Aluminium compared to CFRP, with more extensive and widespread red regions indicating higher stress concentrations. CFRP exhibits better stress distribution and lower stress concentration at the blade connection. The strain contour plot highlights significant deformations in the Aluminium propeller, indicating its susceptibility to high deformation under the applied loading.
4. The nodal stress and strain figures consistently show higher stress and strain levels for Aluminium or Alloy Steel materials compared to CFRP across all models and configurations. In particular, the straight line in the Aluminium propeller's nodal strain graph indicates that all nodes have surpassed their plastic deformation limit, suggesting critical failure, while CFRP exhibits better resistance to plastic deformation.
5. The statistical analysis of stress, strain, and deformation data confirms the differences in behaviour between materials. The maximum stress values are generally higher for Aluminium or Alloy Steel compared to CFRP, indicating potential higher susceptibility to failure. Mean and RMS values provide additional insights into the distribution and characteristics of these parameters for each material.
6. The findings emphasize the advantages of CFRP, including lower weight, better stress distribution, and higher resistance to plastic deformation. These characteristics make CFRP a promising choice for applications where weight reduction, structural integrity, and resilience are critical factors.

CONCLUSION

From the FEA analysis of stress and deformation contour plots, distinct differences in stress concentration and deformation characteristics between CFRP, Aluminium and alloy steel were examined. The maximum stress values for Cast Alloy Steel were 121.1 N/mm^2 (MPa) for the connecting rod and 95.9 N/mm^2 (MPa) for the cam shaft, while CFRP exhibited slightly lower values of 113.1 N/mm^2 (MPa) and 87.8 N/mm^2 (MPa) respectively. The maximum stress values for Aluminium Alloy in the propeller were 162.1 N/mm^2 (MPa), whereas CFRP showed a slightly lower value of 161.4 N/mm^2 (MPa). These findings indicate that Alloy Steel and Aluminium materials experience higher maximum stress levels compared to CFRP, highlighting their higher risk of failure and reduced structural resilience.

Based on these specific insights, it can be concluded that CFRP materials offer advantages over Alloy Steel and Aluminium in terms of stress distribution, deformation characteristics, and resistance to plastic deformation. CFRP demonstrates a more contained stress distribution, lower deformations, and better structural integrity under the applied loading conditions.

FUTURE RESEARCH

While this study provides valuable insights into the mechanical behaviour of CFRP and other materials through computational modelling, it is important to acknowledge the limitations of using software simulations instead of real experimental data. Future studies can address these limitations and enhance the understanding of material behaviour by incorporating experimental data in the following ways:

i. Experimental Validation: Conduct experimental tests to validate the accuracy of the computational models used in this study. This would involve manufacturing CFRP and other structures and subjecting them to controlled loading conditions to measure stress, strain, and deformation. A direct comparison between the experimental data and the simulation results would provide a more robust validation of the computational models.

ii. Material Characterization: Perform comprehensive material characterization experiments to obtain accurate material properties of CFRP and other materials. This would involve conducting tests such as tensile tests, compression tests, and flexural tests to determine mechanical properties like modulus of elasticity, strength, and failure criteria. These experimental results can then be used to improve the accuracy of the material models used in the simulations.

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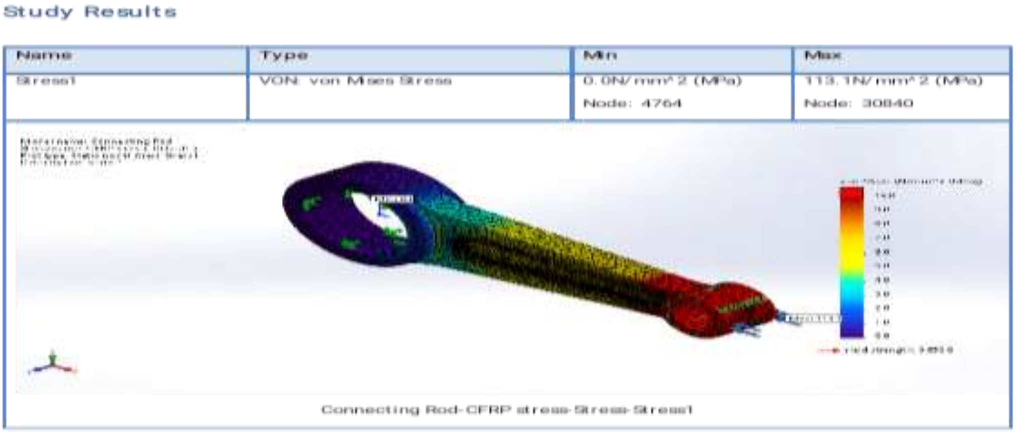
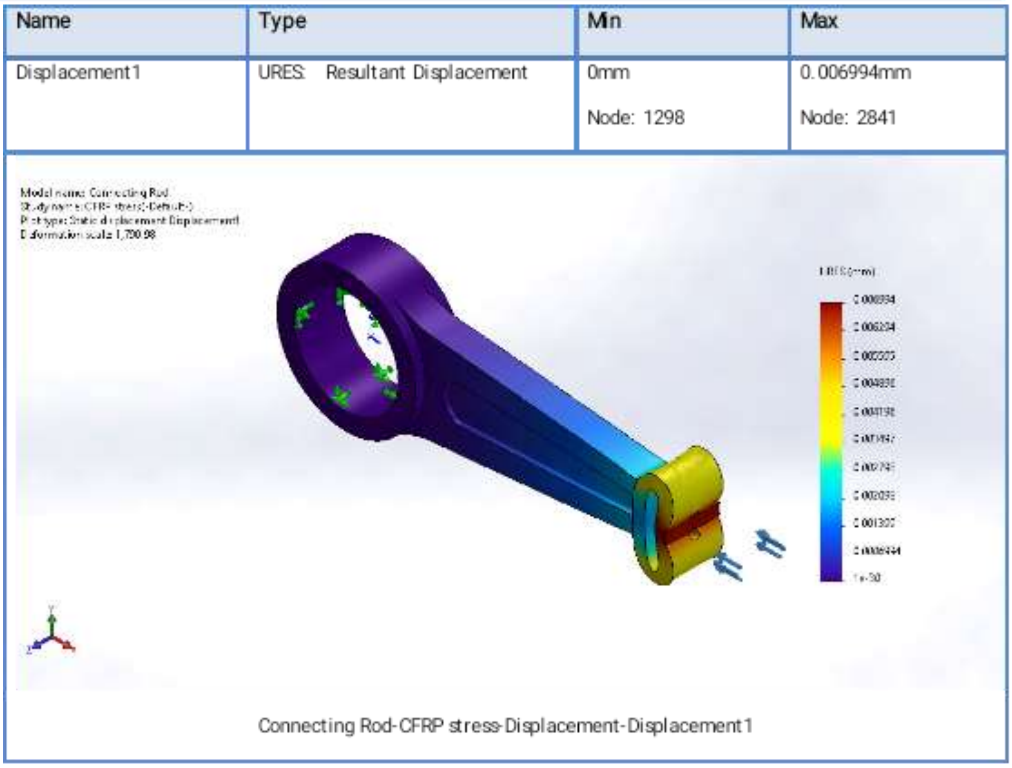
Appendix



Study Results

Name	Type	Min	Max
Stress1	VON: von Mises Stress	0.0N/mm^2 (MPa) Node: 4764	113.1N/mm^2 (MPa) Node: 30840

Connecting Rod-CFRP stress-Stress-Stress1

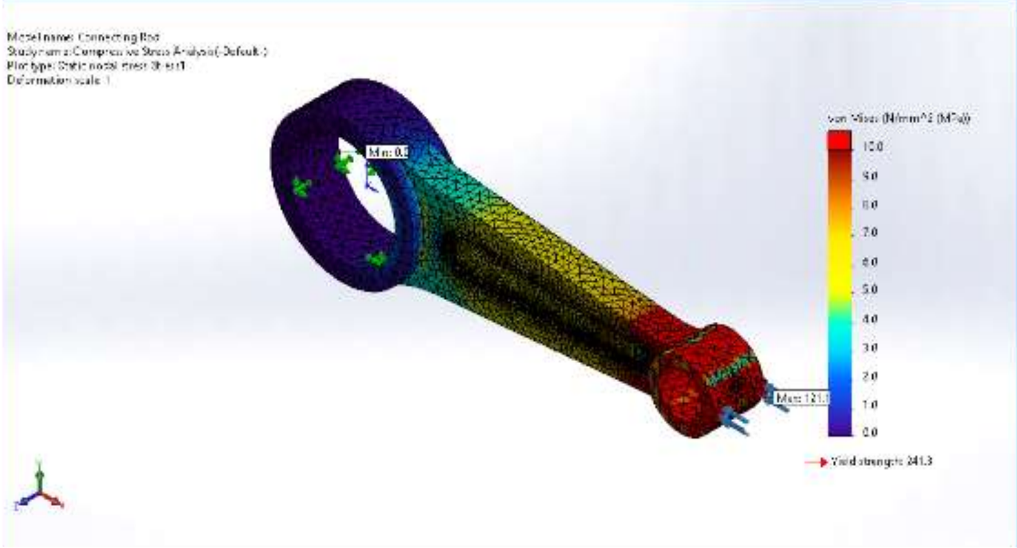


Name	Type	Min	Max
Displacement1	URES: Resultant Displacement	0mm Node: 1298	0.006994mm Node: 2841

Model name: Connecting Rod
Study name: CFRP stress(-Default-)
Plot type: Static displacement Displacement1
Deformation scale: 1,780.98

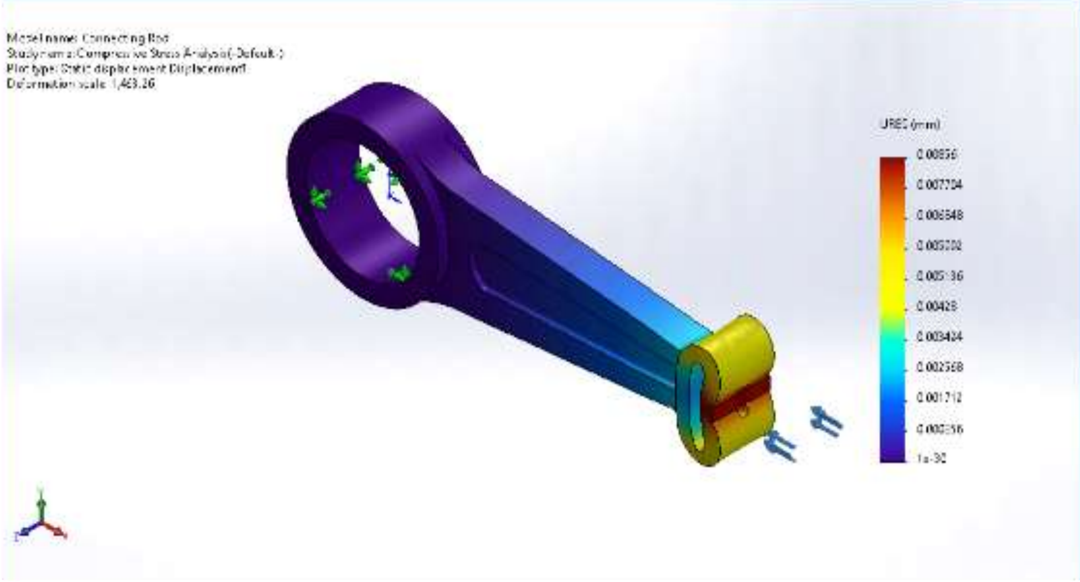
Connecting Rod-CFRP stress-Displacement-Displacement1

Name	Type	Min	Max
Stress1	VON: von Mises Stress	0.0N/mm^2 (MPa) Node: 40685	121.1N/mm^2 (MPa) Node: 30840



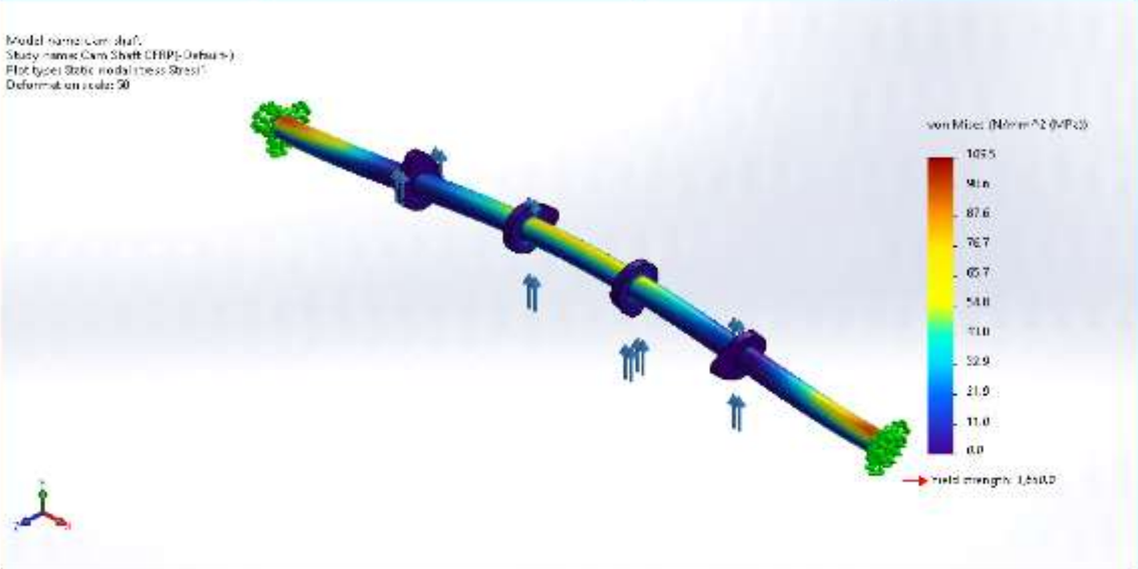
Connecting Rod-Compressive Alloy Steel Stress

Name	Type	Min	Max
Displacement1	URES: Resultant Displacement	0mm Node: 1298	0.00856mm Node: 8162



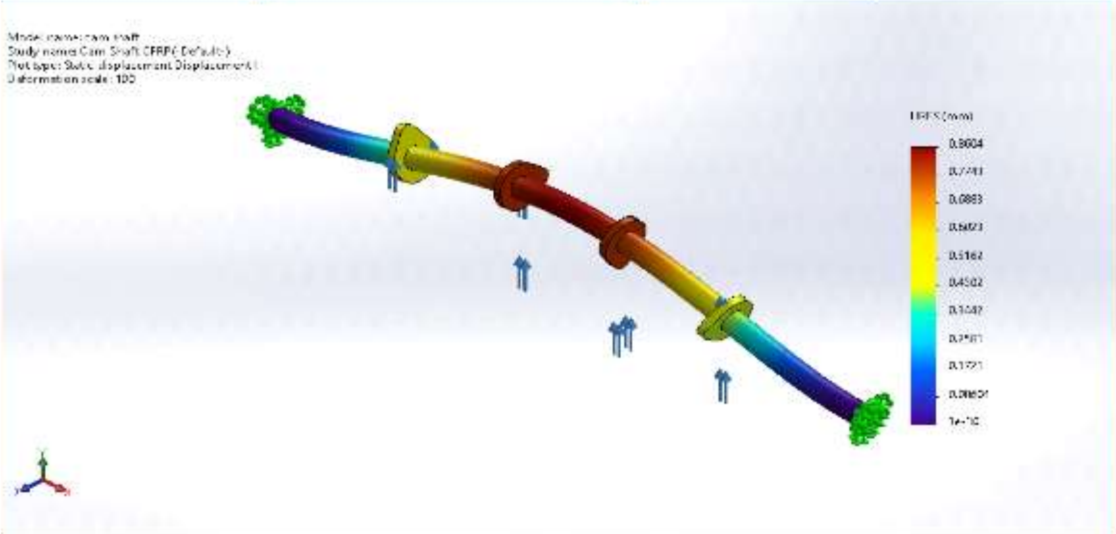
Connecting Rod-Compressive Alloy Steel Strain

Name	Type	Min	Max
Stress1	VON: von Mises Stress	0.0N/mm^2 (MPa) Node: 154	109.5N/mm^2 (MPa) Node: 423



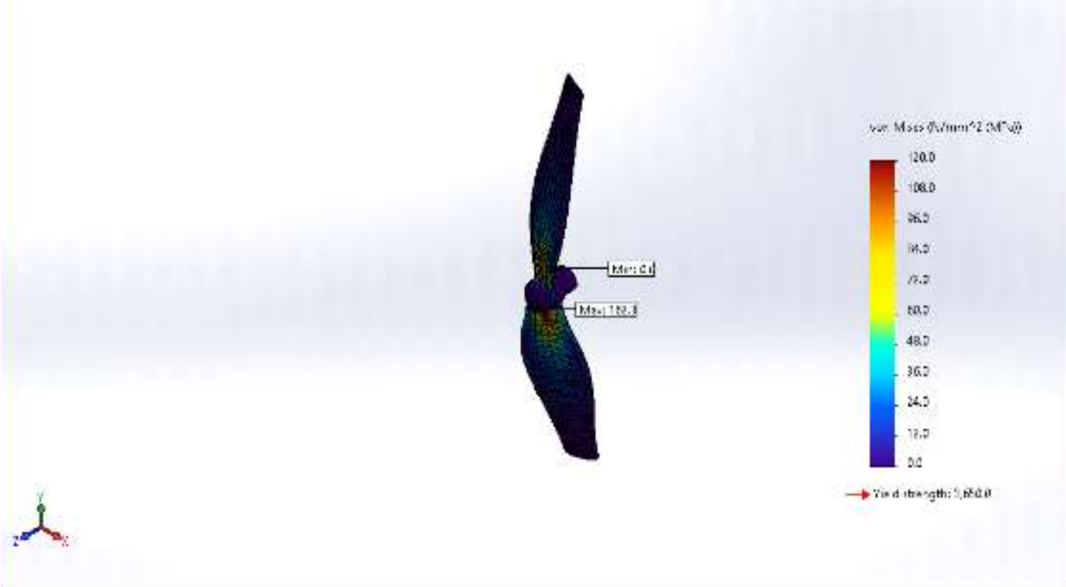
cam shaft-Cam Shaft CFRP-Stress-Stress1

Name	Type	Min	Max
Displacement1	URES: Resultant Displacement	0mm Node: 33	0.8604mm Node: 864



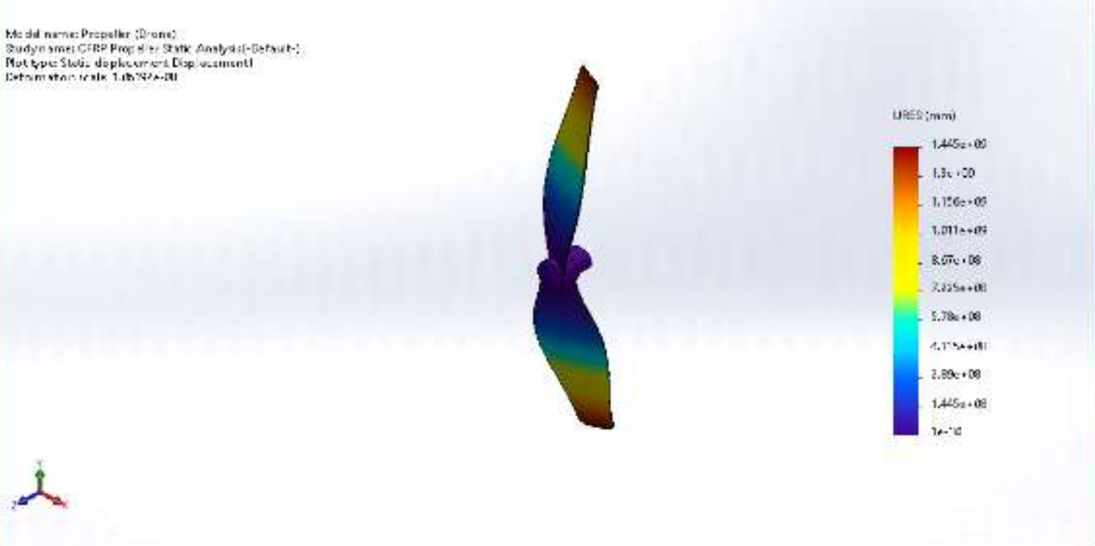
cam shaft-Cam Shaft CFRP-Displacement-Displacement1

Name	Type	Min	Max
Stress1	VON: von Mises Stress	0.0N/mm^2 (MPa) Node: 1573	162.3N/mm^2 (MPa) Node: 158



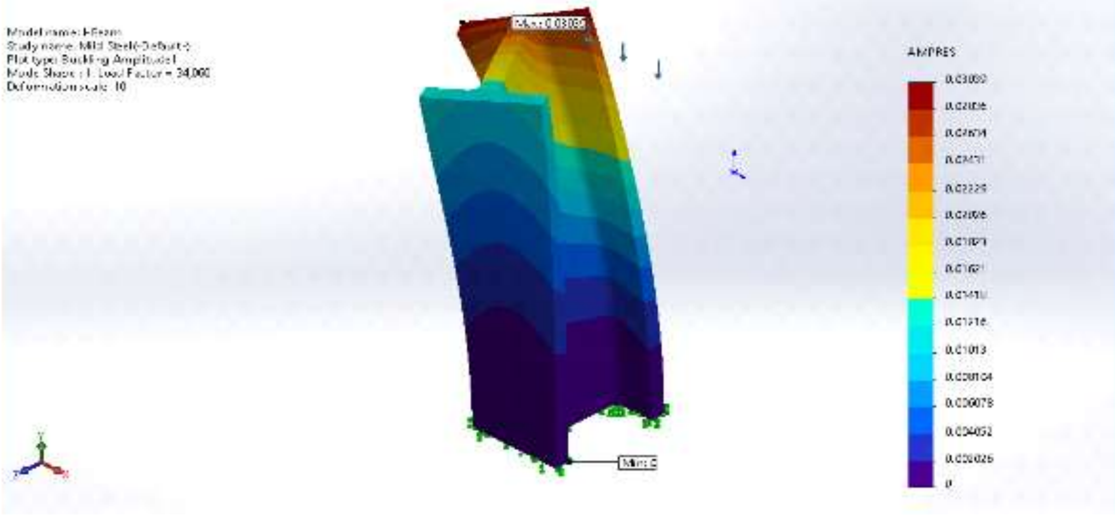
Propeller -CFRP Propeller Static Analysis-Stress-Stress1

Name	Type	Min	Max
Displacement1	URES: Resultant Displacement	0mm Node: 23	1.445e+09mm Node: 6



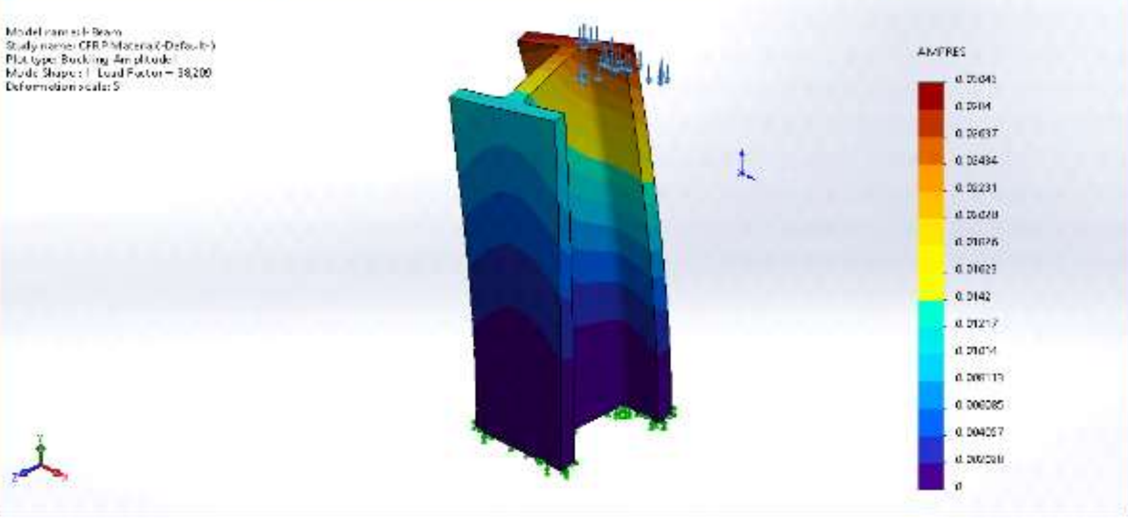
Propeller-CFRP Propeller Static Analysis-Displacement-Displacement1

Name	Type	Min	Max
Amplitude1	AMPRES: Resultant Amplitude Plot for Mode Shape: 1(Load Factor = 34,060.1)	0 Node: 3	0.03039 Node: 26



I-Beam-Mild Steel-Amplitude

Name	Type	Min	Max
Amplitude1	AMPRES: Resultant Amplitude Plot for Mode Shape: 1(Load Factor = 38,209.4)	0 Node: 3	0.03043 Node: 26



I-Beam-CFRP Material-Amplitude