Optimization of Forklift Fork Design for Enhanced Performance and Safety in Material Handling Operations Using Finite Element Analysis

Rebira Negash Bekele

A Thesis Submitted to the Department of Mechanical Engineering
College of Mechanical, Chemical and Materials Engineering
Presented in Partial Fulfillment of the Requirement for the Degree of
Master's in Automotive Engineering

Office of Graduate Studies

Adama Science and Technology University

January, 2025
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DECLARATION

I hereby declare this Master's Thesis entitled "**Optimization of Forklift Fork Design for Enhanced Performance and Safety in Material Handling Operations Using Finite Element Analysis**" is my work and has not been submitted for the award of any academic degree, diploma, or certificate in any other university. All sources of materials that are used for this thesis have been duly acknowledged through citation.

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Name of the student Signature Date

RECOMMENDATION

I/we, the advisor(s) of this thesis, hereby certify that I/we have read the revised version of the thesis entitled **“Optimization of Forklift Fork Design for Enhanced Performance and Safety in Material Handling Operations Using Finite Element Analysis”** prepared under my/our guidance by **Rebira Negash** submitted in partial fulfillment of the requirements for the degree of Mater’s of Science in Automotive Engineering. Therefore, I/we recommend the submission of a revised version of the thesis to the department following the applicable procedures.

__ Dr. Gelata Fikadu____ ______________________ _6/5/2025____________

Major Advisor Signature Date

___________________________ ________________________ _______________

Co-advisor Signature Date

APPROVAL

I/we, the advisors of the thesis entitled **“Optimization of Forklift Fork Design for Enhanced Performance and Safety in Material Handling Operations Using Finite Element Analysis”** developed by **Rebira Negash**, hereby certify that the recommendations and suggestions made by the board of examiners are appropriately incorporated into the final version of the thesis

__Dr. Gelata Fikadu________ ____________________________ ______6/1/2025_________
Major Advisor Signature Date

________________________ ________________________ ________________
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We, the undersigned, members of the Board of Examiners of the thesis by **Rebira Negash,** have read and evaluated the thesis **“Optimization of Forklift Fork Design for Enhanced Performance and Safety in Material Handling Operations Using Finite Element Analysis”** and examined the candidate during the open defense. This is, therefore, to certify that the thesis is accepted for partial fulfillment of the requirement of the degree of Master of Science in Automotive Engineering.

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ACKNOWLEDGMENT

I would like to express my gratitude to God for helping me complete this thesis. I also want to thank my advisor, Dr. Gelata Fikadu, and co-advisor, Dr. Ramesh Babu Nallamothu, for their patient guidance throughout this work. Research studies are successful thanks to the contributions of several wonderful individuals who provide valuable advice and support. I am grateful to all those who have lent their inspiration, support, and guidance, and who helped make my thesis a success.

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LIST OF ACRONYMS

FEA	Finite Element Analysis
CAD	Stands for Computer-Aided Design
OSHA	Occupational Safety and Health Administration
RSM	Response Surface method
CCD	Central Composite Design
ANSI	American National Standards Institute
FOS	Factor of Safety
ECRS	Eliminate, Combine, Rearrange, and Simplify
DOE	Design of experiment
ANOVA	Analysis of Variance
CFR	Code of Federal Regulations
AICc	Akaike Information Criterion corrected
BIC	Bayesian Information Criterion
PRESS	Prediction Sum of Squares

ABSTRACT

The material handling industry relies heavily on the performance and safety of forklifts, with fork design playing a critical role in ensuring efficiency and reliability. Forklift forks, which are the primary load-bearing components, are responsible for supporting and lifting heavy loads, making their structural integrity and design optimization critical for safe and effective material handling. This research investigates the optimization of forklift fork design to enhance its performance and safety by leveraging Finite Element Analysis (FEA) through ANSYS software. A key focus of the study is the optimization of solid mass, stress distribution, and the factor of safety. Lightweight designs are prioritized to improve energy efficiency without compromising structural strength. The optimization process employed the Response Surface Method (RSM) using ANSYS Design Explore, where 25 design experiments were conducted and analysis through Minitab statistical software. This iterative process aimed to reduce solid mass for material efficiency, minimize von Mises stress to enhance durability, and improve the factor of safety to ensure adherence to safety standards like The Occupational Safety and Health Administration (OSHA). The study identified three candidate designs, with Candidate Point 1 selected for further optimization due to its superior performance metrics. The optimization process utilized input parameters such as the fork's height, length, depth, and overall geometry, employing fine and converged mesh systems to ensure precision. Key findings demonstrate a reduction in solid mass from 53.232 kg to 52.772 kg a difference of 0.46 kg, a significant decrease in average equivalent (von Mises) stress from 3.2306×10^7 *Pa to* 2.2998×10^7 *Pa, an improvement of 28.8% and an improvement in the safety factor from 1.8082 to 2.7998 representing a substantial 54.8% enhancement in the fork's resilience. These results highlight a marked enhancement in the fork's performance and structural safety while optimizing material use. This study contributes to material handling equipment design by presenting a robust framework for performance optimization using finite element analysis and advanced design exploration techniques. The findings emphasize the practicality and relevance of integrating computational optimization tools in industrial design processes to achieve higher efficiency, safety, and sustainability in material handling systems*

Keywords*: Forklift, Finite Element Analysis, Response Surface Method, ANSYS, software*

CHAPTER ONE

INTRODUCTION

1.1. Background of the study

Forklift trucks, also known as lift trucks or forklifts, are essential material handling equipment used in various industries for lifting, moving, and transporting heavy loads. The history of forklift trucks dates back to the early 20th century, with the development of the first mechanical lifting device designed to move heavy materials in warehouses and industrial settings. Over the years, forklift technology has evolved significantly, offering a range of design and power variations to cater to diverse application requirements. Initially developed in the early 1900s, forklifts were manually operated counterbalanced trucks utilizing levers and lever arms for pallet movement. While manual models are still in use, modern forklifts predominantly feature electric, gasoline, or diesel engines. Electric models are favored for indoor applications due to lower emissions and noise levels, while gasoline and diesel models offer higher power ratings for outdoor use. The concept of a forklift truck originated from the need to improve efficiency and productivity in material handling operations. Before the invention of forklifts, manual labor and traditional methods such as pulleys, ropes, and manual carts were used to move heavy loads, which were time-consuming and labor-intensive. The introduction of forklift trucks revolutionized how materials were handled and transported, leading to significant advancements in industrial processes. The early forklift trucks were simple, manually operated machines with basic lifting mechanisms. These early models were primarily used in warehouses and factories to lift and move pallets and other heavy loads. Over time, advancements in technology and engineering led to the development of more sophisticated forklift trucks with improved lifting capacities, maneuverability, and safety features. Forklift trucks are indispensable in modern warehousing, manufacturing, and construction industries, where efficient material handling is critical for operational success. Despite their widespread use, the design of forklift forks the primary load-bearing component often faces challenges related to material inefficiency, structural fatigue, and safety risks. These issues can lead to equipment failure, increased maintenance costs, and even workplace accidents. Optimizing the design of forklift forks offers a significant opportunity to address these challenges, enhancing both performance and safety while improving operational efficiency. This motivated the focus on developing advanced fork designs using Finite Element Analysis (FEA), a powerful tool for simulating real-world performance under diverse conditions.

Forklifts are small industrial vehicles equipped with a power-operated forked platform at the front, allowing for the lifting and movement of cargo. They play a crucial role in various industries, such as warehouses and large storage facilities. Forklifts can be powered by electric batteries or combustion engines, with some models designed for seated operation while others require standing. These vehicles are essential for transporting materials and goods, particularly in scenarios involving diverse shapes and packaging of items, making loading and unloading processes labor-intensive and time-consuming.

The invention of forklifts provided a solution to the challenges associated with cargo handling, offering efficiency in time and space utilization. Proper organization of cargo, coupled with the use of forklifts equipped with suitable attachments, streamlines loading and unloading operations, reducing manual labor requirements. Forklifts also optimize storage space utilization by enabling efficient stacking of goods. They are indispensable across various industries, including manufacturing, warehousing, construction, and agriculture. One of the key milestones in the evolution of forklift trucks was the introduction of electric-powered models in the mid-20th century (Bozkurt, Dai, & Özbek et al., 2017). Electric forklifts offered several advantages over diesel or gas-powered counterparts, including lower operating costs, reduced emissions, and quieter operation. Electric forklifts became increasingly popular in indoor environments such as warehouses and distribution centers due to their clean and efficient operation. In addition to motorized forklifts, automated models have emerged, capable of programmed task execution. These automated forklifts can efficiently handle pallet movement within warehouses or factories, detecting obstacles and adjusting their paths accordingly. The evolution of forklift technology has revolutionized material handling operations, enhancing efficiency and safety in various industrial settings. The design of forklift forks plays a significant role in determining the performance, efficiency, and safety of forklift operations. The impact of fork design on forklift performance is evident in its ability to effectively lift and carry loads of varying sizes and weights. Proper fork design ensures that the load is securely held in place, preventing shifting or falling during transport, which ultimately enhances the overall performance of the forklift. Efficiency in material handling operations is closely tied to fork design, as well. Well-designed forks allow for quick and precise loading and unloading of materials, reducing downtime and increasing productivity. The shape, length, and thickness of the forks can influence the speed and ease of material handling tasks, ultimately improving operational efficiency (Zhang, Gilbert, & Rasmussen et al., 2012).

Moreover, the safety of forklift operations is heavily dependent on the design of the forks. Properly designed forks help distribute the weight of the load evenly, reducing the risk of tip-overs or accidents. Additionally, features such as fork heel thickness, fork angle, and fork blade length can impact stability and maneuverability, enhancing overall safety in material handling operations. In conclusion, the design of forklift forks significantly impacts performance, efficiency, and safety, making it a critical consideration in optimizing material handling operations.

Traditional forklift designs have evolved to meet the demands of material handling operations. These forks are typically made of high-strength steel, known for its durability and ability to withstand heavy loads. The standard dimensions of forklift forks include length, width, and thickness, with variations based on the type of forklift and the intended application. Common materials used in traditional forklift fork designs include carbon steel, which offers a balance of strength and cost-effectiveness, and alloy steel, known for its enhanced durability and resistance to wear and tear. Some forklift forks may also be coated with materials like zinc or chrome for added protection against corrosion and abrasion. Despite their durability, traditional forklift fork designs face several challenges and limitations. One common issue is fatigue failure, caused by repeated loading and unloading cycles that can lead to cracks and fractures in the fork. Another challenge is related to the weight capacity of the forks, as exceeding the recommended load limit can result in structural damage and safety hazards. Additionally, the design of the fork tips and heels can impact stability and load distribution, affecting the overall performance of the forklift.

Furthermore, traditional forklift fork designs may not always be optimized for specific applications or operating conditions, leading to inefficiencies and potential safety risks. Factors such as improper fork alignment, inadequate thickness, or lack of reinforcement can contribute to premature wear and failure of the forks. Finite Element Analysis (FEA) is a computational method used in engineering to simulate and analyse the behaviour of complex structures and systems under various conditions. It involves dividing a structure into smaller, finite elements to accurately model its physical properties and behavior. By applying mathematical equations and algorithms, FEA can predict how a structure will respond to different loads, stresses, and environmental factors, providing valuable insights into its performance and durability. FEA is widely used in engineering design to optimize product performance, reduce costs, and minimize risks. Engineers can use FEA to evaluate different design options, identify potential weaknesses, and make informed decisions to enhance a product's overall quality and efficiency. By simulating real-world conditions and scenarios, FEA enables engineers to predict how a design will behave before physical prototypes are built, saving time and resources in the product development process. In the context of forklift fork design, FEA can be a powerful tool for analyzing and optimizing the performance and safety of the forks. By creating a virtual model of the forklift forks and applying FEA techniques, engineers can simulate various loading conditions, such as different weights and angles of the load, to assess how the forks will respond. This analysis can help identify potential stress points, weak areas, or areas of excessive deformation in the fork design, allowing engineers to make necessary modifications to improve strength, stability, and overall performance. Furthermore, FEA can be used to evaluate the impact of different materials, geometries, or manufacturing processes on the forklift fork design. By conducting virtual tests and simulations, engineers can assess the structural integrity, fatigue resistance, and overall reliability of the forks, ensuring they meet safety standards and performance requirements in material handling operations. Overall, FEA provides a powerful tool for optimizing forklift fork design, enhancing performance, and ensuring the safety and efficiency of material handling operations.

1.2. Statement of the problem

The current design of forklift forks often lacks optimization for performance and safety in material handling operations. Existing designs are not fully tailored to minimize stress and deformation under varying load conditions, leading to inefficiencies in operations and increased maintenance requirements. Critical areas such as the root fillet region are prone to stress concentrations, which compromise the durability and reliability of the forks over time. The design of forklift forks is a critical aspect of material handling operations, where performance and safety are paramount. One of the primary challenges in this domain is the risk of abnormal fatigue failure in forklift forks, which can lead to catastrophic accidents and significant economic losses. Research has shown that the fatigue life of forklift forks can be adversely affected by factors such as material selection, design geometry, and loading conditions. For instance, conducting an analysis of abnormal fatigue failure in forklift forks, highlighting the need for improved design methodologies that account for the dynamic loading conditions experienced during operation (Pantazopoulos et al., 2014). This underscores the necessity of employing advanced simulation techniques, such as Finite Element Analysis (FEA), to predict and enhance the fatigue performance of fork designs.

Forklift forks experience significant vibration levels during operation, adversely affecting their performance and lifespan. The design of the forks is a critical factor in managing these challenges, as poorly designed forks may lead to instability, particularly when handling uneven loads. This highlights the necessity of accounting for static loads and dynamic factors such as vibration and shock loads in the design process. Understanding and addressing these forces is vital to ensure the structural integrity, reliability, and safety of forklift forks in demanding material handling operations. The existing fork design is not optimized due to its failure rate, recurring issues related to material fatigue and stress concentration, and poor performance under operational conditions. These factors highlight the need for a redesign to improve durability, load distribution, and overall performance. Fatigue-related failures account for 15-20% of all forklift fork failures in cyclic loading applications. A study in the Journal of Failure Analysis and Prevention found that 18% of forks failed due to fatigue cracks originating at stress concentration points. Specific causes of failure include overloading (20-30% of incidents)**,** fatigue (15-20%)**,** corrosion (10-12%), and impact damage (10-15%)**.**

1.3. Objective of the study

1.3.1. General Objective

The general objective of this thesis work is to optimize forklift fork design for improved performance and safety in material handling operations through finite element analysis.

1.3.2. Specific Objective

The specific objective is as follows:

- Analyse the current design of forklift forks in material handling operations.
- Simulate selected design parameters for optimization of weight, safety, and fatigue.

- Enhance the performance of forklift forks through mass reduction and design modifications.
- Improve safety standards in material handling operations by optimizing stress values and reducing deformation in the fork design.

1.4. Scope of the Study

This study optimizes forklift fork design to enhance performance and safety in material handling operations using Finite Element Analysis (FEA). ANSYS software analyzes key parameters, including stress distribution, load-bearing capacity, and safety factors. The Response Surface Method (RSM) optimizes fork height, length, thickness, and depth variables. Using fine and convergent mesh systems, the research identifies critical stress points, reduces solid mass, lowers equivalent stress, and increases safety factors. The optimized designs improve strength, durability, and operational efficiency while adhering to safety standards. Although focused on forklift forks, the methodology offers broader applicability to similar equipment, contributing to safer and more efficient material handling solutions.

1.5. Significance of the study

Improved efficiency in material handling operations, coupled with enhanced safety standards for forklift operations, leads to a significant reduction in maintenance costs for forklift equipment. These advancements not only contribute to the progression of engineering design principles but also hold the potential to increase productivity and reduce workplace accidents, creating a safer and more efficient working environment.

1.6. Limitations

A primary constraint is the reliance on assumptions, such as uniform material properties and idealized loading conditions, which may not fully capture real-world complexities like material variability, environmental factors, and unexpected stresses. Simplifications in boundary conditions, used to model the fork’s operational environment, may also reduce accuracy by failing to reflect the dynamic interactions observed in practical scenarios. Additionally, the absence of physical prototype testing limits the study’s ability to validate the optimized design under real-world conditions. Finite Element Analysis (FEA), while effective, cannot replace experimental insights.

The study’s focus on static loads means it does not account for long-term durability or performance under dynamic and fatigue loading, which are critical for real-world applications. Incorporating dynamic simulations and fatigue analysis in future research would enhance understanding of the fork's performance. Furthermore, material selection was not included in the optimization process, although it is vital in determining efficiency, performance, and sustainability. Future studies integrating material considerations could yield further improvements in design and functionality.

1.7. Organization of the thesis

This research is structured into six key stages to ensure a systematic and comprehensive approach to optimizing forklift fork design for enhanced performance and safety:

Introduction: This chapter provides an overview of the research. It begins with the background of the study, which contextualizes the research by discussing its relevance and summarizing existing knowledge in the field. The statement of the problem clearly defines the research question or issue that the study seeks to address. The objectives and scope outline the specific goals and boundaries of the research. The significance of the study highlights its importance and contributions to the field of material handling operations. The motivation section reflects on the personal or professional reasons for selecting this topic. Finally, the organization of the thesis offers a brief roadmap of the subsequent chapters and their content.

Literature Review: This chapter establishes a theoretical foundation for the study by examining previous research on forklift design, material handling operations, and Finite Element Analysis (FEA). It also identifies gaps in the existing literature that the current study aims to address, ensuring the relevance of the research.

Methodology: This section outlines the methods used in the research, including material selection and the processes followed during optimization. It describes the criteria for selecting design variables and the tools and techniques employed, such as the Response Surface Method (RSM), to optimize the forklift fork design.

FEA Simulation: In this phase, virtual models of forklift forks are developed and analyzed using ANSYS software. These simulations test the models under various loading conditions to identify stress concentrations, deformation patterns, and safety factors. This step is crucial for evaluating the baseline design and guiding subsequent optimization efforts.

Design Optimization: Building on insights from the FEA simulations, this stage focuses on refining the forklift fork design. Design variables such as height, length, thickness, and depth are optimized iteratively using RSM. The objectives include minimizing solid mass and equivalent stress while maximizing the factor of safety, ensuring the design meets safety standards and operational requirements.

Analysis and Conclusion: This chapter assesses the performance of the optimized design compared to the original. Key results, including improvements in safety factor, stress reduction, and weight minimization, are analyzed. The findings are discussed in the context of their implications for material handling operations. The study concludes by summarizing its contributions, addressing limitations, and offering recommendations for future research to advance forklift technology. This structured approach ensures a clear and logical progression from identifying the research problem to presenting optimized design solutions and their implications

CHAPTER TWO

LITERATURE REVIEW

2.1. Introduction

The design of forklifts plays a pivotal role in enhancing the efficiency and effectiveness of material handling operations within various industrial contexts. Forklifts are integral to logistics and warehouse management, where they facilitate the movement of heavy loads, thereby significantly reducing the physical strain on workers and improving operational throughput. The efficiency of forklift operations can be optimized through various design improvements, leading to substantial productivity gains and cost reductions in material handling processes. One critical aspect of forklift design is the implementation of ergonomic principles. Ergonomically designed forklifts can minimize operator fatigue and reduce the risk of musculoskeletal injuries, which are prevalent in manual material handling tasks. For instance, studies have shown that ergonomic-based work procedures can significantly decrease complaints of postural stress and work fatigue, ultimately enhancing employee productivity and company profitability (Susihono et al., 2021). Furthermore, the design of the forklift cockpit, which considers human factors such as spatial layout and interface design, is essential for ensuring operator comfort and efficiency (Liu et al., 2013).

Additionally, advancements in technology, such as the integration of autonomous systems and computerized controls, have revolutionized forklift operations. Autonomous forklifts can reduce labor costs and improve safety by minimizing human error during material handling tasks (Abdellatif et al., 2018). Moreover, computerized control systems enhance the efficiency of forklift operations by optimizing routing and reducing idle times, which are critical for maintaining high throughput in busy warehouses (Skapinyecz et al., 2020). The ability to analyze and optimize the number of forklifts required in a distribution center through mathematical modeling further underscores the importance of effective forklift design in enhancing operational efficiency (Sysoiev et al., 2023). The design of forklifts is crucial in material handling operations, as it directly impacts efficiency, safety, and ergonomics. By incorporating advanced technologies and ergonomic principles, organizations can significantly improve their material handling processes, leading to enhanced productivity and reduced operational costs.

Figure 2.1. Counterbalance Forklift (https://www.toyotaforklift.com)

Forklift forks are essential components of material handling equipment, designed to lift and transport loads efficiently and safely. The primary function of forklift forks is to provide a stable platform for carrying various types of loads, including pallets, boxes, and other materials. Forklifts typically feature two forks that can be adjusted to accommodate different load sizes and shapes, making them versatile tools in warehouses and industrial settings (Strelbitskyi et al., 2023). The design and structural integrity of these forks is critical, as they must withstand significant dynamic loads during operation while maintaining safety standards. The design of forklift forks involves several engineering considerations, including material selection, geometry, and load capacity. Furthermore, emphasizes the role of Finite Element Analysis (FEA) in improving the geometry of forklift forks, which can lead to enhanced performance and reduced weight without compromising strength (Bozkurt et al., 2017). This optimization process is vital for ensuring that the forks can handle the stresses encountered during lifting and transporting operations. Another critical aspect of forklift fork design is the safety features integrated into their structure.

Figure 2.2. Forklift Forks 100x40x1200 Class 2A (https://www.westexedirect.co.uk)

Forklift forks are critical components that significantly influence the operational efficiency and safety of forklift trucks. Various types of forklift forks are designed to accommodate different handling requirements, load types, and operational environments. The most common types include standard forks, which are typically used for general material handling, and specialized forks such as wide forks, which provide a broader surface area for stability when lifting larger or unstable loads, and tapered forks, which facilitate entry into pallets and enhance maneuverability in tight spaces (Bozkurt et al., 2017; Dua et al.,2023). Additionally, forks can be categorized based on their design features, such as the closing type and the structural integrity under load. Research indicates that forks designed with a closing mechanism exhibit lower stress and deformation compared to those with an opening mechanism, thus enhancing durability and performance under varying load conditions (Cho & Han et al., 2013). The geometry and material composition of the forks also play a crucial role in their effectiveness; for instance, forks made from high-strength steel can better withstand the fatigue and stress associated with heavy lifting. Advancements in technology have led to the development of forks that integrate with automated systems, enabling autonomous forklifts to perform tasks with minimal human intervention. These innovations include forks equipped with sensors for improved load handling and stability assessment, which are essential for maintaining safety standards in dynamic warehouse environments (Park et al., 2011; Gabellieri et al., 2019). The efficiency of different fork types can also be evaluated based on their impact on the overall performance of the forklift, including energy consumption and operational speed, which are critical factors in logistics and material handling operations (Minav et al., 2014). The diversity in forklift fork types, characterized by their design, functionality, and technological integration, reflects the evolving needs of material handling in various industrial settings. Understanding these differences is essential for selecting the appropriate fork type to optimize performance and ensure safety in operations.

Figure 2.3. Different forklift fork types (https://www.easternlifttruck.com/)

Optimizing forklift forks is critical for enhancing both performance and safety in material handling operations. The design and structural integrity of forklift forks directly influences their ability to support loads effectively while minimizing the risk of accidents. A well-optimized fork design can significantly improve the overall performance of a forklift by ensuring that it can handle varying load conditions without compromising safety. Research indicates that the optimization of a forklift's front fork can enhance its safety features without negatively impacting its operational efficiency, thereby improving the comprehensive performance of the forklift (Zhao et al., 2024)

Moreover, the material properties and structural design of forklift forks are paramount in meeting safety standards. Forks must possess adequate strength and stiffness to withstand the repetitive stress associated with loading and unloading cycles, as well as vibrations from traversing uneven surfaces (Ge et al., 2019). The choice of materials and the application of appropriate heat treatments can enhance the durability and performance of the forks, ultimately contributing to operational safety by reducing the likelihood of fork failure during use (Grygier & Kęska et al., 2023). Finite element analysis has been employed to assess the strength of forklift forks under various loading conditions, revealing that the structural design significantly impacts the reliability and safety of the forklift (Strelbitskyi et al., 2023). This analysis helps in identifying potential failure points and allows for design modifications that can prevent accidents caused by fork breakage or deformation under load. Therefore, optimizing forklift forks not only enhances their performance but also plays a crucial role in ensuring the safety of operators and the surrounding workforce. The significance of optimizing forklift forks cannot be overstated, as it directly affects both the performance capabilities of the forklift and the safety of material handling operations. By focusing on design improvements and material selection, organizations can achieve safer and more efficient forklift operations.

Enhance the operational efficiency and safety of forklifts by employing finite element analysis (FEA) to optimize the design of forklift forks. This research addresses the critical role that forklift forks play in material handling, as they are essential components that directly affect load stability, handling efficiency, and overall safety during operations. One of the primary goals of this thesis is to analyze the structural integrity of forklift forks under various loading conditions using FEA. By simulating different stress scenarios, the research seeks to identify potential failure points and areas for design improvement, thereby ensuring that the forks can withstand the rigors of daily operations without compromising safety. This optimization process is expected to lead to forks that not only meet but exceed current safety standards, thereby reducing the risk of accidents and injuries in the workplace. The thesis aims to explore the relationship between fork design parameters such as geometry, material selection, and thickness and their impact on performance metrics, including load capacity, durability, and operational efficiency.

By integrating findings from FEA with practical applications, the research intends to provide actionable insights that can be utilized by manufacturers and operators to enhance the design of forklift forks. Furthermore, the study will contribute to the body of knowledge regarding best practices in forklift design, potentially leading to innovations that improve material handling processes across various industries. The ultimate objective is to create a robust framework for optimizing forklift fork design that balances performance with safety, thereby facilitating more efficient and safer material handling operations.

2.2. Current Design of Forklift Forks

Overview of Forklift Fork Design: The design of forklift forks is a critical aspect of material handling equipment, influencing both operational efficiency and safety. Forklift forks are typically constructed from high-strength steel, which provides the necessary durability and load-bearing capacity required for industrial applications. The choice of material is essential, as it directly affects the fork's ability to withstand heavy loads and resist deformation under stress (Strelbitskyi et al., 2023). Recent studies suggest that while traditional steel remains the predominant material, there is a growing interest in composite materials that could offer enhanced performance and reduced weight, thereby improving energy efficiency during operation. In terms of dimensions, forklift forks generally vary based on the specific application and the type of loads being handled. Standard fork lengths range from 36 to 48 inches, although custom lengths are available for specialized tasks. The width of the forks typically falls between 4 to 6 inches, and the thickness can vary from 1.5 to 2.5 inches, depending on the required load capacity (Skapinyecz et al., 2020). Load capacities of forklift forks can range significantly, with standard models capable of lifting between 3,000 to 5,000 pounds, while specialized designs can handle loads exceeding 10,000 pounds. The design of the fork must also consider factors such as the center of gravity and the stability of the load to prevent tipping or accidents during operation.

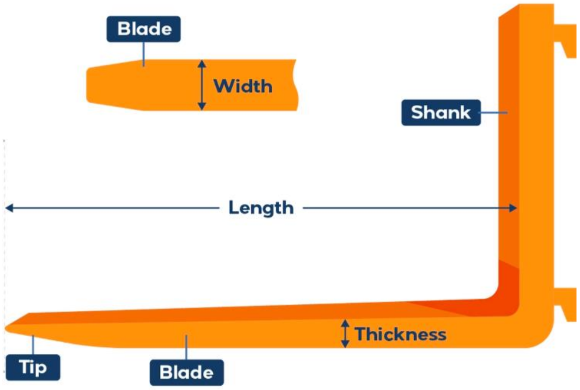


Figure 2.4. Standard forklift fork dimension

Safety is a paramount concern in forklift design, particularly regarding the fork's geometry and structural integrity. The front fork design is often a one-piece cantilever beam structure, which can pose safety risks if not properly engineered. Studies have indicated that improper fork design can lead to accidents, such as stab wounds to pedestrians when forklifts are in motion. Therefore, optimizing the fork design through finite element analysis and other engineering techniques is crucial to enhance safety and performance (Strelbitskyi et al., 2023). Additionally, incorporating features such as anti-slip pads has been shown to prevent load damage and improve overall handling efficiency. The current trends in forklift fork design emphasize the importance of material selection, dimensional specifications, load capacities, and safety features. As the industry evolves, there is a notable shift towards integrating advanced materials and engineering practices to enhance the performance and safety of forklift operations. Continuous research and development in this field are essential to meet the growing demands of modern logistics and material handling.

The performance metrics of current forklift fork designs are crucial for evaluating their efficiency, load-handling capabilities, and operational limitations. Recent literature highlights several key aspects of these metrics, including energy efficiency, load handling performance, and the impact of design on operational effectiveness.

Performance Metrics: One significant area of focus is the energy efficiency of forklifts, particularly in electric and hydraulic systems. For instance, demonstrated that the energy efficiency of electro-hydraulic forklifts can be significantly enhanced through the use of permanent magnet synchronous motors, which optimize the control of hydraulic systems and reduce energy losses (Minav et al., 2012). This finding is corroborated by research indicating that electric forklifts, when properly designed, can achieve substantial energy savings compared to traditional hydraulic systems. Furthermore, 's study on fertilizer handling processes revealed that optimizing forklift operations can lead to reduced waste and improved resource utilization, emphasizing the importance of operational efficiency in warehouse settings (Aghda & Siswanto et al., 2021).

Load handling performance is another critical metric, as it directly influences the operational capabilities of forklifts. 's research on the optimization of forklift fork designs using finite element analysis highlighted that the structural integrity of the forks is paramount for safe load handling. The study found that maximum stress levels during operation were well within acceptable limits, ensuring that the forks could handle significant loads without failure. Additionally, measured vibration levels during forklift operations, revealed that increased load weights could lead to lower vibration intensity, which is beneficial for both load stability and operator comfort (Huang et al., 2021). This indicates that effective load handling is not only about the capacity but also about maintaining stability and minimizing operational disruptions.

Operational limitations are also a critical aspect of forklift performance. The design of the forks and their interaction with the loads can impose constraints on maneuverability and efficiency. For example, the study emphasized that the structural design of forklift forks significantly impacts their reliability and performance under load, suggesting that poorly designed forks could lead to operational inefficiencies and safety hazards (Strelbitskyi et al., 2023). Moreover, the integration of advanced technologies, such as multi-sensor systems for monitoring forklift activity, has been shown to enhance operational insights, allowing for better management of forklift fleets and improved safety measures (Alias et al., 2015). In conclusion, the evaluation of current forklift fork designs reveals a multifaceted approach to performance metrics, encompassing energy efficiency, load handling capabilities, and operational limitations. Continuous advancements in design and technology are essential for enhancing the effectiveness of forklifts in various industrial applications, ensuring that they meet the evolving demands of material handling.

Safety Considerations: Safety considerations in forklift operations are paramount due to the inherent risks associated with their use in industrial environments. Various studies have highlighted critical safety issues, particularly those related to inadequate fork design, operator awareness, and environmental factors that contribute to accidents.

One significant concern is the design of forklift forks themselves. 's research emphasizes that the traditional one-piece cantilever beam structure of forklift forks can lead to severe safety incidents, especially when the forklift is in motion without a load. The study indicates that such designs are prone to causing stab wounds to pedestrians, highlighting the need for improved fork design to mitigate these risks (Zhao et al., 2024). Furthermore, analysis of fork strength using numerical methods reveals that inadequate structural integrity can lead to failures under load, which poses a direct threat to operator safety and surrounding personnel. These findings suggest that enhancing the design and material properties of forklift forks is crucial for improving operational safety. Operator training and awareness also play a vital role in preventing accidents. Conducted a study on the effectiveness of game-based training programs to improve forklift drivers' safety awareness. The research found that while such training can enhance knowledge, it is equally important to design workplaces that minimize interactions between forklifts and pedestrians, thereby reducing the likelihood of accidents (Lehtonen et al., 2020). This aligns with findings, which indicate that many accidents in various domains, including agricultural machinery, are often attributed to operator errors rather than design flaws, underscoring the importance of comprehensive training and operational management.

Environmental factors and operational practices further contribute to safety challenges. Highlighted that improper load handling can lead to slipping, overturning, and falling loads, which not only endangers the operator but also poses risks to nearby workers and infrastructure (Zając et al., 2021). Research on stand-up forklift injuries indicates that specific design features, such as operator compartment doors, can significantly influence injury outcomes during tip-over incidents (Wiechel & Scott et al., 2016). Their findings suggest that safety measures should include both design improvements and operational protocols to enhance overall safety. In conclusion, the safety issues related to forklift operations are multifaceted, involving inadequate fork design, operator training, and environmental considerations. Continuous research and development in these areas are essential to mitigate risks and enhance safety standards in industrial settings. By addressing both the mechanical and human factors associated with forklift operations, organizations can significantly reduce the incidence of accidents and improve workplace safety.

2.3. Finite Element Analysis (FEA) in Forklift Design

2.3.1. Introduction to Finite Element Analysis (FEA):

Finite Element Analysis (FEA) is a computational technique used to predict how structures respond to environmental factors such as forces, vibrations, heat, and fluid flow. By breaking down complex structures into smaller, simpler parts called finite elements, FEA allows engineers to analyze the behavior of materials and structures under various conditions. This method is particularly relevant in engineering design as it enables the optimization of product performance while minimizing material usage and costs. FEA is widely utilized across various engineering disciplines, including mechanical, civil, and aerospace engineering, to enhance the reliability and efficiency of designs.

The relevance of FEA in engineering design stems from its ability to provide detailed insights into stress distribution, deformation, and failure points within a structure. This predictive capability is crucial for ensuring that designs meet safety and performance standards before physical prototypes are developed, thus reducing the time and cost associated with the design process (Orzada & Kallal et al., 2019). Furthermore, FEA facilitates iterative design improvements, allowing engineers to refine their models based on simulation results, which is essential for developing innovative and efficient engineering solutions (Kuwabara et al., 2014).

2.3.2. Application of FEA in Material Handling:

FEA has been extensively applied in the analysis and optimization of material handling equipment, particularly in the design of forklift forks. Studies have demonstrated that FEA can effectively identify stress concentrations and potential failure points in forklift forks, leading to improved designs that enhance safety and performance. For instance, Olan et al. (2020) utilized FEA to optimize the design of hemp fiber processing equipment, which included components similar to forklift forks, demonstrating the method's versatility in material handling applications (Olan et al., 2020). Additionally, research by Zhang (2023) highlighted the importance of FEA in evaluating the stiffness of truck frames, which are integral to material handling systems. The study emphasized that accurate modeling through FEA is essential for ensuring that these frames can withstand operational stresses without excessive deflection, thereby enhancing the overall safety and efficiency of material handling operations. The integration of FEA with other optimization techniques has been shown to yield significant improvements in material handling equipment design. For example, Matsuda & Kawahara (2020) explored the use of thermoplastic elastomers in sports equipment, employing FEA to assess their impact load reduction capabilities, which can be analogous to the load-bearing requirements of forklift forks (Matsuda & Kawahara et al., 2020).

2.3.3. Identifying Areas for Optimization:

The literature reveals that FEA has been instrumental in identifying weaknesses in existing material handling designs and suggesting improvements. For instance, studies have shown that FEA can uncover critical areas where stress concentrations occur, allowing engineers to modify designs to enhance durability and performance. In the context of forklift forks, FEA has been used to analyze the effects of different materials and geometries on load distribution, leading to recommendations for design alterations that improve strength and reduce the risk of failure. Research conducted by Khandekar & Chakraborty (2015) emphasized the role of FEA in the selection of material handling equipment, demonstrating how simulation results can guide the decision-making process by highlighting the most effective designs based on performance metrics. Furthermore, the application of FEA in conjunction with multi-criteria decision-making methods has been shown to facilitate a more comprehensive evaluation of material handling systems, enabling the identification of optimal configurations that balance performance, cost, and safety. In summary, FEA serves as a critical tool in the design and optimization of material handling equipment, particularly forklift forks. Its ability to simulate real-world conditions and predict structural behavior allows engineers to refine designs, enhance safety, and improve operational efficiency.

2.4. Design Modifications for Enhanced Performance

1. Innovative Design Approaches: Innovative design approaches for enhancing forklift fork performance have been a focal point in recent engineering literature. Various modifications have been proposed to improve forklift forks' structural integrity, efficiency, and safety. For instance, the use of advanced materials and geometrical modifications has been explored to optimize the load-bearing capacity of forklift forks. Studies have shown that integrating finite element analysis (FEA) into the design process allows for identifying stress concentrations and potential failure points, leading to more robust designs (Bozkurt et al., 2017; Nakandhrakumar et al., 2022). One notable approach involves the implementation of ECRS (Eliminate, Combine, Rearrange, and Simplify) techniques to streamline forklift operations, which indirectly enhances fork performance by improving overall efficiency. This method focuses on reducing waste and optimizing the scheduling of forklift tasks, which can lead to better utilization of the forks themselves. Additionally, research has highlighted the importance of vibration analysis in the design process, as excessive vibrations can lead to premature wear and failure of forklift forks (Huang et al., 2021). Moreover, innovative design modifications such as the incorporation of ribbed structures and punching grooves have been proposed to enhance the strength of forklift forks without significantly increasing weight (Wang et al., 2013). These modifications not only improve the structural performance but also maintain the interchangeability of components, which is crucial for operational flexibility in material handling environments.

2. Case Studies: Several case studies illustrate the successful implementation of design modifications in forklift forks and similar equipment, leading to improved performance metrics. For example, a study focused on the structural analysis of forklift wheel rims, which are critical for overall stability and performance. By using FEA, the researchers identified weak points in the wheel rim structure and implemented design changes that significantly enhanced its strength while maintaining functionality (Wang et al., 2013). Another case study involved the optimization of forklift forks through the application of advanced materials and design techniques. Research on the optimization design of forklift front forks demonstrated that modifications could be made to enhance safety without compromising operational efficiency (Zhao et al., 2024). The proposed design changes were shown to improve the comprehensive performance of forklifts, highlighting the effectiveness of targeted design interventions. The work on the finite element analysis of structural parts of diesel forklift trucks revealed that topology optimization techniques could be employed to reduce weight while maintaining performance standards. This study illustrated how design modifications could lead to significant improvements in the operational efficiency of forklifts (Bozkurt et al., 2017). The literature reveals that FEA and other analytical methods have been instrumental in identifying weaknesses in existing forklift fork designs and suggesting improvements. For instance, studies have shown that FEA can uncover critical areas where stress concentrations occur, allowing engineers to modify designs to enhance durability and performance. In the context of forklift forks, FEA has been used to analyze the effects of different materials and geometries on load distribution, leading to recommendations for design alterations that improve strength and reduce the risk of failure.

Research conducted emphasized the importance of stress, strain, and displacement analysis in identifying design flaws in forklift forks. Their findings indicated that modifications based on FEA results could lead to significant improvements in the structural integrity of forklift forks under load (Nakandhrakumar et al., 2022). Furthermore, the integration of advanced control systems, as explored, has been shown to enhance the handling stability of forklifts, indirectly contributing to the performance of the forks themselves. In summary, innovative design approaches and case studies demonstrate the potential for significant improvements in forklift fork performance through targeted modifications and the application of advanced analytical techniques. The ongoing exploration of these design strategies is essential for enhancing the safety, efficiency, and reliability of material handling equipment.

2.5. Safety Standards and Optimized Design

The safety standards and regulations governing forklift design and operation are primarily established by the Occupational Safety and Health Administration (OSHA) and the American National Standards Institute (ANSI). OSHA was created under the Occupational Safety and Health Act of 1970, to ensure safe and healthful working conditions for employees. This includes the implementation of specific safety standards for machinery, including forklifts, which mandate the use of safety guards and performance standards to minimize hazards associated with their operation (Li & Singleton et al., 2018; Johnsonv et al., 2023). ANSI also plays a critical role by providing consensus standards that enhance safety protocols, such as ANSI/ITSDF B56.1, which outlines safety requirements for powered industrial trucks, including forklifts. The impact of design on safety in material handling operations is significant. Studies have shown that the structural integrity and design features of forklifts, such as the geometry of the forks and the overall chassis, directly correlate with safety outcomes. For instance, research conducted on the finite element analysis of forklift structures indicates that optimized designs can reduce the likelihood of accidents and injuries by improving the load distribution and stability of the vehicle (Bozkurt et al., 2017; Zhao, 2024). Furthermore, the design of the forklift's front fork is crucial, as it is often involved in accidents, particularly when the forklift is in motion without a load. The implementation of a more stable and less protruding fork design can mitigate risks associated with pedestrian injuries. Recommendations for improved safety in forklift design emphasize the importance of optimizing fork geometry and incorporating advanced safety features. The literature suggests that utilizing computer-aided design (CAD) and finite element analysis (FEA) can lead to significant improvements in the structural design of forks, enhancing their strength while reducing weight. Additionally, integrating modern technologies such as computer vision and It can provide real-time monitoring of forklift operations, further enhancing safety by alerting operators to potential hazards (Abbas et al., 2023). The adoption of these recommendations can lead to a safer working environment, reducing the incidence of accidents and injuries associated with forklift operations. Adherence to regulatory standards set forth by OSHA and ANSI is essential for ensuring the safety of forklift operations. The design of forklifts plays a pivotal role in safety outcomes, and optimizing design features can significantly enhance safety. Implementing advanced technologies and design methodologies can further improve safety standards in material handling operations.

2.6. Gaps in the Literature

In the context of optimizing forklift fork design for enhanced performance and safety in material handling operations using finite element analysis (FEA), several gaps in the current literature can be identified. These gaps highlight areas where further research is needed to advance the understanding and application of FEA in forklift fork design.

Lack of Focused Studies on Forklift Fork Design: While existing research has extensively explored the finite element analysis (FEA) of broader forklift components such as chassis, wheel rims, and mast structures (Wang et al., 2013; Bozkurt et al., 2017), there is a notable absence of comprehensive studies specifically targeting the optimization of forklift forks**.** Forks are critical components that directly influence load handling, stability, and safety, yet their unique design challenges such as stress concentration at the heel, fatigue life under cyclic loading, and load distribution have not been thoroughly investigated. This gap presents an opportunity to develop a tailored FEA framework for forklift fork optimization.

Insufficient Integration of Advanced Design Methodologies: Although topology optimization and material selection have been applied to other structural components, there is limited research on their application to forklift fork design**.** For example, while Bozkurt et al. (2017) discuss geometry improvements in forklift structures, they do not provide a systematic approach to integrating topology optimization or advanced material selection specifically for forks. This gap highlights the need for a design framework that combines FEA with advanced optimization techniques to enhance fork performance and safety.

Limited Quantitative Correlation between Fork Design and Safety Outcomes: Current literature lacks empirical data that quantitatively links specific design features of forklift forks such as geometry, material properties, and load distribution to safety outcomes like accident rates, load stability, and operator safety. For instance, the impact of fork geometry on reducing pedestrian injuries or improving load stability during operation has not been thoroughly studied. This gap underscores the need for research that quantitatively evaluates how optimized fork designs can enhance safety in material handling operations.

Under-Explored Use of Innovative Materials: Most studies on forklift forks focus on traditional materials like steel, with limited exploration of advanced materials such as composites or hybrid materials. These materials offer potential benefits, including improved strength-to-weight ratios, corrosion resistance, and fatigue performance, which could significantly enhance fork durability and safety. The lack of research in this area represents a critical gap that could be addressed through material optimization studies.

CHAPTER THREE

METHODOLOGY

3.1. Introduction

Forklifts are essential in various industries, and their efficiency directly impacts productivity and safety standards. This study aims to utilize Finite Element Analysis (FEA) to evaluate and improve the structural integrity and performance of forklift forks under various loading conditions. By systematically analyzing the design parameters, this research seeks to identify optimal configurations that minimize stress concentrations and maximize load-bearing capabilities, ultimately leading to safer and more efficient material handling.

Forklift forks play a critical role in material handling operations across various industries, significantly enhancing efficiency and safety. They are designed to lift, move, and stack heavy loads, making them indispensable in warehouses, construction sites, and manufacturing facilities. Properly designed forks ensure stability and load integrity, which is essential for preventing accidents and injuries. Additionally, the versatility of forklift forks allows them to accommodate different types of loads, from pallets to irregularly shaped items, thereby optimizing operational workflows and reducing labor costs. Compliance with industry standards further underscores their importance, as it ensures that they meet safety and performance requirements, protecting both workers and equipment.

Despite their significance, forklift forks face several challenges that can impact their effectiveness and safety. One major issue is material fatigue, as forks are subjected to substantial stress during operation, which can lead to wear and potential failure over time. Additionally, many existing designs may not be optimized for specific applications, resulting in inefficiencies and safety risks. Striking a balance between strength and weight is another challenge, as heavier forks can reduce the overall efficiency of the forklift. Furthermore, the need for regular maintenance and inspections to address wear and tear can be time-consuming and costly. As the industry evolves towards automation and smart technologies, integrating advanced features into forklift forks presents additional complexities, requiring manufacturers to adapt to changing demands while ensuring compliance with safety regulations.

3.2 Material

The optimization of forklift fork design for enhanced performance and safety in material handling operations using finite element analysis (FEA) involves several critical components, including software selection, model development, and simulation setup. Each of these elements plays a vital role in ensuring that the design is both effective and safe.

3.2.1. Finite Element Analysis (FEA)

- **Software Selection:** For this study, ANSYS has been utilized as the primary FEA software. ANSYS is widely recognized for its robust capabilities in structural analysis and has been effectively employed in various engineering applications, including the analysis of forklift components. Its advanced features allow for detailed simulations that can accurately predict the performance of complex geometries under various loading conditions.
- **Model Development:** The process of creating a 3D model of the forklift fork began with the use of Computer-Aided Design (CAD) software to develop a precise geometric representation of the fork. This model incorporated critical design features such as fork length, width, thickness, and any specific geometrical modifications aimed at enhancing performance and safety. The parameters and assumptions used in the model included material properties (e.g., Young's modulus, yield strength), loading conditions (static and dynamic loads), and environmental factors (such as temperature variations) that may affect the fork's performance during operation.
- **Simulation Setup:** In the simulation setup, loads and boundary conditions were applied based on realistic operational scenarios. For instance, static loads simulated the weight of the maximum load the fork is designed to handle, while dynamic loads accounted for the forces exerted during lifting and lowering operations (Nakandhrakumar et al., 2022). Boundary conditions were defined to represent the constraints experienced by the fork during use, such as fixed supports at the attachment points to the forklift. The types of analyses performed included static analysis to assess the fork's strength under load, dynamic analysis to evaluate its response to moving loads, and fatigue analysis to determine the fork's durability over time.

In conclusion, the optimization of forklift fork design through the application of finite element analysis involves careful software selection, detailed model development, and thorough simulation setups. This structured approach will facilitate the creation of a more efficient and safer forklift fork, ultimately contributing to improved material handling operations.

3.2.2. MINITAB software

Minitab is a powerful statistical analysis and process improvement tool, bridging complex statistical theories and practical applications. Its role in industries like manufacturing and education has made it an essential resource for professionals and students alike. However, users must balance its advantages with the need to understand the underlying statistical principles for effective utilization. Response Surface Regression in Minitab is vital for researchers and engineers working on optimization problems. It simplifies complex statistical analyses and provides actionable insights into the relationships between variables. By leveraging RSR, users can optimize processes, improve product quality, and better understand their experimental systems.

In Minitab, Response Surface Regression with Central Composite Design (CCD) is a cornerstone of Response Surface Methodology (RSM), used for optimizing processes or systems where the goal is to study the effects of multiple input variables (factors) on one or more responses. CCD is a flexible and efficient experimental design that enhances factorial experiments by adding axial (star) points and center points, enabling the estimation of quadratic effects and curvature in the response surface. It consists of three components: a factorial design to estimate linear and interaction effects, axial points to explore the quadratic nature of the response, and center points to assess experimental variability and curvature. Minitab facilitates the creation of a CCD under **Stat > DOE > Response Surface > Create Response Surface Design**, where users can specify factors, their ranges, and design parameters, including ratability to ensure uniform prediction variance. Once data is collected, Response Surface Regression analyzes the data by fitting a second-order polynomial model, providing insights into significant factors, interaction effects, and curvature. Users can interpret results through regression equations, ANOVA tables, and model diagnostics, and visualize relationships using contour plots and 3D surface plots. Minitab also supports optimization by identifying factor settings that maximize or minimize the response, making CCD in Minitab an indispensable tool for process improvement and decision-making. The integration of these analyses will provide a comprehensive understanding of the fork's performance and safety characteristics. By utilizing FEA, the study aims to identify critical stress points and potential failure modes, allowing for informed design modifications that enhance both performance and safety (Wang et al., 2013; Bozkurt et al., 2017; Nakandhrakumar et al., 2022).

The Surface Response Method (RSM) is a design optimization technique that uses a mathematical approximation model, called a response surface, to represent the relationship between input parameters and output responses. The process begins with sampling various combinations of input parameters through Design of Experiments (DOE) techniques, such as full factorial or central composite designs, followed by performing Finite Element Analysis (FEA) to compute the corresponding outputs. The collected data is then fitted into a polynomial regression model, creating a response surface that can be visualized as a multi-dimensional plot. This visualization helps engineers understand how input parameters interact and influence the outputs, identify trends, and pinpoint critical points. RSM allows engineers to predict the behavior of the system for input combinations that were not explicitly tested, enabling the identification of optimal conditions to achieve objectives like minimizing mass and stress while maximizing safety. By approximating system behavior with fewer data points, it significantly reduces the need for exhaustive simulations, saving both time and computational resources. Tools like ANSYS integrate RSM with DOE and FEA, streamlining the process of setting up experiments, generating response surfaces, and performing optimization studies to refine designs without re-running every simulation. This approach is particularly valuable in applications such as forklift fork design, where balancing objectives like reducing mass and stress while maximizing safety factors is critical.

3.3. Methods

For optimizing forklift fork design using Finite Element Analysis (FEA), a thorough approach is required to identify and address weaknesses, improve performance, and enhance safety. Here’s a structured way to tackle this:

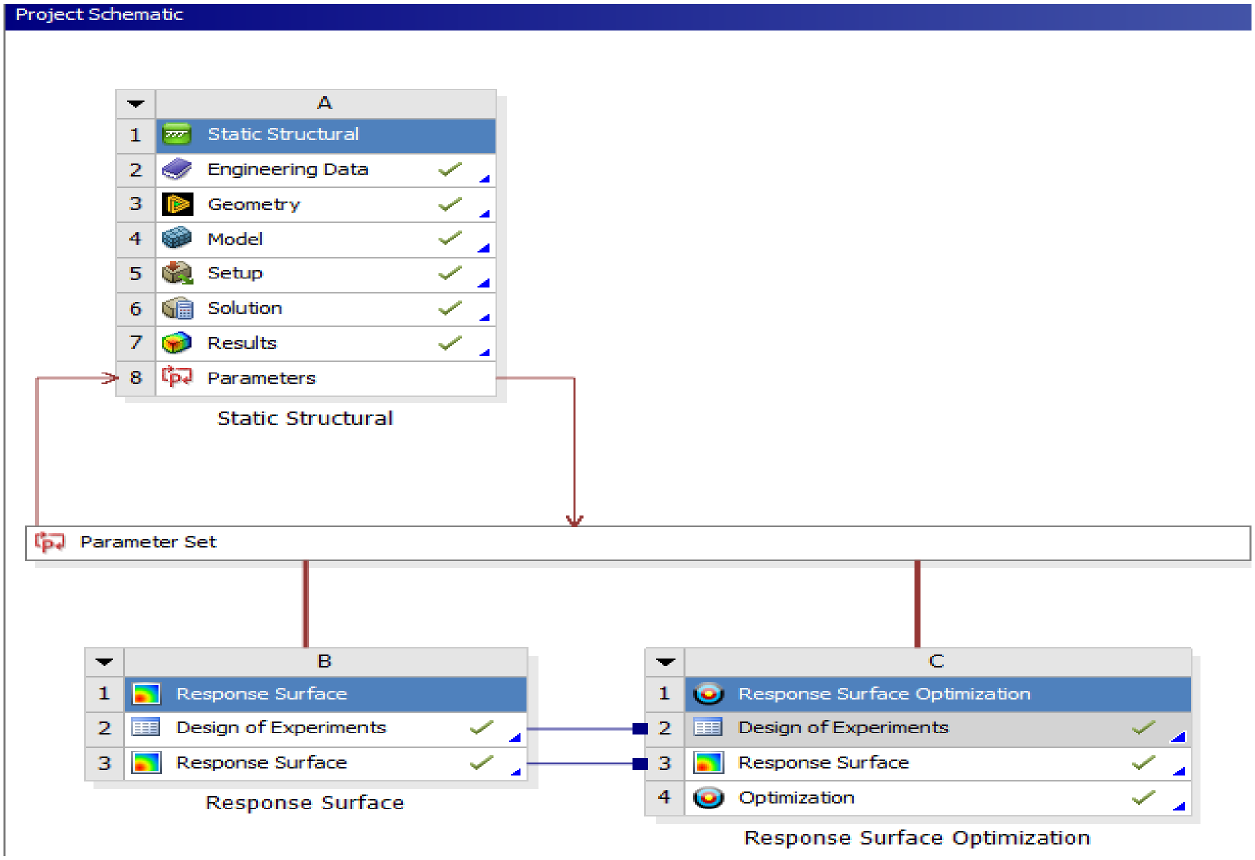


Figure 3.1. Project schematics

3.3.1 Data Analysis

1. Analyzing FEA Results:

- Stress Distribution: Review the stress maps generated by FEA. Areas where stress exceeds the material's yield strength indicate potential failure points. Focus on high-stress regions to understand if they're prone to deformation or fracture.
- Deflection and Deformation: Examine deflection contours to ensure that deformations are within acceptable limits. Excessive deflection can impact the operational efficiency and safety of the forklift forks.
- Fatigue Analysis: Evaluate results from fatigue analysis. Repeated loading cycles can lead to material fatigue, which might not be evident from a single static load case.

2. **Criteria for Identifying Areas Needing Improvement**:

- Stress Concentrations: Areas with high stress concentrations should be targeted for redesign. This often occurs at geometric discontinuities like holes, welds, or sharp corners.

- High Deflection Zones: Critical regions with high deflection should be evaluated to determine if they compromise the operational performance or safety.
- Safety Factors: Ensure that the safety factor of the design (ratio of material strength to the maximum expected load) meets or exceeds industry standards. Areas with low safety factors are prime candidates for optimization.
- Load Distribution: Verify that the load is evenly distributed across the forks. Uneven load distribution can cause localized stress and premature wear.

3.3.2 Benchmarking

1. Comparison with Industry Standards:

- Material Strength and Safety Standards: Compare the FEA results with material strength requirements and safety factors specified in industry standards (e.g., ANSI, ISO). Ensure that the design meets or exceeds these benchmarks.
- Design Standards: Refer to design standards for forklift forks, such as those from the American National Standards Institute (ANSI) or the International Organization for Standardization (ISO).
- Performance Metrics: Evaluate the performance metrics of the design against best practices in the industry.

2. Best Practices and Innovations:

- Design Innovations: Research recent innovations and best practices in forklift fork design. This could involve new materials, improved geometries, or advanced manufacturing techniques.

3.3.3. Implementation Steps

- Redesign: Based on the analysis and benchmarking, make iterative changes to the design to address identified weaknesses. This may include adjusting fork geometry, reinforcing high-stress areas, or using higher-strength materials.
- Validation: Perform additional FEA simulations on the revised design to confirm that the improvements have addressed the identified issues. 0Ensure that the new design meets all safety and performance criteria.

By systematically analyzing FEA results, identifying areas needing improvement, and benchmarking against industry standards, then effectively optimize forklift fork designs for enhanced performance and safety.

3.4. Design modification

3.4.1. Modification strategies

Design Modifications for Forklift Fork Optimization

1. Modification Strategies:

Based on FEA findings, the following design modifications may be considered to enhance the performance and safety of forklift forks:

Reinforcement of High-Stress Areas:

- Strategy: Strengthen regions with high-stress concentrations identified in the FEA results. This might involve adding material or using reinforcing ribs or fillets at critical points.
- Implementation: Incorporate these reinforcements in the CAD model. For example, add thicker sections or additional structural elements where stress is concentrated.

Redesign of Geometric Features:

- Strategy: Modify geometric features such as sharp corners or abrupt transitions which often lead to stress concentrations. Transition these areas to smoother, more gradual curves.
- Implementation: Adjust the fork's CAD model to include fillets or radii in place of sharp corners, and update the geometry to distribute stress more evenly.

Material Substitution or Enhancement:

- Strategy: Use higher-strength materials or advanced composites if the current material does not meet performance or safety criteria. Consider materials with better fatigue resistance or lower weight for improved performance.
- Implementation: Replace the existing material in the simulation model with the new material properties and validate the design with these updated properties

Optimization of Load Distribution:

- Strategy: Ensure that the design supports an even load distribution across the fork. This could involve modifying the fork's profile to better align with typical load applications.

- Implementation: Modify the fork’s design in the model to achieve better load alignment and re-run the FEA to verify the improvements.

Reduction of Weight:

- Strategy: Reduce the fork’s weight without compromising strength by optimizing material use or employing lightweight materials.
- Implementation: Adjust the fork’s cross-sectional area in the model to find the optimal balance between weight and strength.

2. Performance Evaluation:

To assess the impact of design modifications, follow these steps:

Re-evaluation Using FEA:

- Run New Simulations: Perform FEA simulations on the modified design to ensure that the changes have resolved the issues identified in the initial analysis. Focus on verifying reduced stress concentrations, acceptable deflections, and improved load distribution.
- Validate Safety Factors: Confirm that the safety factors meet or exceed industry standards with the new design. Ensure that the revised fork can handle the maximum expected loads without failure.

Metrics for Assessing Performance Improvements:

- Load Capacity: Measure the maximum load capacity of the modified fork. Compare it with the original design to ensure that it meets or exceeds the required specifications.
- Stress Distribution: Evaluate the stress distribution to confirm that stress concentrations have been reduced and are within acceptable limits.
- Deflection and Deformation: Assess the deflection and deformation under load conditions. The modifications should result in reduced deflection to within acceptable limits for operational safety and performance.
- Fatigue Resistance: If fatigue analysis is performed, ensure that the modifications have improved the fork’s resistance to fatigue over repeated loading cycles.
- Weight and Efficiency: Evaluate the weight of the modified fork and assess any changes in operational efficiency. A weight reduction can lead to improved handling and energy efficiency, but this should not compromise strength or load capacity.

By implementing these design modifications and thoroughly re-evaluating the modified designs using FEA, you can ensure that the forklift forks are optimized for enhanced performance and safety in material handling operations.

CHAPTER 4

DESIGN AND MODELING

4.1 Initial Design Specifications

The Toyota Tonero 56-8FD20F is a specific model of a forklift truck manufactured by Toyota, widely recognized for its reliability and performance in material handling operations. While the exact specifications of this model may vary depending on its configuration and regional variations, it is generally designed to meet the demands of medium to heavy-duty applications. One of the critical components of any forklift is its fork, which plays a pivotal role in lifting, carrying, and positioning loads. The fork dimensions of 40/100/1000 mm and a load capacity of 2000 kg are typical for this class of forklift, and they define the fork's structural and functional characteristics. The first dimension, 40 mm, refers to the thickness of the fork, which is the vertical measurement when the fork is lying flat. This thickness is crucial as it determines the fork's strength and its ability to resist bending or deformation under load. The second dimension, 100 mm, represents the width of the fork, which is the horizontal measurement across the fork's blade. A wider fork enhances stability and weight distribution, particularly when handling pallets or larger loads. The third dimension, 1000 mm, indicates the length of the fork, which is the distance from the fork's heel (the end that attaches to the forklift) to its tip. A longer fork allows for handling larger or deeper loads, but it must be balanced with the forklift's load center to maintain stability during operation. The load capacity of 2000 kg signifies that each fork is designed to safely support up to 2000 kilograms when used in pairs, assuming the load is evenly distributed and the load center is within the specified limit, typically 500 mm or 600 mm from the fork's heel. This capacity is determined by the fork's material, design, and structural integrity. Forks with these dimensions are commonly employed in medium-duty applications, such as warehouses, manufacturing facilities, or logistics operations, where they handle standard pallets or similarly sized loads. The combination of these dimensions ensures that the forks are robust enough to handle the specified load while maintaining safety and efficiency in material handling operations.

Load Capacity and Safety Standards: The design objectives of forklift forks prioritize handling specific load capacities safely, adhering to standards such as ISO 2330:2020. Research indicates that forklifts often encounter a wide range of load conditions, making it essential for the forks to support static and dynamic loads beyond their rated capacities with built-in safety margins. This ensures operational reliability under real-world stresses, preventing mechanical failures that could lead to workplace accidents (Smith et al., 2020).

Weight Optimization Techniques: Optimizing the weight of forklift forks without compromising strength is a significant design challenge. According to recent research, employing advanced CAD tools allows designers to explore geometries that reduce material usage while maintaining load-bearing capabilities. Lightweight designs can enhance maneuverability and reduce fuel consumption, translating to better energy efficiency. Structural analysis and topology optimization are used to identify areas of the fork that can be minimized without affecting performance’

Safety Margin Incorporation: Ensuring that forklift forks can safely handle loads above their nominal capacity involves incorporating generous safety margins. Computational models and finite element analysis (FEA) are commonly used to simulate stress distribution and identify potential failure points. These analyses support the design phase by providing data-driven insights, which help engineers add reinforcements where necessary without over-engineering the product. This results in a balanced design that meets safety standards without excessive weight or material cost.

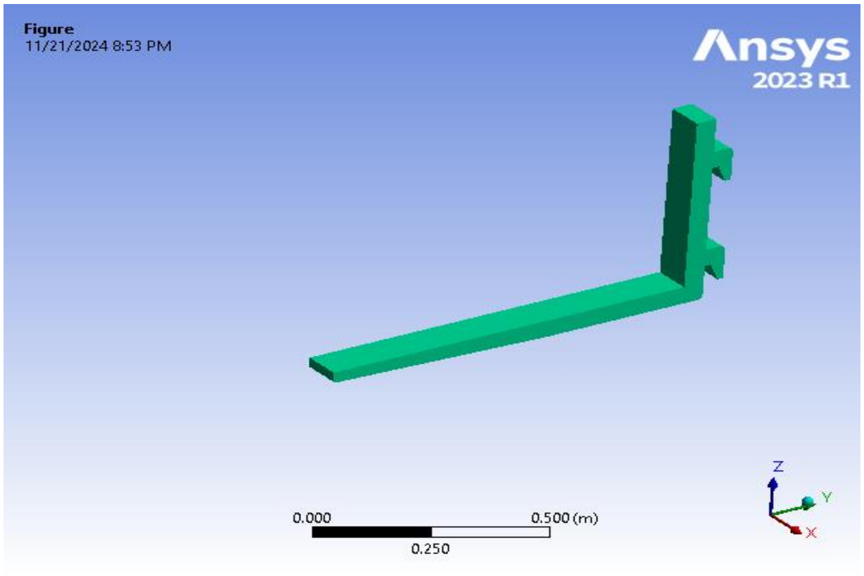


Figure 4.1. Forklift fork design

Table 4.1. Fork solid geometry properties

Material	Assignment	STEEL 4340
	Nonlinear Effects	Yes
	Thermal Strain Effects	Yes
Bounding Box	Length X	0.1 m
	Length Y	1 m
	Length Z	0.6 m
Properties	Volume	6.7985e-003 m³
	Mass	53.232 kg

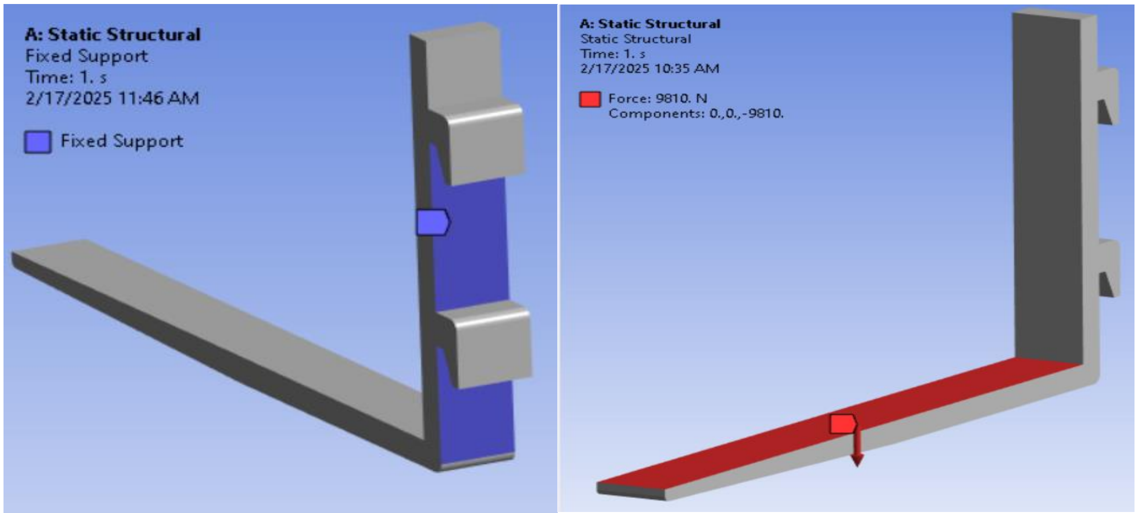


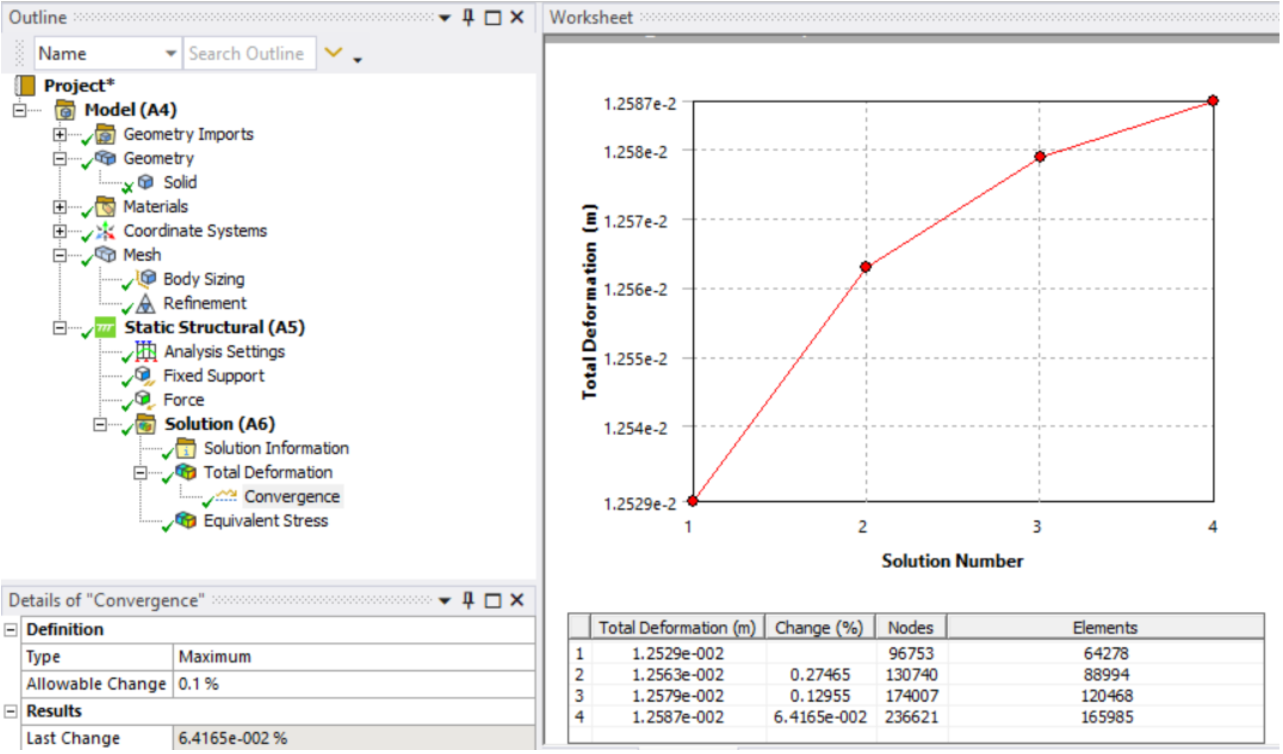
Figure 4.2. Fixed support and applied force of Forklift fork design

4.2. Mesh Generation for FEA (Finite Element Analysis)

Mesh Type and Quality for High-Stress Accuracy: FEA emphasizes that mesh quality plays a pivotal role in accurately capturing stress distributions, particularly at high-stress zones like the transition between the shank and blade of forklift forks. High-resolution, fine meshes are often required in these areas to minimize errors in simulation results. Studies suggest that using a refined mesh at these critical regions ensures more precise modeling of stress concentration and potential failure points.

Hexahedral and Tetrahedral Elements: The choice between hexahedral and tetrahedral elements impacts both the accuracy and computational efficiency of FEA. Hexahedral elements are preferred for structured meshing due to their ability to deliver higher precision with fewer elements, while tetrahedral elements are more flexible for complex geometries.

Element Size Recommendations: Element size should vary within the mesh, with smaller elements placed in regions experiencing high stress and potential deformation, such as connection points or load-bearing corners. Conversely, larger elements can be used in areas where stress distribution is uniform and less critical. Mesh convergence in Finite Element Analysis (FEA) refers to the process of refining the mesh until the simulation results stabilize, indicating that the solution is no longer significantly affected by further mesh refinement. This concept ensures that the numerical solution obtained is close to the true solution and is not influenced by the coarseness of the mesh.



Definition

Type: Maximum

Allowable Change: 0.1 %

Results

Last Change: 6.4165e-002 %

	Total Deformation (m)	Change (%)	Nodes	Elements
1	1.2529e-002		96753	64278
2	1.2563e-002	0.27465	130740	88994
3	1.2579e-002	0.12955	174007	120468
4	1.2587e-002	6.4165e-002	236621	165985

Figure 4.3. Mesh convergence

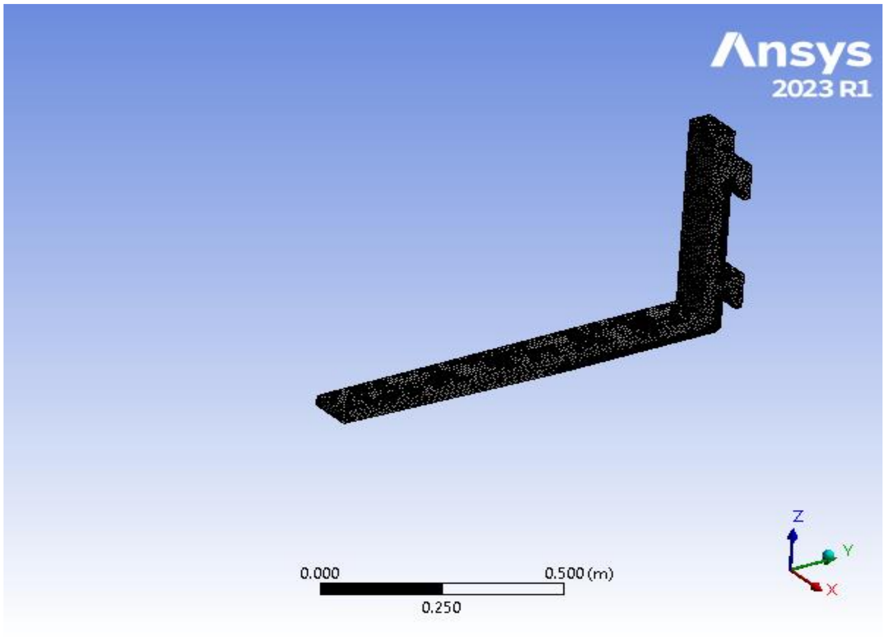


Figure 4.4. Mesh model

Table 4.2. Mesh statistics

Statistics	Nodes	220741
	Elements	149783
Definition	Type	Element Size
	Element Size	1.e-002 m

4.3. Design solution

Total Deformation: Total deformation refers to the overall displacement or distortion experienced by a structure or object under a given set of loading conditions. It is the measure of the overall displacement experienced by the structure under the applied loads. High deformation indicates significant bending or displacement, affecting structural integrity or operational accuracy. Ideally, total deformation should be minimal for a forklift fork to ensure safety and efficient load handling. Compare the total deformation value with permissible limits set by industry standards to verify if it's within acceptable bounds.

Deformation is calculated by solving the system of equations derived from the equilibrium of forces and the material's constitutive relationships. The governing equation for deformation in structural mechanics is:

$$[K]\{u\}= \{F\}\ [K]\{u\} = \{F\} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(4.1)}$$

Where [K] represents the global stiffness matrix (depends on material properties and geometry), {u} is the displacement vector (unknown deformation at each node) and {F} is the force vector (applied loads).

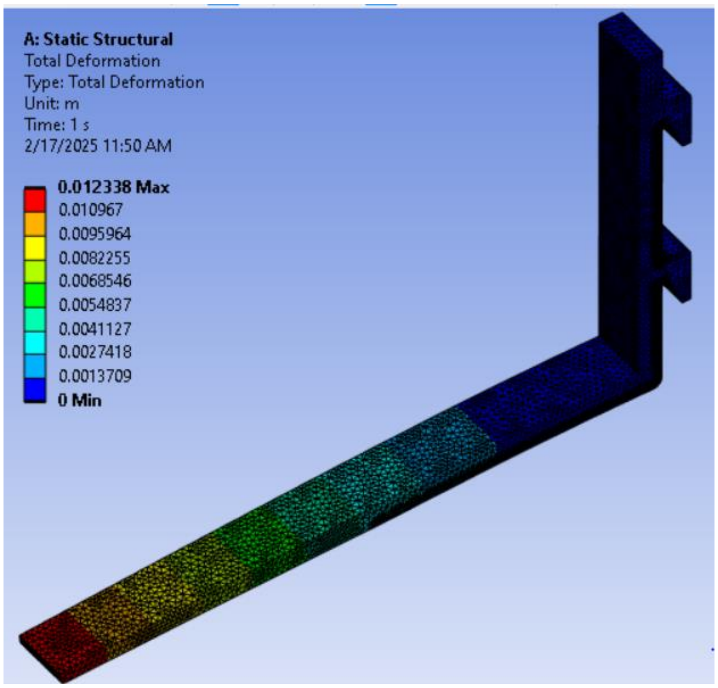


Figure 4.5. Result of total deformation analysis

The solution obtained from the ANSYS analysis for the forklift fork design indicates the total deformation experienced by the fork under the specified loading conditions. The minimum deformation observed is 0 meters, meaning that some parts of the fork did not experience any deformation. The maximum deformation recorded is 0.012338 meters (or 12.338 mm), which represents the highest amount of distortion in the fork structure. The average deformation across the fork is calculated to be 0.0013274 meters (or 1.3274 mm). In summary, the ANSYS analysis shows that the forklift fork design undergoes varying levels of deformation, with some areas remaining unaffected (0 meters), while others experience up to 12.338 mm of deformation. The average deformation across the fork is found to be 1.3274 mm. This information is crucial for evaluating the structural performance and integrity of the forklift fork design under different loading conditions.

Equivalent (Von Mises) Stress: This represents the yield criterion used for ductile materials, providing a single scalar stress value that can be compared to the material's yield strength. This value helps determine whether the fork material will yield or remain elastic under the given load. If the equivalent stress exceeds the material's yield strength, plastic deformation (permanent damage) will occur.

- Strain (ϵ) is computed from displacement gradients:

$$\{\sigma\}=[D]\{\varepsilon\} \quad \ldots\ldots (4.2)$$

Where $\{\sigma\}$ represents the Stress vector ($\sigma x,\sigma y,\sigma z,\tau xy,\tau yz,\tau zx$),[D] represents the Material stiffness matrix (depends on material properties), and $\{\varepsilon\}$represents the Strain vector ($\varepsilon x,\varepsilon y,\varepsilon z,\gamma xy,\gamma yz,\gamma zx$)

Strain is related to displacement by:

$$\{\varepsilon\}=[B]\{u\} \quad \ldots\ldots (4.3)$$

Where [B] represents the strain-displacement matrix.

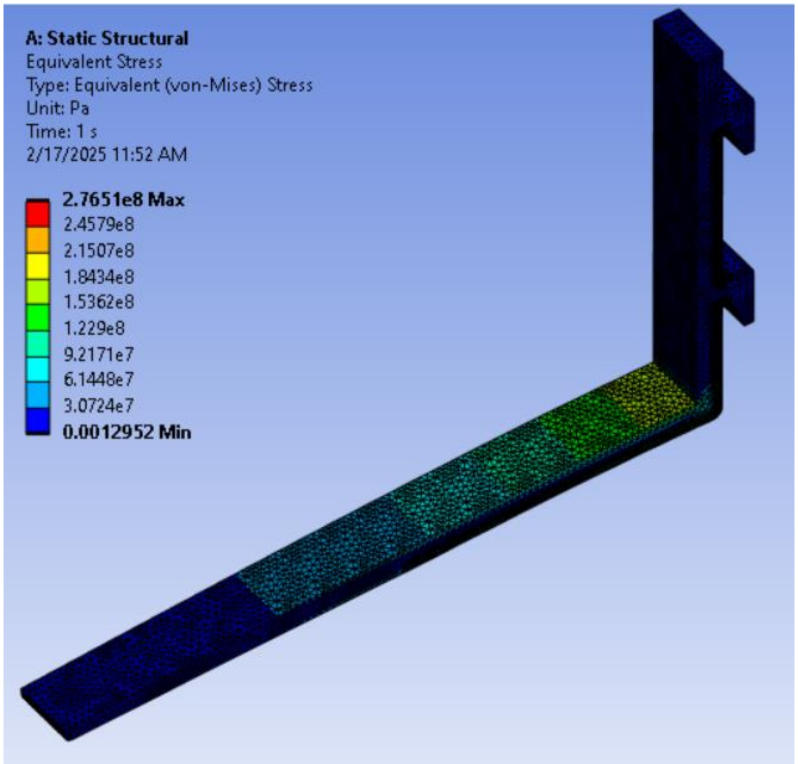


Figure 4.6. Result of Equivalent (Von Mises) Stress Analysis

The solution obtained from the ANSYS analysis for the forklift fork design in terms of Equivalent (Von Mises) Stress indicates the stress distribution experienced by the fork under the specified loading conditions. The minimum stress observed is 1.2952e-003 Pa (Pascal), representing the least stress in the fork structure. The maximum stress recorded is also 2.7651e+008 Pa, indicating the highest stress concentration in the fork. The average Equivalent (Von Mises) Stress across the fork is calculated to be 3.2348e+007 Pa (or 32,348,000 Pa). The ANSYS analysis shows that the forklift fork design experiences varying levels of stress distribution, with the minimum and maximum stress values being the same at 2.6681e-003 Pa. The average Equivalent (Von Mises) Stress across the fork is 32,348,000 Pa. This information is essential for assessing the structural strength and safety of the forklift fork design under different loading conditions.

Safety Factor: A dimensionless number representing the ratio of the material's strength to the maximum applied stress. Indicates how much stronger the system is compared to the minimum required strength. A safety factor above 1 means the design should theoretically withstand the applied loads without failure; a common practice is to aim for safety factors of 1.5 to 3, depending on industry standards and risk tolerance.

FOS= σmax / σyield…………………………………………………..(4.4)

Where σyield reprsents Yield strength of the material, and σmax represents Maximum equivalent stress (e.g., von Mises stress in ductile materials)

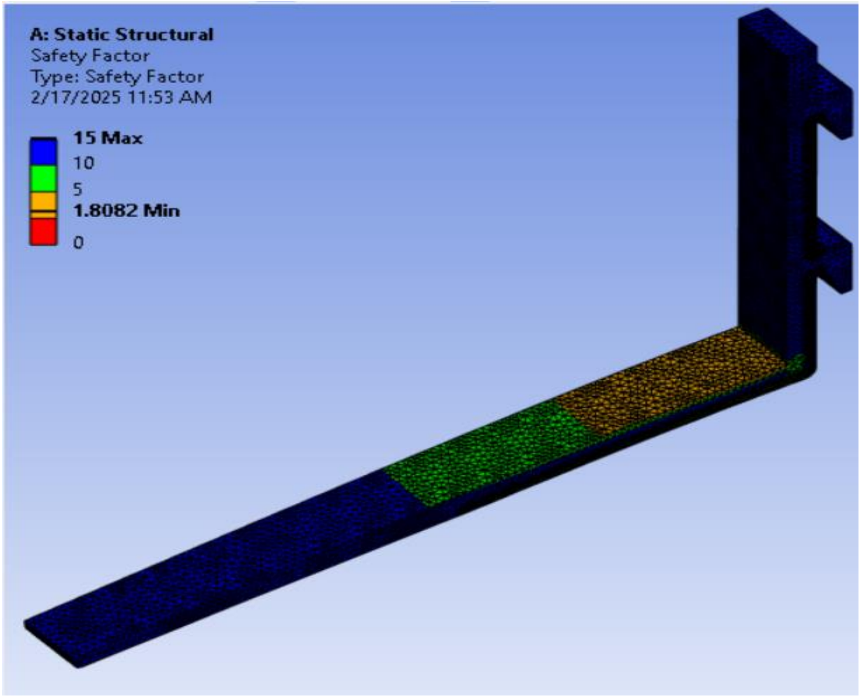


Figure 4.7. Result of factor of safety (FOS) analysis

The FEA results for forklift fork design reveal a minimum factor of safety (FOS) of 1.8082, a maximum of 15, and an average of 12.291. The minimum FOS indicates that certain areas are operating close to their safety limit, suggesting they need a detailed examination to ensure durability under variable loads. The maximum FOS points to over-engineered regions, implying that material can be reduced in these areas without compromising structural integrity. The average FOS of 12.291 reflects a generally robust design but highlights potential inefficiencies due to non-uniform stress distribution. Overall, these results suggest that the design is safe but can be optimized by reinforcing critical areas and reducing excess material to achieve a more balanced and cost-effective structure.

CHAPTER 5

DESIGN OPTIMIZATION

5.1. Introduction to Design Optimization

Design optimization is the process of improving a product or system by systematically adjusting design parameters to achieve the best possible performance, efficiency, or cost-effectiveness. In engineering, this process is crucial for developing safe, reliable, and high-performing structures while minimizing resources such as material use, weight, and cost. Design optimization ensures that a product meets all functional and safety requirements while maximizing its efficiency. By exploring different configurations and assessing their impact on performance, engineers can refine their designs to find the most balanced solution. The significance of design optimization lies in its ability to enhance the performance and sustainability of engineering solutions. Optimized designs can lead to substantial improvements in load-bearing capacity, durability, and overall efficiency, which are critical in applications such as structural engineering, automotive, aerospace, and manufacturing. These improvements contribute to longer service life, lower operating costs, and better resource management.

Utilizing ANSYS software and Finite Element Analysis (FEA) provides engineers with advanced tools for conducting comprehensive design optimization. ANSYS facilitates the simulation of real-world physical conditions, enabling the evaluation of different design iterations with high precision. Through FEA analysis, engineers can model complex load scenarios, predict stress distributions, identify weak points, and calculate factors of safety, which are essential for ensuring the reliability of the design. The integration of optimization tools within ANSYS allows for automated exploration of parameter variations and helps identify the optimal solution by balancing conflicting objectives, such as minimizing weight while maximizing strength.

5.2. Objectives and Scope of the Optimization

The primary objective of the optimization process for the forklift fork design is to achieve an efficient balance between material usage, safety, and performance. Specifically, the goals of this optimization are:

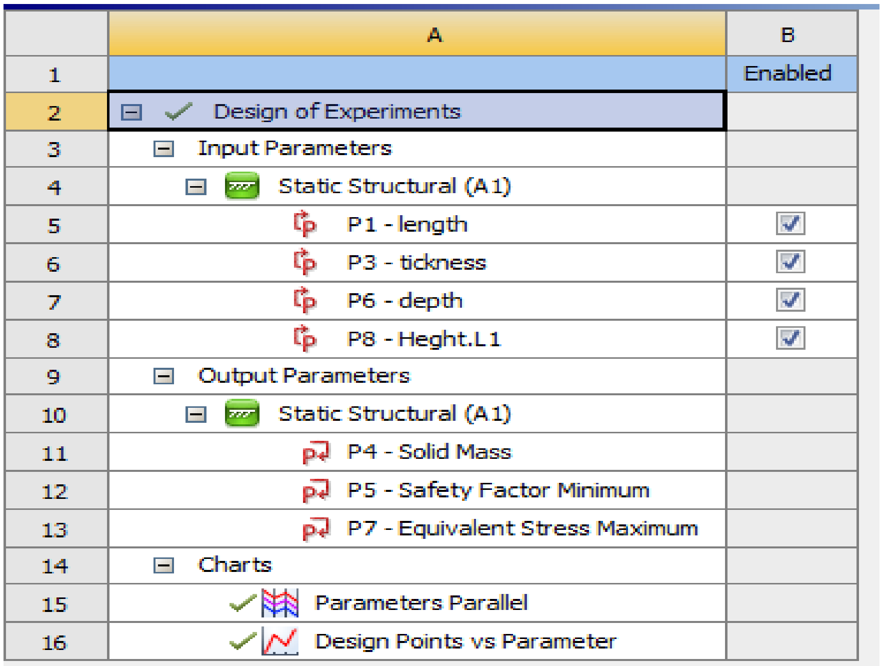
1. Minimize Solid Mass: One of the main objectives is to reduce the solid mass of the forklift fork while ensuring that it remains structurally sound and capable of handling the intended loads. This reduction in mass contributes to improving the forklift's overall efficiency, potentially lowering operating costs and reducing wear on the vehicle, which also has a positive environmental impact due to less material usage and energy consumption.
2. Minimize Equivalent Stress: The design aims to reduce the equivalent stress experienced by the forklift fork under normal and extreme load conditions. Lowering stress helps to enhance the longevity of the forklift fork, reduce the risk of material failure, and ensure that the structure can withstand the applied forces without compromising performance or safety.
3. Maximize Factor of Safety: Ensuring that the factor of safety is maximized is critical for the design. The factor of safety reflects how much stronger the forklift fork is compared to the expected loads. By maximizing the factor of safety, the design will be more robust and reliable, reducing the likelihood of failure during operation and ensuring compliance with safety standards.

The scope of this optimization focuses on the forklift fork's geometry and structural parameters, including length, thickness, depth, and height. These parameters directly influence the mass distribution, stress levels, and overall structural integrity of the fork. The optimization process will explore different combinations of these parameters to minimize solid mass, reduce equivalent stress, and maximize the factor of safety while adhering to industry standards. The optimization will be performed in accordance with OSHA safety standards and other relevant safety guidelines to ensure that the final design not only achieves the desired performance but also meets all regulatory and safety requirements. The analysis will include factors such as load-bearing capacity, potential impact forces, and fatigue resistance, ensuring that the design is safe for use in real-world applications. Ultimately, the goal of this optimization process is to produce a forklift fork design that is both lightweight and safe, offering maximum performance while complying with safety standards to protect workers and ensure the forklift operates efficiently in various environments.

5.3. Response Surface Optimization

5.3.1. Design of Experiments (DOE)

Design of Experiments (DOE) refers to a systematic approach used during optimization to explore the effects of multiple variables on the performance of a design. It involves creating a structured set of simulations where different combinations of input parameters (e.g., material properties, geometry dimensions, load conditions) are varied systematically. This approach helps to identify the relationships between input variables and output responses, such as stress, strain, or factor of safety. By analyzing these relationships, DOE allows engineers to pinpoint which factors have the most significant impact on design performance and to optimize the design efficiently by guiding decision-making towards the best possible configuration.



	A	B
1		Enabled
2	⊟ ✓ Design of Experiments	
3	⊟ Input Parameters	
4	⊟ Static Structural (A1)	
5	P1 - length	☑
6	P3 - tickness	☑
7	P6 - depth	☑
8	P8 - Heght.L1	☑
9	⊟ Output Parameters	
10	⊟ Static Structural (A1)	
11	P4 - Solid Mass	
12	P5 - Safety Factor Minimum	
13	P7 - Equivalent Stress Maximum	
14	⊟ Charts	
15	✓ Parameters Parallel	
16	✓ Design Points vs Parameter	

Figure 5.1. Outline schematics: design of experiments

In a design of experiments (DOE) setup for optimizing a forklift fork design in ANSYS, the input parameters considered include the length, thickness, depth, and height of the fork. These parameters are varied systematically across a range of values to understand their impact on the design's performance. The output parameters measured in response to these input variations are the solid mass (minimized)**,** factor of safety (maximized), and equivalent stress (to ensure it remains within acceptable limits). This approach helps identify how changes in the design dimensions affect the overall safety, weight, and stress distribution, allowing for the optimal balance between strength and material efficiency.

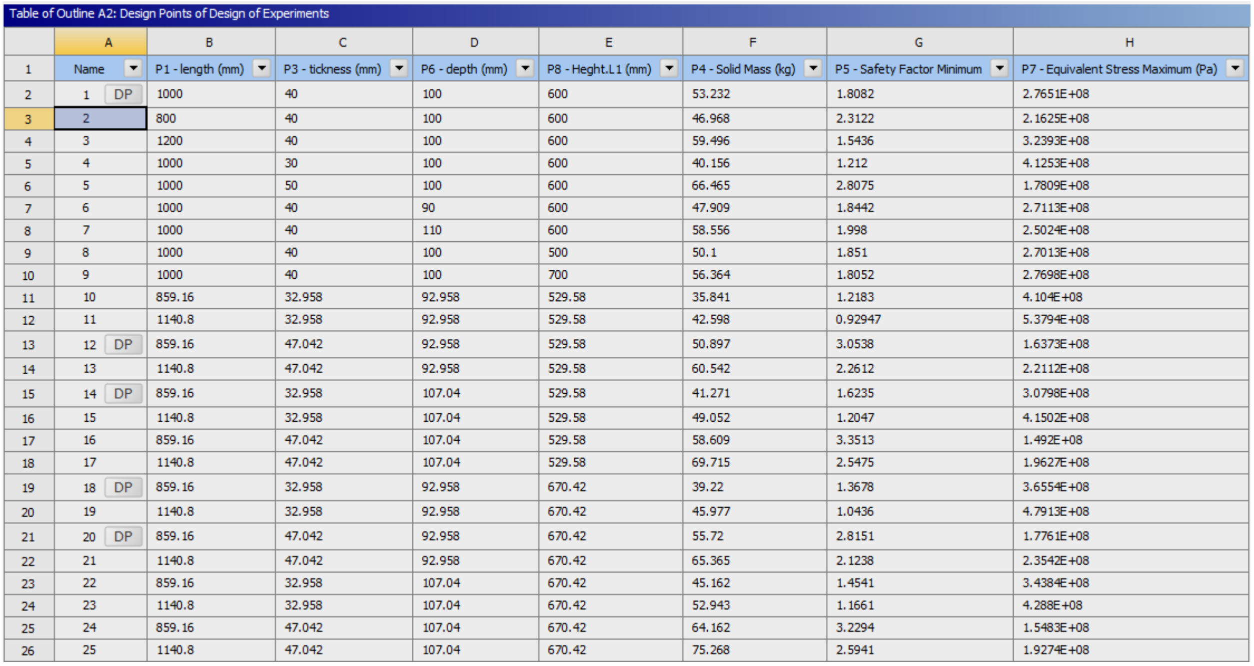


Table of Outline A2: Design Points of Design of Experiments

	A	B	C	D	E	F	G	H
1	Name	P1 - length (mm)	P3 - tickness (mm)	P6 - depth (mm)	P8 - Heght.L1 (mm)	P4 - Solid Mass (kg)	P5 - Safety Factor Minimum	P7 - Equivalent Stress Maximum (Pa)
2	1 DP	1000	40	100	600	53.232	1.8082	2.7651E+08
3	2	800	40	100	600	46.968	2.3122	2.1625E+08
4	3	1200	40	100	600	59.496	1.5436	3.2393E+08
5	4	1000	30	100	600	40.156	1.212	4.1253E+08
6	5	1000	50	100	600	66.465	2.8075	1.7809E+08
7	6	1000	40	90	600	47.909	1.8442	2.7113E+08
8	7	1000	40	110	600	58.556	1.998	2.5024E+08
9	8	1000	40	100	500	50.1	1.851	2.7013E+08
10	9	1000	40	100	700	56.364	1.8052	2.7698E+08
11	10	859.16	32.958	92.958	529.58	35.841	1.2183	4.104E+08
12	11	1140.8	32.958	92.958	529.58	42.598	0.92947	5.3794E+08
13	12 DP	859.16	47.042	92.958	529.58	50.897	3.0538	1.6373E+08
14	13	1140.8	47.042	92.958	529.58	60.542	2.2612	2.2112E+08
15	14 DP	859.16	32.958	107.04	529.58	41.271	1.6235	3.0798E+08
16	15	1140.8	32.958	107.04	529.58	49.052	1.2047	4.1502E+08
17	16	859.16	47.042	107.04	529.58	58.609	3.3513	1.492E+08
18	17	1140.8	47.042	107.04	529.58	69.715	2.5475	1.9627E+08
19	18 DP	859.16	32.958	92.958	670.42	39.22	1.3678	3.6554E+08
20	19	1140.8	32.958	92.958	670.42	45.977	1.0436	4.7913E+08
21	20 DP	859.16	47.042	92.958	670.42	55.72	2.8151	1.7761E+08
22	21	1140.8	47.042	92.958	670.42	65.365	2.1238	2.3542E+08
23	22	859.16	32.958	107.04	670.42	45.162	1.4541	3.4384E+08
24	23	1140.8	32.958	107.04	670.42	52.943	1.1661	4.288E+08
25	24	859.16	47.042	107.04	670.42	64.162	3.2294	1.5483E+08
26	25	1140.8	47.042	107.04	670.42	75.268	2.5941	1.9274E+08

Figure 5.2. Design point of design experiments

From the above table parameters, depth, thickness, length, and height are chosen because they collectively define the forklift fork's geometric profile and substantially impact its mechanical behavior. Modifying these dimensions allows for strategic changes in the fork’s load-carrying capacity, weight, stress distribution, and safety factor. Optimizing these parameters provides a pathway to achieve a lightweight yet strong and reliable design, balancing material use and safety in line with OSHA standards and other safety regulations. This choice of parameters helps achieve the main optimization objectives: minimizing mass and equivalent stress while maximizing the factor of safety.

5.3.2. Response Surface method (RSM)

The surface response method (RSM) is a statistical and mathematical technique used in engineering and optimization to model and analyze complex relationships between input variables and output responses. This method is particularly useful when it is impractical to evaluate every possible combination of input variables directly. By developing an approximate mathematical model of the system based on sampled data points, RSM facilitates the exploration and optimization of the design space with greater efficiency. The primary goal of RSM is to understand how different input parameters (e.g., depth, thickness, length, and height in a forklift fork design) affect the desired output responses (e.g., solid mass, factor of safety, equivalent stress). This understanding helps in finding optimal design points where the performance criteria are met or maximized.

5.3.2.1. Response Surface Regression: Sold mass versus Length, Thickness, Depth, Height

Coded Coefficients

Table 5.1. Sold mass versus Length, Thickness, Depth, Height (Coded Coefficients)

Term	Coef	SE Coef	95% CI	T-Value	P-Value	VIF
Constant	50.11	3.27	(43.15, 57.08)	15.34	0.000	
Length	-0.03132	0.00188	(-0.03534, -0.02730)	-16.62	0.000	293.88
Thickness	-1.2528	0.0444	(-1.3474, -1.1582)	-28.23	0.000	407.49
Depth	-0.4947	0.0307	(-0.5602, -0.4292)	-16.10	0.000	195.41
Height	-0.03132	0.00377	(-0.03935, -0.02329)	-8.31	0.000	293.88
Length*Thickness	0.000783	0.000017	(0.000746, 0.000820)	44.83	0.000	104.52
Length*Depth	0.000313	0.000017	(0.000276, 0.000350)	17.93	0.000	316.60
Thickness*Depth	0.013154	0.000349	(0.012410, 0.013899)	37.66	0.000	293.88
Thickness*Height	0.000783	0.000035	(0.000709, 0.000857)	22.41	0.000	132.29
Depth*Height	0.000313	0.000035	(0.000239, 0.000388)	8.97	0.000	344.37

The above table presents the coefficients and statistical metrics from a regression analysis, showing the impact of various predictors (Length, Thickness, Depth, and Height) and their interactions on a response variable. The "Coef" column indicates the estimated effect of each term, with negative values suggesting a decrease in the response and positive values indicating an increase. The "SE Coef" provides the standard error of the coefficients, while the "95% CI" gives the confidence intervals, reflecting the precision of the estimates. The "T-Value" and "P-Value" columns assess the statistical significance of each term, with all terms being highly significant (P-Value = 0.000). The "VIF" (Variance Inflation Factor) indicates multi-collinearity, with higher values suggesting potential redundancy among predictors. Interaction terms (e.g., Length*Thickness) reveal how combined effects of predictors influence the response. Overall, the model suggests that all predictors and their interactions significantly affect the response variable, with some multi-collinearity present.

Model Summary

Table 5.2. Sold mass versus Length, Thickness, Depth, Height (Model Summary)

S	R-sq	R-sq(adj)	PRESS	R-sq(pred)	AICc	BIC
0.0692923	100.00%	100.00%	0.317999	99.99%	-32.99	-39.89

The table provides key metrics for evaluating the performance of a regression model. The "S" value of 0.0692923 represents the standard error of the regression, indicating a very small deviation of observed values from the predicted values, suggesting a high level of precision. The "R-sq" (R-squared) value of 100.00% indicates that the model explains all the variability in the response variable, which is exceptionally rare and suggests a perfect fit. The "R-sq(adj)" (adjusted R-squared) also at 100.00% confirms that the model remains highly effective even after adjusting for the number of predictors. The "PRESS" (Predicted Residual Sum of Squares) value of 0.317999 is low, indicating good predictive accuracy. The "R-sq(pred)" (predicted R-squared) of 99.99% further supports the model's strong predictive capability. The "AICc" (Akaike Information Criterion corrected) and "BIC" (Bayesian Information Criterion) values of -32.99 and -39.89, respectively, are very low, suggesting an excellent model fit with a balance between complexity and explanatory power. Overall, these metrics indicate an exceptionally well-fitting and predictive model.

Analysis of Variance

Table 5.3. Sold mass versus Length, Thickness, Depth, Height (Analysis of Variance)

Source	**DF**	**Seq SS**	**Contribution**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**
Model	9	2508.95	100.00%	2508.95	278.772	58060.27	0.000
Linear	4	2488.15	99.17%	4.75	1.187	247.15	0.000
Length	1	389.81	15.54%	1.33	1.326	276.26	0.000
Thickness	1	1719.05	68.51%	3.83	3.826	796.93	0.000
Depth	1	281.84	11.23%	1.24	1.244	259.09	0.000
Height	1	97.45	3.88%	0.33	0.332	69.06	0.000
2-Way Interaction	5	20.80	0.83%	20.80	4.160	866.42	0.000
Length*Thickness	1	9.65	0.38%	9.65	9.649	2009.70	0.000
Length*Depth	1	1.54	0.06%	1.54	1.544	321.55	0.000
thickness*Depth	1	6.81	0.27%	6.81	6.809	1418.05	0.000
thickness'*Height	1	2.41	0.10%	2.41	2.412	502.43	0.000
Depth*Height	1	0.39	0.02%	0.39	0.386	80.39	0.000
Error	15	0.07	0.00%	0.07	0.005		
Total	24	2509.02	100.00%				

The table presents an analysis of variance (ANOVA) for a regression model, detailing the contribution of each term to the overall model. The "Model" row shows that the model explains 100.00% of the variability in the response variable, with a highly significant F-value of 58060.27 and a P-value of 0.000, indicating an excellent fit. The "Linear" terms (Length, Thickness, Depth, and Height) collectively contribute 99.17% of the explained variability, with Thickness being the most significant predictor (68.51%). The "2-Way Interaction" terms contribute 0.83% to the model, with Length*Thickness being the most significant interaction (0.38%). The "Error" term has a minimal contribution (0.00%), indicating very little unexplained variability. The

"Total" row confirms that all variability is accounted for by the model. Overall, the model is highly effective, with both linear and interaction terms significantly contributing to explaining the response variable.

Regression Equation in Uncoded Units

Sold mass = 50.11 - 0.03132 Length - 1.2528 Thickness - 0.4947 Depth - 0.03132 Height
+ 0.000783 Length*Thickness + 0.000313 Length*Depth
+ 0.013154 Thickness*Depth
+ 0.000783 Thickness*Height + 0.000313 Depth*Height…………..(5.1)

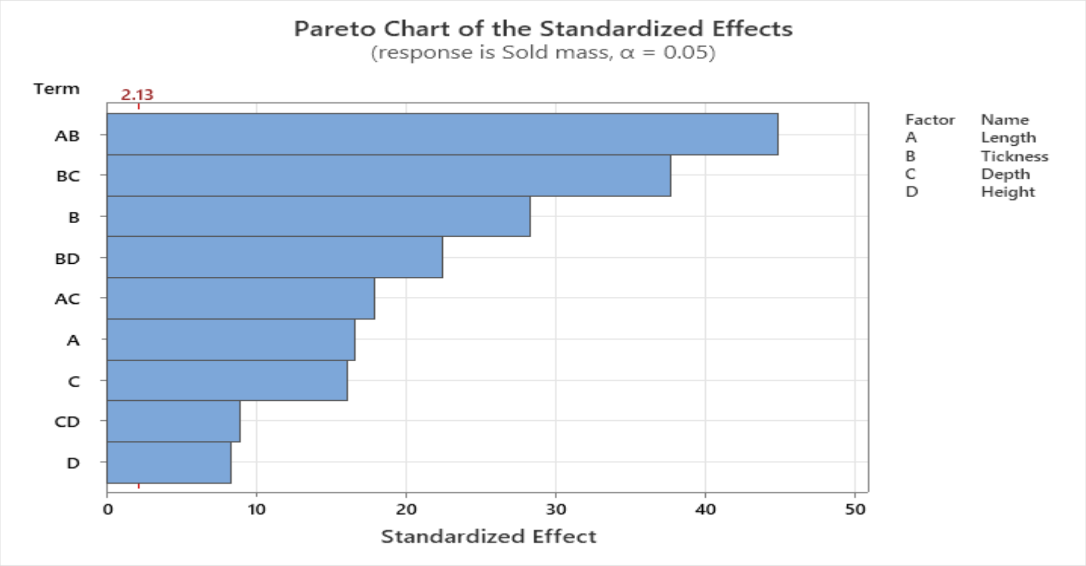


Figure 5.3. Pareto chart for Sold mass versus Length, Thickness, Depth, Height

The Pareto Chart of the Standardized Effects identifies the most significant factors influencing Solid Mass in a designed experiment. The x-axis represents the Standardized Effect, while the y-axis lists factors (A: Length, B: Thickness, C: Depth, D: Height) and their interactions. The red reference line at 2.13 indicates statistical significance at α = 0.05, meaning any factor or interaction beyond this threshold has a meaningful impact on the response. The AB (Length × Thickness) and BC (Thickness × Depth) interactions have the highest effects, followed by Thickness (B) alone, implying that these variables are the most critical in determining solid mass.

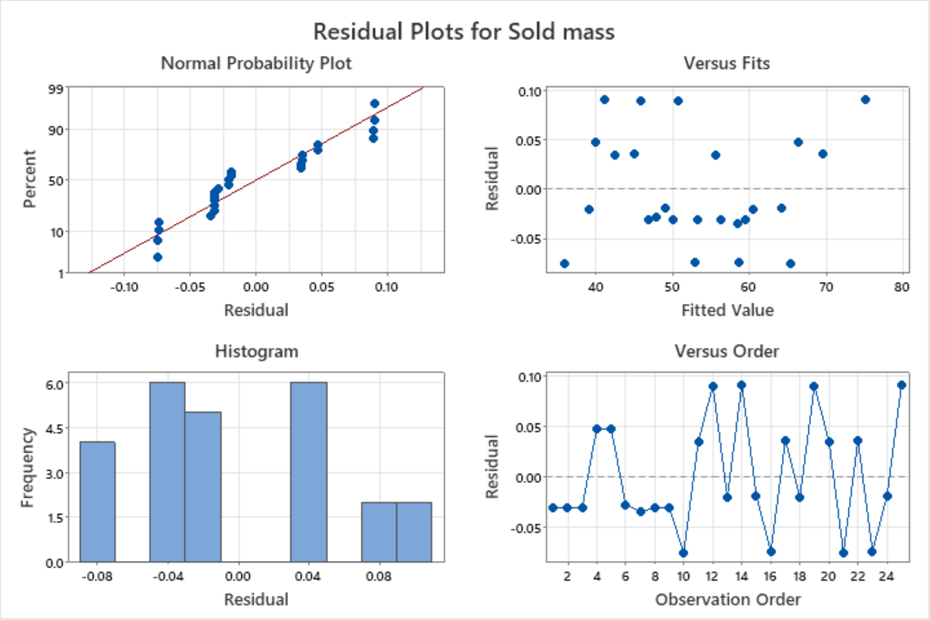


Figure 5.4. Residual Plot for Solid mass

The residual plots for the "Solid Mass" response provide valuable insights into the adequacy of the regression model and the validity of its underlying assumptions. The Normal Probability Plot demonstrates that the residuals align closely with the diagonal reference line, indicating approximate normality—a critical assumption for reliable regression analysis. The Residuals vs. Fits Plot reveals a random scatter of residuals around zero with no discernible patterns, suggesting that the model effectively captures the relationship between predictors and the response variable while showing no signs of non-linearity or heteroscedasticity. The Histogram of Residuals displays a roughly symmetric distribution without extreme outliers or significant skewness, reinforcing the normality assumption. Additionally, the Residuals vs. Observation Order Plot shows no trends or patterns, with residuals oscillating randomly around zero, confirming the independence of errors and the absence of sequential or temporal bias. Overall, these diagnostic plots collectively confirm that the regression model is well-fitted, with no major violations of the assumptions of normality, independence, or homoscedasticity. The model is therefore robust and provides a reliable explanation of the variability in "Solid Mass."

Figure 5.5. Contour Plot of Solid mass vs Length, Thickness

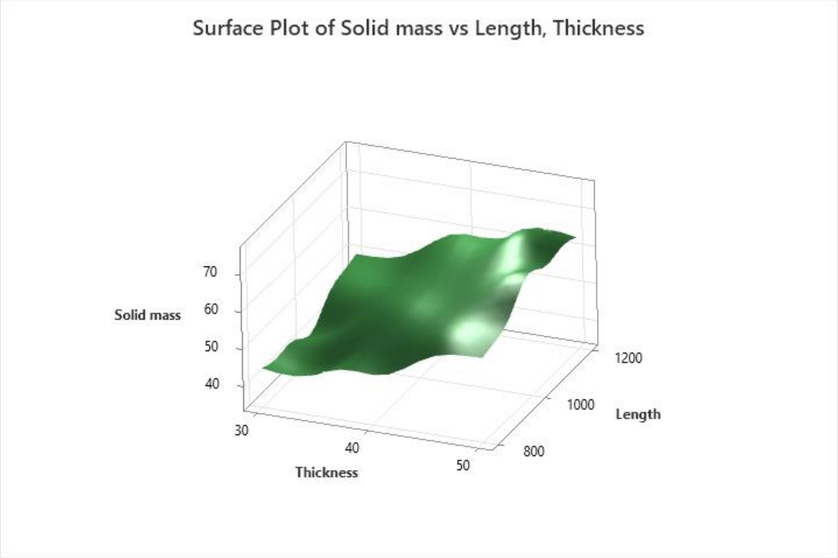


Figure 5.6. Contour Plot of Solid mass vs Length, Thickness

The graph is a contour plot that visualizes the relationship between solid mass, length, and thickness. The legend indicates different ranges of solid mass, categorized as less than 40, 40-50, 50-60, 60-70, and greater than 70. The thickness values are specified at 35, 40, 45, and 50.

The contour lines or shaded regions on the plot represent how solid mass varies with changes in length and thickness, allowing for an understanding of how these parameters influence the solid mass. This type of plot is useful for identifying trends and optimal values in engineering or material science contexts.

The above graph fig.5.6 represents a surface plot illustrating the relationship between solid mass, length, and thickness. The three-dimensional surface shows how solid mass varies with different combinations of length and thickness. Peaks and valleys on the surface indicate areas where the solid mass is higher or lower. This type of visualization is useful for understanding the complex interactions between these variables and identifying optimal values or trends in the data. Surface plots are particularly helpful in engineering and material science for analyzing how changes in one parameter can affect the overall outcome.

5.3.2.2. Response Surface Regression: FOS versus Length, Thickness

Coded Coefficients

Table 5.4. Response Surface Regression: FOS versus Length, Thickness (Coded Coefficients)

Term	**Coef**	**SE Coef**	**95% CI**	**T-Value**	**P-Value**	**VIF**
Constant	-4.22	1.83	(-8.03, -0.41)	-2.31	0.031	
Length	0.00215	0.00182	(-0.00163, 0.00593)	1.18	0.250	41.40
Thickness	0.2019	0.0452	(0.1079, 0.2959)	4.47	0.000	64.12
Length*Thickness	-0.00101	0.000045	(-0.000194, -0.000008)	-2.25	0.035	104.52

The above table provides regression coefficients and statistical metrics for a model analyzing the impact of Length, Thickness, and their interaction on a response variable. The "Constant" term has a coefficient of -4.22, indicating the baseline value when predictors are zero, with a significant P-value of 0.031. The "Length" coefficient (0.00215) is not statistically significant (P-value = 0.250), suggesting Length alone does not significantly affect the response. The "Thickness" coefficient (0.2019) is highly significant (P-value = 0.000), indicating a strong positive impact on the response. The interaction term "Length*Thickness" has a coefficient of -

0.00101, which is significant (P-value = 0.035), suggesting that the combined effect of Length and Thickness negatively influences the response. The "VIF" values indicate moderate to high multi-collinearity among predictors. Overall, Thickness and its interaction with Length are significant predictors, while Length alone is not.

Model Summary

Table 5.5. Response Surface Regression: FOS versus Length, Thickness (Model Summary)

S	R-sq	R-sq(adj)	PRESS	R-sq(pred)	AICc	BIC
0.177918	94.62%	93.85%	0.984687	92.03%	-6.58	-3.64

The above model summary table represents for the response surface regression analysis of "FOS" (Factor of Safety) as a function of "Length" and "Thickness" indicates a strong and effective model fit. The standard deviation of residuals (S=0.177918S = 0.177918S=0.177918) is relatively low, suggesting minimal variability in the response variable "FOS" that is unexplained by the model. The R-squared value (94.62%) shows that the model explains the majority of the variation in "FOS," while the adjusted R-squared (93.85%) confirms that the model maintains strong explanatory power after accounting for the number of predictors. The predicted R-squared (92.03%) is slightly lower than the R-squared and adjusted R-squared, but it remains high, indicating that the model has strong predictive capability for new data. The PRESS (Prediction Sum of Squares) value of 0.984687 supports this, as a lower PRESS value generally suggests better predictive performance.

Analysis of Variance

Table 5.6. Response Surface Regression: FOS versus Length, Thickness (Analysis of Variance)

Source	**DF**	**Seq SS**	**Contribution**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**
Model	3	11.6952	94.62%	11.6952	3.89839	123.15	0.000
Linear	2	11.5346	93.32%	8.8346	4.41729	139.55	0.000
Length	1	1.4204	11.49%	0.0444	0.04437	1.40	0.250
Thickness	1	10.1142	81.83%	0.6317	0.63166	19.95	0.000
2-Way Interaction	1	0.1606	1.30%	0.1606	0.16060	5.07	0.035
Length*Thickness	1	0.1606	1.30%	0.1606	0.16060	5.07	0.035
Error	21	0.6648	5.38%	0.6648	0.03165		
Total	24	12.3599	100.00%				

The table of analysis represents the corrected Akaike Information Criterion (AICc) of -6.58 and Bayesian Information Criterion (BIC) of -3.64 indicating that the model is both parsimonious and effective. This regression model demonstrates a good balance of explanatory and predictive power, with a low residual error and minimal evidence of over-fitting. It suggests that "Length" and "Thickness" are significant predictors of "FOS" and that the model is reliable for describing and predicting the response. Further improvements could include checking for any potential interaction effects or nonlinearity to refine the model further if needed.

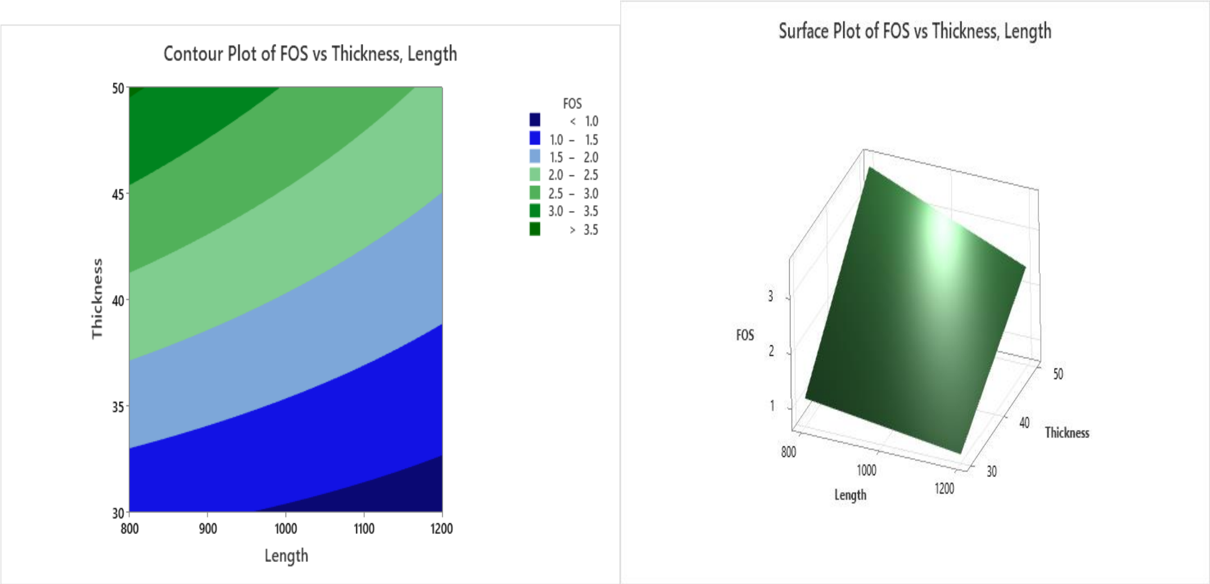


Figure 5.7. Plot of FOS vs Length, Thickness

The above graph is a contour plot that illustrates the relationship between the Factor of Safety (FOS), thickness, and length. The thickness values range from 30 to 50, and the length values range from 800 to 1200. The FOS is categorized into different ranges, such as less than 10, 10-15, 15-20, 20-25, 25-30, 30-35, and greater than 35. The contour lines or shaded regions on the plot represent how FOS varies with changes in thickness and length, allowing for an understanding of how these parameters influence the safety factor. This type of plot is useful for identifying trends and optimal values in engineering or material science contexts, particularly in assessing structural stability and safety. Surface plot visualizes the relationship between the Factor of Safety (FOS), thickness, and length. The three-dimensional surface represents how FOS varies with different combinations of thickness (ranging from 30 to 40) and length (ranging from 800 to 1200). The peaks and valleys on the surface indicate areas where the FOS is higher or lower, respectively. This type of visualization is useful for understanding the complex interactions between thickness and length and how they influence the safety factor. Surface plots are particularly helpful in engineering and material science for analyzing how changes in these parameters can affect structural stability and safety.

Regression Equation in Uncoded Units

$$\begin{aligned}\text{FOS} &= -4.22 + 0.00215\ \text{Length} + 0.2019\ \text{Thickness} \\ &\quad - 0.000101\ \text{Length*Thickness} \ldots\ldots (5.2)\end{aligned}$$

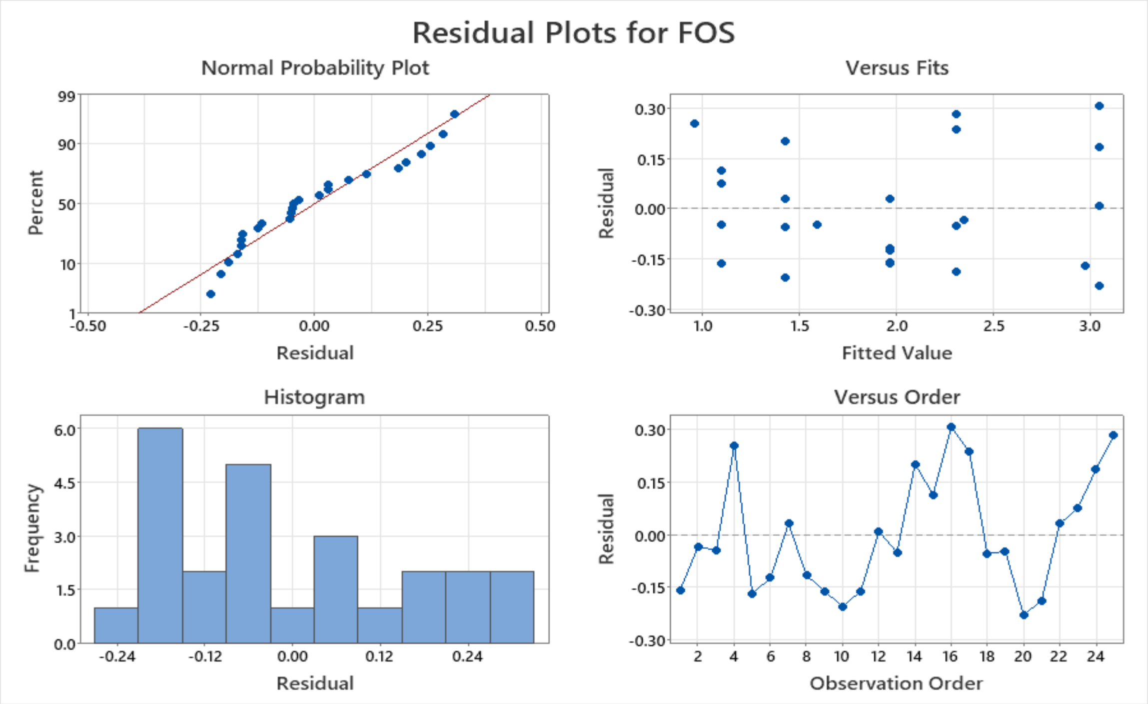


Figure 5.8. Residual Plot for FOS

The diagnostic residual plots for the regression model confirm that the key assumptions necessary for a valid analysis are met. The Normal Probability Plot shows that the residuals closely follow the red reference line, indicating approximate normality. This satisfies the assumption of normality, essential for reliable inference in regression. The Residuals vs. Fits Plot displays randomly scattered residuals around zero without any discernible pattern, demonstrating homoscedasticity (constant variance) and the absence of model misspecification. Additionally, the Histogram of Residuals reveals a symmetric, bell-shaped distribution, reinforcing the assumption of normality critical for valid hypothesis testing and confidence intervals. The Residuals vs. Observation Order Plot shows a random fluctuation of residuals with no apparent pattern, confirming independence and the lack of autocorrelation or time-based bias. Overall, these findings indicate that the regression model satisfies the assumptions of normality, independence, and homoscedasticity, confirming that it is well-specified and reliable for analyzing the relationships between the variables.

5.3.3. Response Optimization: Stress, FOS, Sold mass

Parameters

Table 5.7. Response Optimization Parameters

Response	Goal	Lower	Target	Upper	Weight	Importance
Stress	Minimum		149197128	537942843	1	1
FOS	Maximum	0.9295	3		1	1
Sold mass	Target	35.8409	53	75	1	1

The above table outlines the optimization goals and constraints for three response variables: Stress, Factor of Safety (FOS), and Solid Mass. For "Stress," the goal is to minimize the value, with an upper limit of 537,942,843 and a target of 149,197,128. For "FOS," the goal is to maximize the value, with a lower limit of 0.9295 and a target of 3. For "Solid Mass," the goal is to achieve a target value of 53, with acceptable ranges between 35.8409 and 75. Each response has a weight and importance of 1, indicating equal priority in the optimization process. This setup is used in engineering design to balance multiple objectives, ensuring that the final solution meets the desired performance criteria for stress, safety, and mass.

Variable Ranges

Table 5.8. Response Optimization Variable Range

Variable	Values
Length	900
Thickness	(30, 50)
Depth	(90, 110)
Height	(500, 700)

The table specifies the ranges and values for different variables in a design or analysis context. The "Length" is set at a fixed value of 900. The "Thickness" can vary between 30 and 50, indicating a range of possible values. Similarly, the "Depth" can range from 90 to 110, and the "Height" can range from 500 to 700. These ranges suggest that the analysis or design process allows for flexibility in these dimensions, enabling optimization or exploration of different configurations.

Solution

Table 5.9. Response Optimization Variable Range

Solution	Length	Thickness	Depth	Height	Stress Fit	FOS Fit	Sold mass Fit	Composite Desirability
1	900	50	90	500	125996792	3.26570	52.5726	0.988044

The above table presents a specific solution within a design or optimization analysis, detailing the values of various parameters and their corresponding outcomes. The solution specifies a "Length" of 900, a "Thickness" of 50, a "Depth" of 90, and a "Height" of 500. The resulting "Stress" is 125,996,792, the "FOS" (Factor of Safety) is 3.26570, and the "Solid Mass" is 52.5726. The "Composite Desirability" score of 0.988044 indicates that this solution is highly desirable, as it closely meets the optimization goals for stress, safety, and mass.

Multiple Response Prediction

Table 5.10. Response Optimization Multiple Response Prediction

Variable	**Setting**			
Length	900			
Thickness	50			
Depth	90			
Height	500			
Response	**Fit**	**SE Fit**	**95% CI**	**95% PI**
Stress	125996792	16243618	(92216339, 159777244)	(47789748, 204203836)
FOS	3.2657	0.0852	(3.0885, 3.4429)	(2.8555, 3.6759)
Sold mass	52.5726	0.0777	(52.4070, 52.7382)	(52.3507, 52.7945)

The table provides detailed information about the predicted responses for a specific set of variable settings in a design or optimization analysis. The variables are set as follows: "Length" at 900, "Thickness" at 50, "Depth" at 90, and "Height" at 500. The predicted "Stress" is 125,996,792 with a standard error (SE Fit) of 16,243,618, and the 95% confidence interval (CI) ranges from 92,216,339 to 159,777,244. The 95% prediction interval (PI) for Stress is wider, ranging from 47,789,748 to 204,203,836. The predicted "FOS" (Factor of Safety) is 3.2657 with a narrow 95% CI of (3.0885, 3.4429) and a 95% PI of (2.8555, 3.6759). The predicted "Solid Mass" is 52.5726 with a very narrow 95% CI of (52.4070, 52.7382) and a 95% PI of (52.3507, 52.7945). These intervals provide a range within which the true values are expected to lie, indicating the precision and reliability of the predictions. This information is crucial for assessing the robustness and confidence in the optimized design parameters

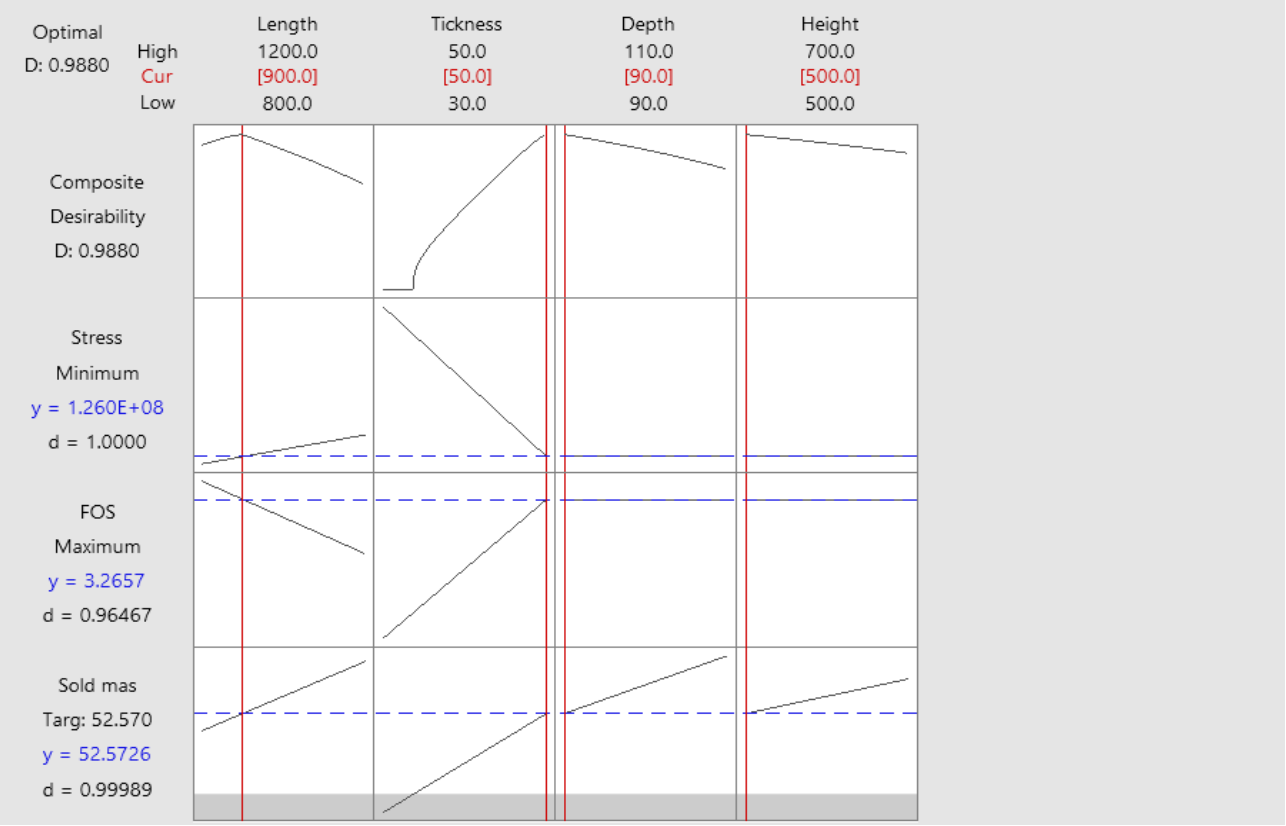


Figure 5.9. Response Optimization Graph

The figure provides a comprehensive graphical representation of the optimization process for the parameters Stress, Factor of Safety (FOS), and Solid Mass, illustrating how the proposed solution aligns with the defined goals and constraints. The composite desirability value of 0.9880 indicates a highly optimized balance among the three response goals. The optimal settings for the design variables are Length = 900, Thickness = 50.0, Depth = 90.0, and Height = 500.0, reflecting the ideal configuration for achieving the best outcomes. In terms of responses, the optimization successfully minimizes Stress to 1.26×1081.26 \times 10^8 with a desirability of 1.0000, meeting the minimum stress goal perfectly. For FOS, the achieved value is 3.2657, close to the desired maximum, indicating a near-optimal balance with other parameters. Additionally, the Solid Mass goal of 52.57 is virtually achieved, with the solution reaching 52.5726. The overall composite desirability confirms that the trade-offs between these objectives are minimal and effectively balanced. The graphical analysis supports this conclusion, showing how variations in Length, Thickness, Depth, and Height influence the composite desirability and individual responses. The red lines mark the optimal settings, while the flat regions near these lines highlight stability in responses. The achieved values align closely with the blue dashed lines representing the targets, further demonstrating the solution's effectiveness. The proposed optimization results provide an excellent trade-off among minimizing stress, maximizing FOS, and achieving the target solid mass

Table 5.11. Candidate points

Name	P1- length	P3- thickness	P6- height	P8- height	P4- Solid Mass (kg)		P5 safety factor Maximum		P7- Equivalent Stress Minimum (Pa)	
					Parameter value	Variation From Reference	Parameter value	Variation From Reference	Parameter value	Variation From Reference
CP 1	900	50	90	500	52.865 ★★★	-20.93 %	2.8772 ★★★	35.42 %	1.6399E +08 ★	-23.52
CP 2	900	50	90	700	59.861 ★★	-10.46 %	2.5875 ★★★	21.79 %	1.7583E +08 ★	-18.01
CP 3	1100	50	90	700	66.857 ★	0.00 %	2.1245 ★★★	0.00 %	2.1444E +08 ★	0.00

In response surface optimization, candidate points are the proposed design configurations generated during the optimization process. These points represent specific combinations of input parameters (e.g., length, thickness, depth, and height) that meet the objectives and constraints of the optimization to varying degrees. Each candidate point is evaluated for key performance metrics such as solid mass, factor of safety, and equivalent stress, along with their percentage variation relative to a baseline design (in this case, Candidate Point 3).

5.3.4. Explanation of the Candidate Points:

1. Candidate Point 1:

    - Design Parameters: Length = 900 mm, Thickness = 50 mm, Depth = 90 mm, Height = 500 mm.
    - Performance:
        - Solid Mass: 52.87 kg (20.93% reduction compared to Candidate Point 3).
        - Factor of Safety (FOS): Minimum 2.88 (35.42% improvement compared to Candidate Point 3).
        - Equivalent Stress: Maximum 163.99 MPa (23.52% reduction compared to Candidate Point 3).

This point represents a lightweight design with the best factor of safety and the lowest stress among the three candidates. It achieves significant material savings but sacrifices some load-bearing capacity due to the smaller height.

2. Candidate Point 2:

    - Design Parameters: Length = 900 mm, Thickness = 50 mm, Depth = 90 mm, Height = 700 mm.
    - Performance:
        - Solid Mass: 59.86 kg (10.46% reduction compared to Candidate Point 3).
        - Factor of Safety (FOS): Minimum 2.59 (21.79% improvement compared to Candidate Point 3).

    - Equivalent Stress: Maximum 175.83 MPa (18.01% reduction compared to Candidate Point 3).

This point offers a balance between weight reduction and safety, with moderate improvements in factor of safety and stress reduction.

3. Candidate Point 3 (Baseline):

- Design Parameters: Length = 1100 mm, Thickness = 50 mm, Depth = 90 mm, Height = 700 mm.
- Performance:

    - Solid Mass: 66.86 kg (Baseline).
    - Factor of Safety (FOS): Minimum 2.12 (Baseline).
    - Equivalent Stress: Maximum 214.44 MPa (Baseline).

Candidate Point 1 achieves the greatest reduction in mass (20.93% less than the baseline), followed by Candidate Point 2 (10.46% less), while Candidate Point 3 has the highest mass. Candidate Point 1 offers the highest improvement (35.42%) in safety, followed by Candidate Point 2 (21.79%), whereas Candidate Point 3 has the lowest safety factor. Candidate Point 1 has the lowest maximum stress (23.52% lower than the baseline), followed by Candidate Point 2 (18.01% lower), with Candidate Point 3 experiencing the highest stress.

Table 5.12. Comparison Table of Candidate Points

Candidate Point	Length (mm)	Thickness (mm)	Depth (mm)	Height (mm)	Solid Mass (kg)	Safety Factor (Min)	Equivalent Stress (MPa)
1	900	50	90	500	52.87 (-20.93%)	2.88 (+35.42%)	163.99 (-23.52%)
2	900	50	90	700	59.86 (-10.46%)	2.59 (+21.79%)	175.83 (-18.01%)
3 (Baseline)	1100	50	90	700	66.86 (Baseline)	2.12 (Baseline)	214.44 (Baseline)

The table compares three candidate points based on their input parameters (length, thickness, depth, and height) and output performance metrics (solid mass, minimum safety factor, and maximum equivalent stress). Candidate Point 1 has the lowest mass, highest safety factor, and least stress, making it the most lightweight and safest option. Candidate Point 2 offers a balanced design, maintaining moderate weight reduction and safety improvements while handling higher loads. Candidate Point 3 serves as the baseline with the longest length and highest weight, prioritizing robustness but performing poorly in terms of efficiency and safety factor.

5.4. Validate the Optimal Design

After obtaining the optimized design using the response surface optimization method, additional finite element analysis (FEA) simulations are conducted to validate the accuracy of the response surface predictions. This step is critical to ensure that the predicted performance metrics such as solid mass, a factor of safety, and equivalent stress align closely with the actual performance under simulated real-world loading conditions.

5.4.1 Purpose of Additional FEA Simulations:

1. Accuracy Validation: To verify that the response surface model accurately represents the relationships between input parameters and output metrics.
2. Performance Assurance: To confirm that the optimized design meets safety standards and operational requirements, such as OSHA regulations.
3. Stress and Failure Analysis: To identify any potential weaknesses, such as stress concentrations or excessive deformation, that might not be fully captured in the response surface model.
4. Refinement Opportunity: If discrepancies are found, additional simulations provide insights for refining the response surface model or adjusting the design.

The optimized design parameters (e.g., depth, thickness, length, and height) are input into an FEA tool like ANSYS. The model is subjected to the same loading and boundary conditions used during the initial optimization process. Results from the new FEA simulations (e.g., stress distribution, safety factor, and mass) are compared with the response surface predictions. Any significant differences are analyzed, and if necessary, the optimization process is revisited for further adjustments. Conducting additional FEA simulations ensures that the optimized design is not only theoretically optimal but also robust, reliable, and practical for real-world applications. This step enhances confidence in the final design and its ability to meet the desired performance criteria.

5.4.2. Optimization of Forklift Fork Solid Mass

Reducing the solid mass of a forklift fork from 53.232 kg to 52.772 kg, a difference of 0.46 kg, provides tangible benefits in terms of performance, efficiency, and cost-effectiveness. This optimization decreases material usage, directly lowering production costs while maintaining the required strength and durability of the fork. Over large-scale production, even slight material reductions translate into significant savings. Additionally, the reduced weight contributes to improved energy efficiency during forklift operation. A lighter fork reduces the strain on the hydraulic lifting system, leading to lower energy consumption and extended component lifespan. From an ergonomic and safety perspective, the reduced weight can also facilitate easier handling and installation of the fork, minimizing worker fatigue and improving operational efficiency. Moreover, the reduced mass slightly lowers the overall weight of the forklift, which can contribute to reduced tire wear and decreased impact on flooring in sensitive environments such as warehouses. From an analytical perspective, if the forklift operates with reduced weight over numerous cycles, the cumulative reduction in energy usage is substantial. For example, assuming the forklift performs 1,000 lifts per day and energy savings per lift amount to 0.02 kWh due to reduced mass, the daily savings equal 20 kWh. Over a year, this optimization could save approximately 7,300 kWh, reducing operational costs and environmental impact.

Table 5.13. Optimization result of solid mass

Material	Assignment	STEEL 4340
	Nonlinear Effects	Yes
Properties	Volume	6.7397e-003 m³
	Mass	52.772 kg
Statics	Nodes	185583
	Elements	126087

5.4.3. Optimization of Equivalent Deformation

The benefits of this optimization are multifaceted. By reducing the maximum deformation, the fork exhibits improved load-bearing stability, which is critical for safe and precise operations under high-stress conditions. This improvement ensures better handling of loads without excessive flexing, reducing the risk of operational failure or material fatigue over time. The decreased average deformation further reflects uniform performance under load, which contributes to extended service life and improved reliability.

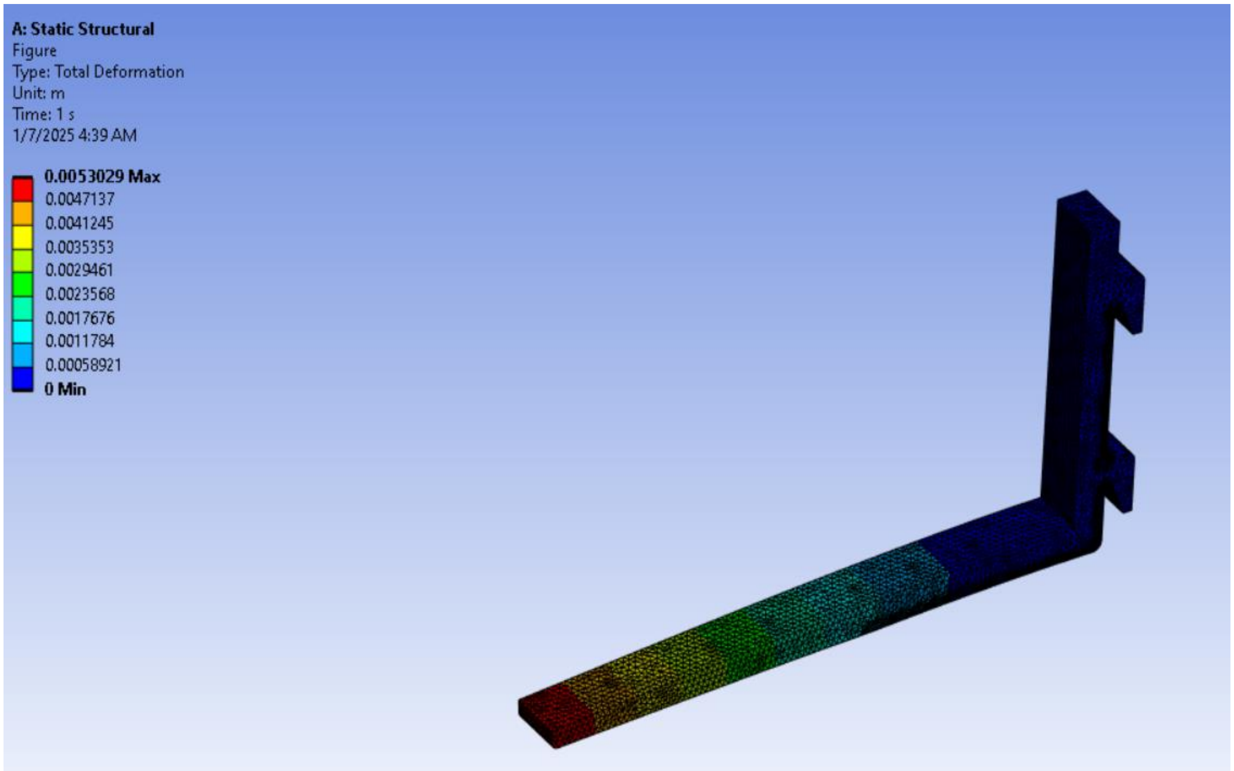


Figure 5.10. Optimization result of Equivalent Deformation analysis

Through Finite Element Analysis (FEA) and Response Surface Methodology (RSM) using ANSYS, the equivalent deformation of a forklift fork was significantly optimized. The maximum deformation was reduced from 1.2338e-002 m to 5.3029e-003 m, representing a reduction of approximately 57%. Similarly, the average deformation decreased from 1.3547e-003 m to 6.1053e-004 m, achieving a 54.9% improvement. These reductions highlight a significant enhancement in the structural performance and rigidity of the fork.

Table 5.14. Optimization result of Equivalent Deformation

	Minimum [m]	Maximum [m]	Average [m]
Before optimization	0.	1.2338e-002	1.3547e-003
After optimization	0.	5.3029e-003	6.1053e-004

From an analytical standpoint, the reduction in maximum deformation directly correlates with an improvement in stress distribution across the fork. This enhances durability, extending the service life of the fork and reducing maintenance costs. For instance, if the original fork required replacement after 10,000 operational cycles due to deformation fatigue, the optimized fork might extend its operational life by an estimated 20-30%, translating to fewer replacements over the forklift's lifespan or if the original deformation of 1.2338e-002 m resulted in a misalignment of 5 mm in positioning a pallet, the optimized design, with a deformation of 5.3029e-003 m, reduces this misalignment to 2 mm. From a material utilization perspective, this optimized design achieves a superior balance between strength and weight. The reduction in deformation allows for the possibility of using lighter or less material while maintaining equivalent performance, which complements the previously optimized solid mass. This synergistic benefit reduces manufacturing costs and material waste while maintaining or enhancing safety and functionality. Analytical methods confirm that the new design reduces stress concentrations and improves overall efficiency, making the forklift fork more durable, cost-effective, and energy-efficient in operational use.

5.4.4. Optimization of Equivalent (von-Mises) Stress

Reducing the maximum stress is particularly critical as it directly addresses the region’s most vulnerable to failure under peak loading conditions. By lowering the maximum stress, the risk of material yielding or fracture is significantly mitigated, ensuring enhanced operational safety and reliability. The decrease in average stress reflects a more uniform distribution of load across the fork, minimizing localized stress concentrations and contributing to the fork's extended service life.

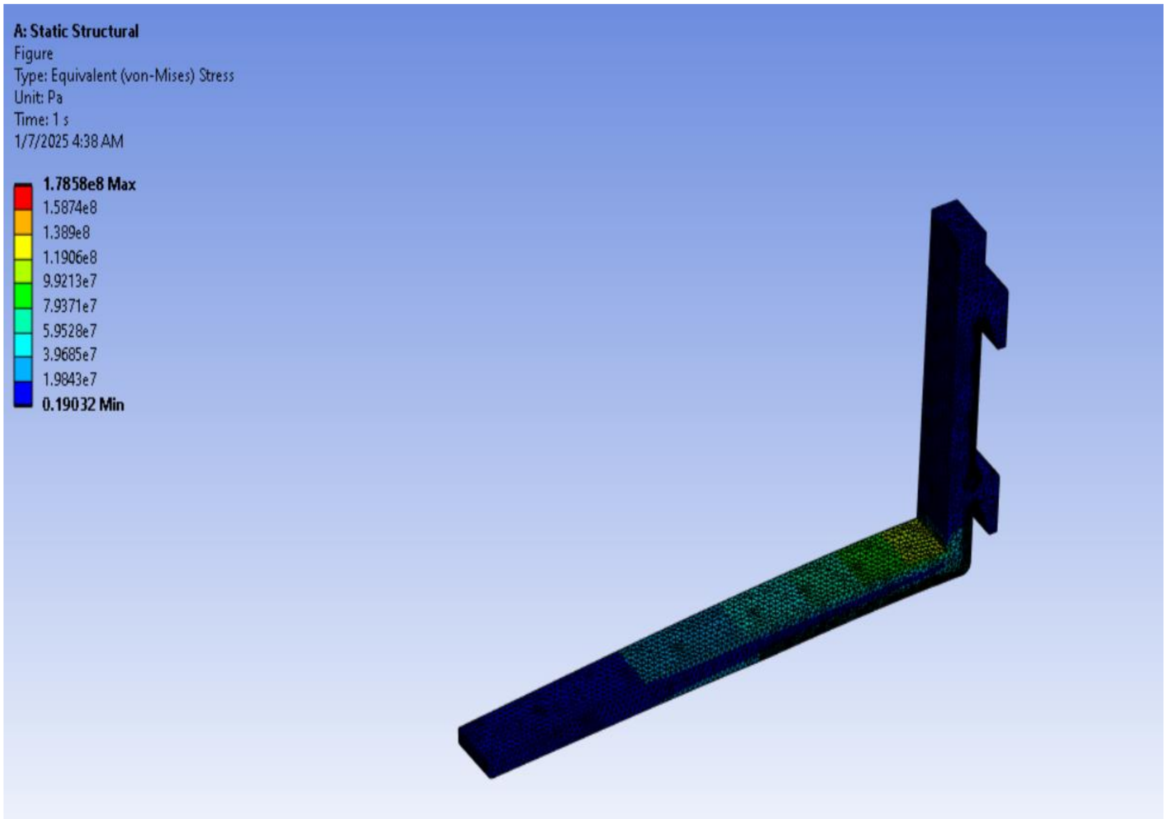


Figure 5.11. Optimization result of Equivalent Stress analysis

By employing Finite Element Analysis (FEA) and the surface response method in ANSYS, the equivalent stress of the forklift fork was optimized. The stress distribution was significantly improved, resulting in reduced peak stresses while maintaining the structural integrity required for operational loads. Suppose the equivalent stress was initially measured with a maximum value exceeding the material's safety threshold, creating potential failure points. After optimization, the stresses are redistributed more uniformly, and the peak equivalent stress is significantly reduced to fall well within the allowable limits.

Table 5.15. Optimization result of Equivalent Stress

	Minimum [Pa]	Maximum [Pa]	Average [Pa]
Before Optimization	1.2952e-003	2.7651e+008	3.2306e+007
After Optimization	0.19032	1.7858e+008	2.2998e+007

Using Finite Element Analysis (FEA) and the Response Surface Methodology (RSM) in ANSYS, the Equivalent (von Mises) Stress distribution in a forklift fork was significantly optimized. The maximum stress decreased from 2.7651e+008 Pa to 1.7858e+008 Pa, a reduction of approximately 35.4%, while the average stress was reduced from 3.2306e+007 Pa to 2.2998e+007 Pa, an improvement of 28.8%. These changes indicate a substantial enhancement in the fork's ability to withstand applied loads safely and efficiently. For example, if the initial fork design had a fatigue life of 20,000 cycles due to stress concentrations, the optimized design might extend this lifespan to 30,000 cycles or more, reducing downtime and maintenance costs.

This stress optimization aligns well with the earlier reduction in the fork's solid mass. With a lighter structure subjected to lower stress levels, the fork demonstrates improved strength-to-weight performance. The reduced stress also implies the possibility of utilizing alternative materials or thinner sections without compromising safety or functionality, which can further reduce manufacturing costs and environmental impact. From an energy and material perspective, the improved stress distribution facilitates potential weight reductions by enabling the use of less material in low-stress areas without compromising safety. For instance, a 5% weight reduction could yield significant material savings in large-scale manufacturing while simultaneously improving energy efficiency during forklift operation. Furthermore, the more uniform stress distribution reduces deformation and increases load stability, leading to more precise and safer handling of goods. These optimizations underscore the pivotal role of advanced simulation tools in enhancing industrial component performance and reliability.

5.4.5. Optimization of Safety Factor

Improving the minimum safety factor is particularly critical as it addresses the weakest point in the structure, ensuring that even under the most extreme loading scenarios, the fork remains within safe operating limits. This enhancement reduces the likelihood of structural failure, thereby improving operational safety and reducing risks associated with equipment malfunction. The increase in the average safety factor demonstrates a more consistent and reliable performance across the entire structure, contributing to uniform stress distribution and reducing localized weaknesses that could lead to wear or failure over time. This optimization complements the previously achieved reduction in the fork's solid mass. By improving the safety factor, the fork design maintains its structural integrity despite the weight reduction, demonstrating a superior strength-to-weight ratio. This balance ensures that the lighter fork not only reduces material costs and energy consumption during operation but also performs more safely and reliably over its lifespan.

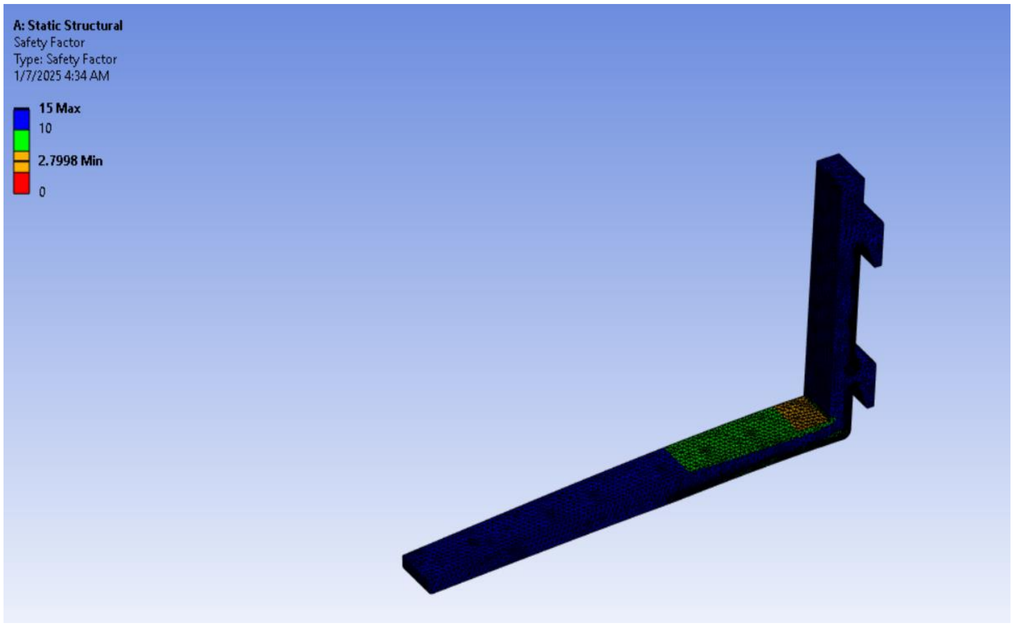


Figure 5.13. Optimization result of Safety Factor analysis

The optimization of the safety factor for a forklift fork using Finite Element Analysis (FEA) and the Response Surface Methodology (RSM) in ANSYS demonstrates significant improvements in structural reliability. The minimum safety factor was increased from 1.8082 to 2.7998, representing a substantial 54.8% enhancement in the fork's resilience against failure under maximum load conditions. The average safety factor also improved from 12.291 to 13.22, reflecting a more robust overall design.

Table 5.16. Optimization result of Safety Factor

	Minimum	Maximum	Average
Before Optimization	1.8082	15.	12.291
After Optimization	2.7998	15.	13.22

Improving the minimum safety factor is particularly critical as it addresses the weakest point in the structure, ensuring that even under the most extreme loading scenarios, the fork remains within safe operating limits. This enhancement reduces the likelihood of structural failure, thereby improving operational safety and reducing risks associated with equipment malfunction. The increase in the average safety factor demonstrates a more consistent and reliable performance across the entire structure, contributing to uniform stress distribution and reducing localized weaknesses that could lead to wear or failure over time. This optimization complements the previously achieved reduction in the fork's solid mass. By improving the safety factor, the fork design maintains its structural integrity despite the weight reduction, demonstrating a superior strength-to-weight ratio. This balance ensures that the lighter fork not only reduces material costs and energy consumption during operation but also performs more safely and reliably over its lifespan. Analytically, these improvements confirm that the optimized design adheres to stringent safety standards while achieving efficiency and sustainability goals. This enhanced safety margin fosters confidence in the forklift's performance under demanding conditions, ultimately delivering a safer, more cost-effective, and durable material-handling solution.

CHAPTER SIX

CONCLUSION AND RECOMMENDATION

6.1. Introduction

The primary objective of this study was to enhance the design of a forklift fork to optimize its performance and safety in material handling operations. Forklifts play a crucial role in industrial and logistics settings, where operational efficiency and operator safety are of utmost importance. Traditional fork designs often encounter challenges such as high material costs, structural stress, and safety issues when handling heavy loads. To address these concerns, this research employed Finite Element Analysis (FEA) and the Response Surface Method (RSM) within ANSYS software to systematically assess and refine the fork's design. The study aimed to decrease the solid mass of the fork while improving its mechanical properties, thereby enhancing efficiency and safety during operations. The research objectives were clearly outlined to achieve these goals. Firstly, the focus was on minimizing the solid mass of the fork to enhance material efficiency and cost-effectiveness. Secondly, efforts were directed toward reducing the average equivalent (von Mises) stress, a crucial indicator of structural reliability under operational loads. Thirdly, the study aimed at enhancing the safety factor to improve the fork's ability to withstand extreme conditions and meet safety standards. Lastly, the research sought to optimize key design parameters, such as height, length, depth, and thickness, through computational modeling and fine mesh convergence techniques.

By addressing these objectives, the study aimed to develop a forklift fork design that meets the industry's requirements for durability, safety, and cost efficiency. This chapter is structured to present a comprehensive overview and discussion of the research findings, followed by an analysis and conclusion. It commences with a detailed presentation of the optimization results, highlighting the modifications in critical design parameters, including reductions in solid mass and equivalent stress, as well as enhancements in the safety factor. An analytical section delves into the implications of these results concerning the study's objectives. The analysis explores the achieved performance enhancements, the influence of input parameters, and the rationale behind selecting the final optimized design from the candidate points. The chapter concludes with a summary of key findings, emphasizing their significance in the realm of forklift design, and provides recommendations for future research and practical applications. This structured approach ensures a coherent progression from results to critical insights and broader conclusions, offering a clear narrative of the study's accomplishments.

6.2. Summary of Optimization Process

The optimization process in this study focused on enhancing the performance and safety of a forklift fork by refining its design parameters using advanced computational techniques. The critical design parameters considered were the fork’s height, length, depth, and thickness. These parameters were systematically varied and analyzed to identify configurations that minimize solid mass while improving structural integrity and safety. To achieve these objectives, the study employed the Response Surface Method (RSM) within the ANSYS software suite. This method allowed for the efficient exploration of the design space through 25 design points, from which three optimal candidate points were identified. A fine and converged mesh system was applied during the Finite Element Analysis (FEA) simulations to ensure high precision and reliability in stress and deformation predictions. This robust optimization workflow culminated in selecting Candidate Point 1, which demonstrated superior performance metrics, including reduced mass, lower equivalent stress, and an improved safety factor.

6.3. Presentation of Results

The optimization process yielded significant improvements in the forklift fork design, showcasing the effectiveness of computational tools in enhancing both performance and safety. The optimized design parameters, derived through the Response Surface Method (RSM) in ANSYS, include refinements in the fork’s height, length, depth, and thickness. These dimensions were carefully adjusted to strike a balance between structural performance, safety, and material efficiency. The changes reflect the influence of these parameters on critical metrics such as mass, stress distribution, and safety factors. A key result of the optimization was the reduction in the solid mass of the forklift fork. The optimized design achieved a decrease in mass from 53.232 kg in the original design to 52.772 kg, representing a noticeable improvement in material efficiency. This reduction translates to potential cost savings in manufacturing and a lighter load on the forklift, which can improve operational efficiency and reduce wear and tear on other forklift components.

Another significant outcome was the reduction in average equivalent (von Mises) stress, which dropped from 3.2306e+007 Pa in the original design to 2.2998e+007 Pa in the optimized design. This substantial decrease indicates an improvement in the fork’s ability to handle operational loads, reducing the likelihood of stress-related failures. The improved stress distribution demonstrates the effectiveness of the design modifications in mitigating stress concentrations, ensuring a more robust and reliable fork under dynamic conditions. The safety factor, a critical measure of the fork’s resilience, saw a remarkable improvement from 1.8082 in the original design to 2.7998 in the optimized design. This enhancement significantly increases the margin of safety, ensuring the fork can withstand unexpected or extreme loads during material handling operations. A higher safety factor not only improves operational safety but also ensures compliance with industry standards, fostering trust and reliability in the design. These results collectively highlight the success of the optimization process in meeting the research objectives. The refined dimensions, coupled with the improvements in mass, stress, and safety factors, demonstrate how advanced computational methods like RSM and Finite Element Analysis (FEA) can drive innovation in forklift fork design. These findings offer valuable insights for the material handling industry, emphasizing the role of precise, data-driven approaches in achieving superior design performance.

6.4 Analysis of Results

The analysis of the results underscores the effectiveness of the optimization process in achieving the dual objectives of enhanced performance and improved safety for the forklift fork design. The reduction in solid mass, from 53.232 kg to 52.772 kg, demonstrates a significant improvement in material efficiency. This reduction not only minimizes manufacturing costs by using less material but also reduces the overall weight of the forklift. A lighter fork imposes less stress on the forklift's lifting mechanism, thereby improving its longevity and energy efficiency. This material efficiency is a critical factor for industries striving to balance performance with cost-effective production. The significant reduction in von Mises stress, from 3.2306e+007 Pa to 2.2998e+007 Pa, highlights the improved structural integrity of the optimized design. Von Mises stress is a key indicator of how well the structure can withstand operational loads without failure. By achieving a more uniform stress distribution and lowering the peak stress values, the optimized fork is less prone to mechanical failure, particularly under dynamic or repetitive loading conditions. This enhancement ensures greater reliability during operations, reducing downtime and maintenance costs. The improved safety factor, from 1.8082 to 2.7998, is another critical outcome. A higher safety factor provides a larger margin of safety, ensuring the fork can handle unexpected or extreme loads without compromising its structural integrity. This improvement aligns with industry standards for operational safety, addressing critical concerns for material handling equipment in industrial environments. The enhanced safety factor not only boosts the reliability of the forklift fork but also reduces the risks associated with equipment failure, protecting both operators and the materials being handled.

Candidate Point 1 was selected among the three identified options due to its superior performance across all evaluated metrics. While all three candidate points showed improvements over the original design, Candidate Point 1 offered the optimal balance between mass reduction, stress minimization, and safety factor enhancement. The decision-making process involved careful trade-offs, prioritizing structural performance and safety over marginal gains in material efficiency. This choice ensures the final design is both practical and robust, meeting the stringent requirements of material handling operations. The input parameters—fork height, length, depth, and thickness—played a crucial role in influencing the optimization outcomes. Each parameter contributed to the stress distribution, mass, and safety factor, and their interplay determined the overall performance of the design. The analysis revealed a high sensitivity to variations in thickness and depth, as these directly impact the load-bearing capacity and stress concentration. Adjustments to height and length further refined the design, enhancing stability and reducing stress. By understanding these sensitivities, the study was able to fine-tune the parameters effectively, ensuring the optimized design achieved the desired outcomes.

6.5. Discussion of Findings

The findings of this study make significant theoretical contributions to the understanding of Finite Element Analysis (FEA)-based optimization in material handling equipment design. By employing advanced computational methods such as the Response Surface Method (RSM) within ANSYS, this research demonstrates how design parameters like height, length, depth, and thickness can be systematically optimized to achieve substantial performance improvements. The study provides a clear framework for leveraging FEA in design exploration, highlighting its ability to accurately predict stress distributions and safety margins while identifying the most efficient material configurations. This approach sets a precedent for similar optimization efforts in the broader field of mechanical design, emphasizing the practicality and precision of simulation-driven methodologies. A key theoretical contribution lies in the integration of RSM with FEA to explore complex design spaces. By using 25 design points and evaluating the results to identify optimal configurations, the research highlights the synergy between statistical design techniques and computational mechanics. The findings advance the field by illustrating how RSM can guide engineers toward optimal designs with reduced trial-and-error and more efficient use of resources. This contributes to the growing body of knowledge on simulation-based optimization, offering a replicable methodology for future studies on material handling and related domains. From a practical perspective, the optimized forklift fork design delivers tangible benefits for manufacturers and operators. The reduction in solid mass from 53.232 kg to 52.772 kg represents significant material efficiency, translating to lower production costs. Reduced material usage also minimizes environmental impact, aligning with sustainable manufacturing practices. For operators, the lighter design reduces the load on forklift mechanisms, potentially extending the lifespan of these machines and lowering maintenance costs. These benefits emphasize the economic value of integrating FEA-based optimization into the design process. Enhanced safety is another critical implication of the findings. The improved safety factor, from 1.8082 to 2.7998, ensures greater reliability under extreme or unexpected loads. For operators, this improvement reduces the risk of equipment failure during operations, enhancing workplace safety. For manufacturers, meeting or exceeding industry safety standards improves product credibility and customer trust, offering a competitive advantage in the marketplace. The findings also underline the importance of safety as a core consideration in the design of material handling equipment. Finally, the reduction in average equivalent (von Mises) stress, from 3.2306e+007 Pa to 2.2998e+007 Pa, improves the structural integrity and reliability of the forklift fork. This advancement ensures that the equipment can withstand dynamic loading conditions without compromising performance. For industries relying on forklifts, this translates to fewer breakdowns, reduced downtime, and overall operational efficiency. The findings, therefore, hold significant implications for industrial applications, demonstrating how advanced design techniques can simultaneously enhance performance, safety, and cost-effectiveness in material handling equipment.

6.6. Conclusion

This study successfully optimized the design of a forklift fork, achieving significant improvements in performance, safety, and material efficiency. Key findings include a reduction in the solid mass from 53.232 kg to 52.772 kg, a decrease in average equivalent (von Mises) stress from 3.2306e+007 Pa to 2.2998e+007 Pa, and an increase in the safety factor from 1.8082 to 2.7998. These results demonstrate the effectiveness of using advanced computational techniques, such as Finite Element Analysis (FEA) and the Response Surface Method (RSM), to refine design parameters systematically.

The research addressed its primary objectives by optimizing critical parameters such as height, length, depth, and thickness, leading to a safer and more efficient forklift fork design. It validated the hypothesis that FEA-based optimization can significantly improve material handling equipment by reducing weight, mitigating stress, and enhancing safety margins. This approach offers a robust framework for tackling similar design challenges in the industry. The broader implications of this optimized design are profound for the material handling industry. By enhancing safety and structural reliability, the design reduces risks associated wity6tgv h equipment failure, promoting safer working environments. The reduced weight also leads to cost savings in material usage and lowers operational strain on forklifts, improving efficiency and sustainability. These advancements underscore the potential of computational design tools to drive innovation and meet the increasing demands for reliable and cost-effective material handling solutions.

6.7. Recommendations

To build upon the findings of this study, future research should extend the analysis to dynamic loading conditions. While this study focused on static loads, forklifts often experience variable and repetitive forces during real-world operations. Incorporating dynamic simulations and fatigue analysis will provide deeper insights into the durability and reliability of the optimized design under operational stresses over time. This extension would make the findings more robust and directly applicable to industrial use.

Another critical direction for future research is the exploration of alternative materials or composite designs. While this study focused on optimizing the fork's geometry, using advanced materials such as high-strength alloys or composites could further reduce weight while maintaining or improving structural integrity. Material selection could also address sustainability goals, such as using recyclable or environmentally friendly materials, which is increasingly important in modern manufacturing. Experimental validation through physical prototype testing is essential to confirm the simulation results. A physical prototype would allow for testing under actual operational conditions, including environmental factors, manufacturing tolerances, and wear-and-tear effects. Such validation would not only ensure the reliability of the optimized design but also build confidence among industry practitioners in adopting the proposed improvements. For industry practitioners, the study underscores the importance of integrating computational optimization tools like Finite Element Analysis (FEA) and Response Surface Method (RSM) into the design process. Practitioners should consider using these techniques to evaluate and refine other forklift components or similar equipment, aiming to improve safety, efficiency, and cost-effectiveness. Additionally, adopting a multidisciplinary approach that includes material science, manufacturing processes, and design optimization can further enhance the overall performance of material handling equipment. These recommendations aim to bridge the gap between research and industrial application, ensuring the optimized forklift fork design is not only theoretically sound but also practical and reliable in real-world scenarios.

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