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Mechanical Properties Analysis of Stainless Steel 304 Linear Guide Rail Using Autodesk Inventor and MATLAB

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Abstract

This study investigates the mechanical properties of a stainless steel 304 linear guide rail using a combination of Autodesk Inventor and MATLAB. The primary objective is to analyze the von Mises stress distribution, displacement, and safety factor of the linear guide rail under varying load conditions, as well as to develop a model representing the relationship between stress and strain. A detailed 3D model of the guide rail was created using Autodesk Inventor, followed by finite element analysis (FEA) to evaluate stress and strain distribution across different sections of the rail. The simulation was conducted to assess the structural response under multiple loading scenarios, ensuring its reliability for real-world applications. Furthermore, a linear regression analysis was performed using MATLAB to establish a predictive model correlating stress and strain, enabling more accurate forecasting of the material's mechanical behavior. The results revealed that the maximum von Mises stress obtained from the simulation was 23.595 MPa, with a corresponding maximum displacement of 0.397 mm. The safety factor analysis confirmed the rail's structural integrity, with a minimum safety factor of 10.595, well above the failure threshold. These findings indicate that the linear guide rail meets the necessary mechanical performance requirements for its intended application.

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1. Introduction

The rapid expansion of urban mass transit systems has been a defining trend in recent decades, driven by increasing urbanization worldwide. Every year, mass transit and subway systems collectively transport approximately 55 billion passengers. Since the early 2000s, thousands of kilometers of new rapid transit and subway networks have been constructed globally, with numerous light rail and metro extensions currently under development [1]. In Indonesia, the capital city of Jakarta has experienced significant growth in its transportation infrastructure with the introduction of the Electric Rail Train (KRL), Mass Rapid Transit (MRT), and Light Rail Transit (LRT) systems [2]. A critical factor in the development of efficient and reliable mass transit systems is the selection of durable materials that can withstand operational demands. One essential component in these systems is the Platform Screen Door (PSD), which enhances passenger safety by preventing access to railway tracks while also contributing to the efficiency of train operations.

PSDs, commonly installed at platform edges in modern metro stations, play a crucial role in ensuring passenger security and operational safety [3]. Given their importance, PSD structures require high-performance materials, and stainless steel 304 has emerged as a preferred choice due to its excellent mechanical properties, corrosion resistance, and durability in harsh environments. Stainless steels are widely used in engineering applications where resistance to corrosion and mechanical wear is essential [4]. Among the key structural elements of PSDs are guide rails, which directly impact the precision and stability of the system. High-dimensional accuracy and optimized cross-sectional design are essential for long guide rails used in PSD applications [5]. The roller linear guide, commonly employed as both a guiding mechanism and a load-bearing component in mechanical systems, offers high positioning accuracy, low friction, and excellent precision retention. These

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attributes make roller linear guides indispensable in computer numerical control (CNC) machining equipment and other high-precision applications [6]. From a mechanical perspective, the strength and ductility of SS304 significantly influence its load-bearing capacity. Research has highlighted that SS304 can achieve improved yield strength while maintaining considerable ductility through treatments such as cyclic torsion, resulting in favorable mechanical properties [7], [8]. This is particularly advantageous for guide rails as they must withstand dynamic loads and stress over an extended service life. Moreover, the microstructural stability of SS304 under varying conditions of stress and strain contributes to its effectiveness in high-wear applications, aligning with findings regarding the role of gradient structures in improving mechanical performance [7], [8], [9].

Stainless steel is an alloy containing at least 11.5% chromium by weight, which provides superior corrosion resistance compared to conventional carbon steel. Unlike carbon steel, which forms active iron oxide upon exposure to moisture—leading to accelerated corrosion—stainless steel develops a passive chromium oxide layer that prevents further oxidation and degradation [10]. Stress corrosion cracking (SCC) is another critical issue that can compromise the integrity of SS304 components under cyclic loading conditions [7], [8], [9]. Given that guide rails are subjected to constant mechanical stress from train operations, it is vital to mitigate SCC risks through effective surface treatments and coatings that reduce the susceptibility to crack initiation and propagation. Research demonstrates methods such as titanium ion implantation to significantly enhance the resistance of SS304 to SCC, thereby prolonging the useful life of PSD systems [7], [8], [9].

This study focuses on analyzing the mechanical properties of linear guide rails used in PSD structures made from stainless steel 304. To achieve this, Autodesk Inventor and MATLAB software are employed to simulate and evaluate stress and strain distribution along the guide rail. Autodesk Inventor, a CAD-based solid modeling program developed by Autodesk Inc., facilitates detailed structural modeling and analysis, while MATLAB provides advanced numerical computing capabilities for engineering simulations [11]. This research aims to enhance the understanding of stainless steel 304's mechanical response in PSD applications, contributing to the development of more efficient and reliable transit infrastructure.

2. Methods

2.1. Research stages

This study follows a systematic methodology to ensure a comprehensive analysis of the linear guide rail design and its structural performance. The research begins with a literature review, where relevant literature, including journal articles, textbooks, and conference papers, is reviewed. This step provides a theoretical foundation and insights into existing studies related to linear guide rails, finite element analysis, and mechanical design principles.

Following the literature review, data collection is conducted by performing calculations and estimating dimensions based on previous studies. These parameters are crucial in defining the design specifications of the linear guide rail and serve as inputs for the subsequent modeling and simulation processes. The design modeling phase involves creating a 3D representation of the linear guide rail using Autodesk Inventor. The collected dimensional data are used to develop an accurate virtual model, ensuring precise geometric representation, structural integrity, and assembly configuration. This step is essential for visualizing the design before proceeding to computational analysis.

To evaluate the structural behavior of the linear guide rail, a Finite Element Analysis (FEA) is performed using Autodesk Inventor. The model is discretized into finite elements, allowing for a detailed numerical assessment of stress distribution, deformation, and safety factors. The simulation considers three different rider load variations: 36,940 N, 73,880 N, and 110.82 N, enabling an in-depth investigation of the guide rail's mechanical response under various loading conditions. Finally, the analysis of simulation results focuses on interpreting key performance indicators such as stress distribution, displacement, and safety factors. These results provide valuable insights into the structural integrity and reliability of the linear guide rail. The findings serve as a reference for assessing the strength and operational safety of the system, ensuring that the design meets performance and durability requirements.

2.2. Simulation software

This study utilizes two primary software tools, Autodesk Inventor and MATLAB, for the design, simulation, and computational analysis of the linear guide rail system.

Autodesk Inventor is a Computer-Aided Design (CAD) software developed in the United States as an advanced extension of AutoCAD [12]. It provides a robust platform for 2D and 3D modeling, assembly design, and simulation. Some key advantages of Autodesk Inventor include its ability to design and modify components in both 2D and 3D, facilitate assembly simulations and analyses, create motion representations of pre-assembled components, and generate technical drawings from part designs [13][14]. These capabilities make it an essential tool for developing and evaluating the structural integrity of the linear guide rail before conducting physical tests.

MATLAB is powerful software used for numerical computing, data analysis, and simulation. Its programming language is inherently matrix-based, meaning that all operations are performed using rows and columns as fundamental data structures. This approach simplifies mathematical computations, making MATLAB an efficient tool for engineers, scientists, and researchers working with numerical data, simulations, and control systems [15].

One of MATLAB's significant advantages is its extensive toolbox support, which enhances its functionality for specialized applications. These toolboxes include Simulink for system modeling and simulation, Neural Network Toolbox for artificial intelligence and machine learning, Stateflow for control logic design, and Data Acquisition Toolbox for hardware interfacing. Additionally, MATLAB provides toolboxes such as Communications Blockset for signal transmission, Fuzzy Logic Toolbox for decision-making applications, Image Acquisition Toolbox for image processing, and Signal Processing Blockset for signal analysis. These toolboxes extend MATLAB's applications across multiple engineering and scientific disciplines [16].

Another notable feature of MATLAB is its simplified coding structure, which eliminates the need for explicit array declarations before use. Unlike traditional programming languages such as Fortran and C, MATLAB allows users to write code more intuitively without requiring variable type definitions, thereby improving readability and reducing syntax complexity.

Moreover, MATLAB significantly enhances program development efficiency, as it provides built-in functions, a high-level scripting environment, and interactive capabilities. Compared to conventional programming languages, MATLAB enables faster development, testing, and implementation of computational models, making it a preferred choice for complex mathematical analysis, simulations, and algorithm development in engineering and scientific research.

2.3. Linear guide rails in PSD (Platform Screen Door)

In Platform Screen Door (PSD) systems, linear guide rails serve a critical function by ensuring the smooth and precise movement of the rail sliding block, which facilitates the opening and closing of the doors. The correct functioning of these guide rails is essential to maintain seamless operations and prevent potential malfunctions that could affect the overall system performance. Typically, the linear guide rail is positioned beneath the door structure, as depicted in Figure 1, and is primarily implemented in elevated area PSDs where enhanced stability and precision are required.

Beyond their mechanical function, PSDs incorporating linear guide rails also provide security and maintenance advantages. The controlled sliding mechanism reduces the risk of misalignment, ensuring consistent door movement and minimizing wear over time. Additionally, the design contributes to easier cleaning and maintenance, which enhances the overall reliability and longevity of the system [17]. As shown in Figure 2, the rail ends of the linear guide have been coated with zinc, which serves as a protective layer to improve corrosion resistance. This coating is particularly important in outdoor environments where exposure to moisture and varying temperatures could accelerate material degradation.

Figure 1. Linear guide rail location on the platform screen door

2.4. Contact stiffness in roller linear guide rails

The contact stiffness of roller linear guides is a key factor in determining the load distribution and elastic deformation of the rollers under applied forces. The roller linear guide consists of several critical components, including the rail, slider, roller, cage assembly, and endplate. This system facilitates precise and smooth linear motion by employing four rows of recirculating rollers, as illustrated in Figure 3. To enhance performance and minimize mechanical wear, cages are positioned between the rollers to prevent direct contact and reduce friction. This design improves load distribution and ensures consistent operation over extended periods. Additionally, the endplate is securely attached to the end of the slider, ensuring a stable and controlled recirculating motion of the rollers, which contributes to increased rigidity and durability of the system [6]. Figure 4 presents the design modeling dimensions of the linear guide rail, which is based on the structural representation shown in Figure 3.

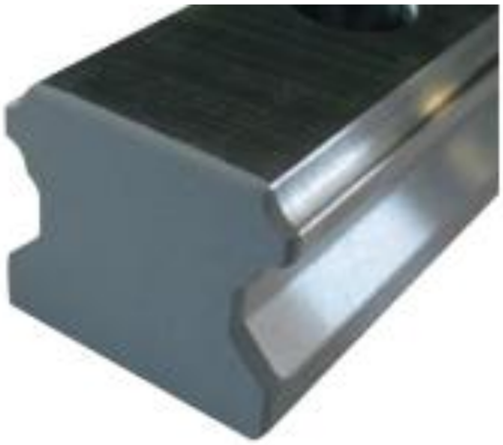


Figure 2. Linear guide rail physical appearance

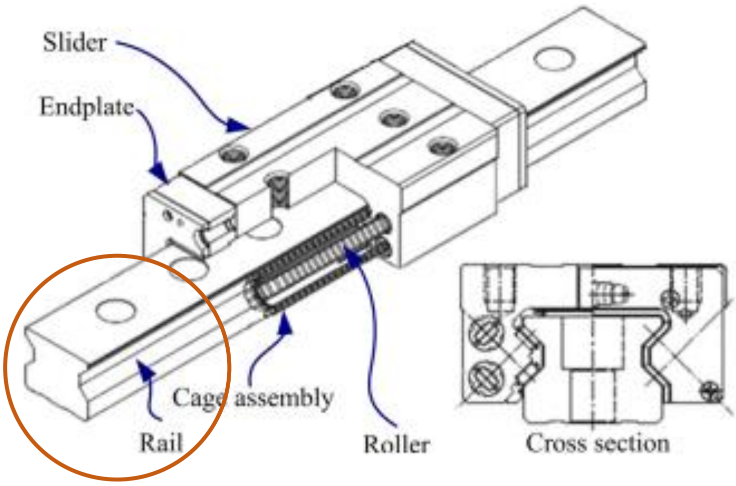


Figure 3. Structure of the linear guide rail

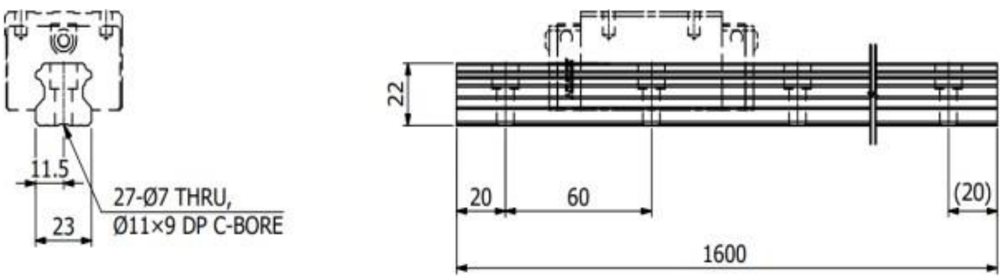


Figure 4. Dimensions of the guide rail

2.5. Linear Guide Rail Specifications

The technical specifications of the linear guide rail used in this study are presented in Table 1 and Figure 4. While Table 2 shows the material properties of the rail. These specifications define the dimensional, material, and performance characteristics essential for ensuring optimal functionality and durability of the guide rail system. The selected linear guide rail is designed to support high-precision movement, withstand applied loads, and minimize friction, making it suitable for Platform Screen Door (PSD) applications.

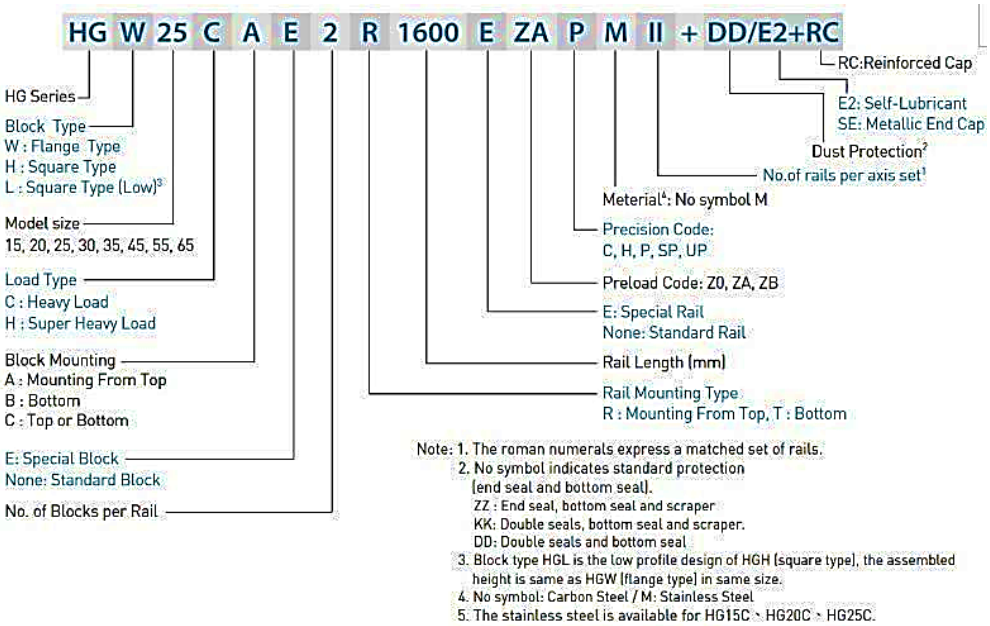


Figure 5. Linear guide rail serial code/symbol indication

Table 1. Linear guide rail material specifications

HGR25R1600CM	
Series	**HG**
Model Size	25
Rail Mounting Type	R
Rail Length	1600
Precision Code	C
Material	M-Stainless Steel
Dust Protection of Rail	Bold Cap
Type of E Dimension	Symmetrical (E1=E2)
Butt-Join	No

Table 2. Material stainless steel technical data

Name	**Stainless Steel**	
General	Mass density	8 g/cm^3
	Yield strength	250 MPa
	Ultimate tensile strength	540 MPa
Stress	Young's modulus	193 GPa
	Poisson's ratio	0,3 ul
	Shear modulus	74,2308 GPa

Figure 6. Linear guide rail model using Inventor simulation

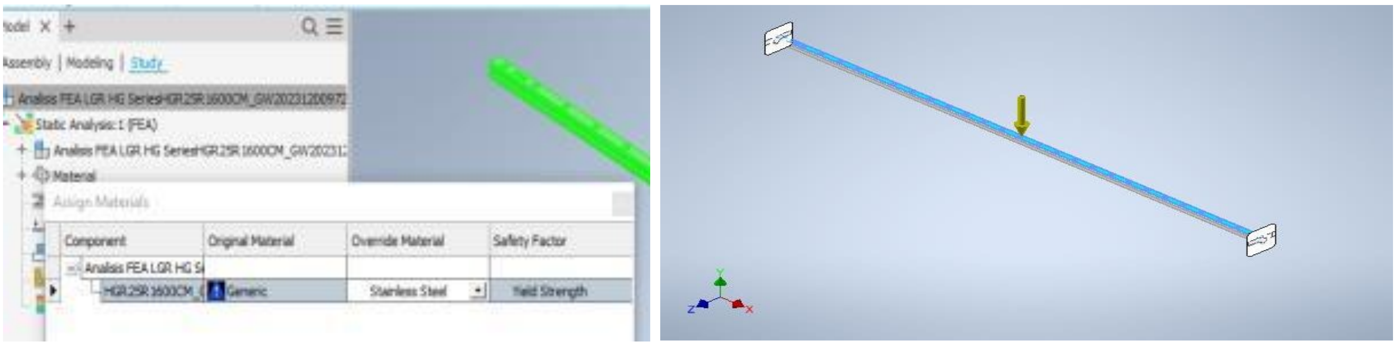


Figure 7. Configuration (left figure) and constraints (right figure) applied in Inventor simulation

3. Results and Discussion

3.1. Linear Guide Rail Design Modeling

Following the collection of technical data, the design modeling of the linear guide rail was conducted using Autodesk Inventor, as shown in Figure 6. This stage involved creating a 3D representation of the guide rail based on predefined technical specifications.

The material selected for the linear guide rail is stainless steel, as illustrated in Figure 7 and detailed in Table 2. Stainless steel offers several advantages, including high stability during operation, ease of maintenance, durability, and resistance to corrosion. The material properties of stainless steel include a density of 8 g/cm^3, a yield strength of 250 MPa, and an ultimate tensile strength of 540 MPa. Additionally, its mechanical properties include a Young's modulus of 193 GPa, a Poisson's ratio of 0.3, and a shear modulus of 74.23 GPa, making it suitable for structural applications requiring high strength and stiffness.

Subsequently, the modeling simulation was carried out to analyze the structural behavior of the linear guide rail under different loading conditions. Constraints were applied to specific regions of the model to ensure accurate simulation results, as shown in Figure 7. These constraints help in assessing the mechanical response of the guide rail, including stress distribution, displacement, and factor of safety, providing critical insights for performance evaluation and optimization.

After collecting technical data, we will next do design modeling using Inventor as seen in Figure 6. below.

3.2. Linear guide rail simulation results

The structural performance of the linear guide rail was evaluated through simulation, focusing on von Mises stress, displacement, and safety factor. The results provide insights into the mechanical response of the guide rail under different loading conditions.

Von Misses Stress

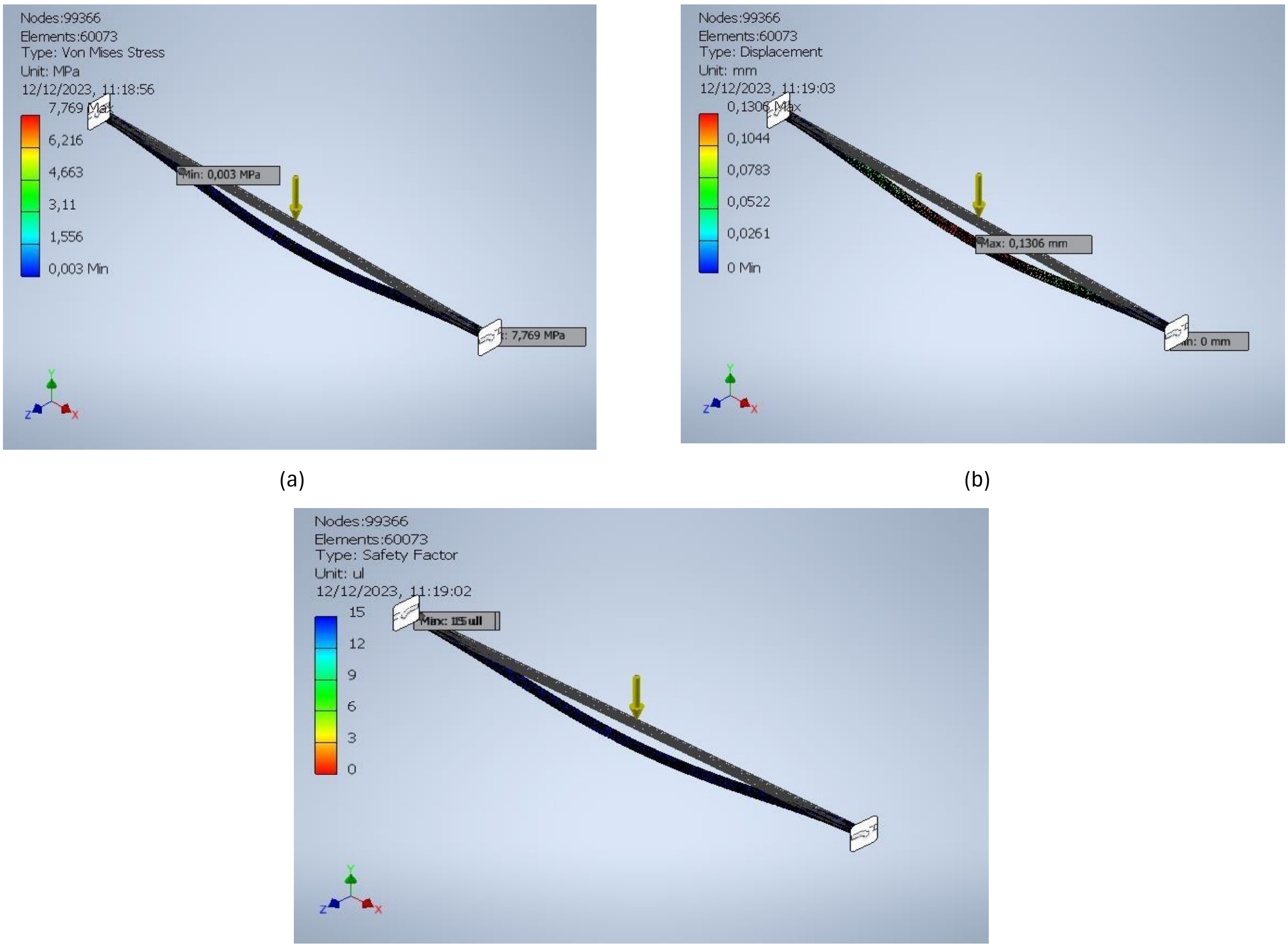
The von Mises stress is a key parameter in assessing material strength and failure potential. It represents the equivalent stress calculated based on the stress-strain relationship in the material. As shown in Figure 8(a), the maximum stress at a load of 36.94 N is 7.769 MPa, distributed along the length of the guide rail. Table 3 summarizes the stress values for varying loads of 36.94 N, 73.88 N, and 110.82 N. The results indicate that as the applied load increases, the stress values proportionally rise, with a maximum recorded stress of 23.595 MPa at 110.82 N.

Table 3. Stress results based on load applied

Load (N)	Maximum Stress (MPa)	Minimum Stress (MPa)
110.82	23.595	0.00974574
73.880	15.73	0.00649716
36.940	7.769	0.00320901

Displacements

The displacement analysis determines the extent of deformation experienced by the linear guide rail under loading. At a load of 36.94 N, the maximum displacement is 0.1306 mm, while the minimum displacement remains 0 mm, as illustrated in Figure 8(b). Table 4 presents the displacement values at different load levels, showing a direct correlation between the applied load and the resulting displacement. The highest displacement recorded is 0.3965 mm at a load of 110.82 N, confirming that increased loading results in greater deformation.



(a) (b) (c)

Figure 8. Simulation results from Autodesk Inventor; (a) Von Mises Stress; (b) Displacements; (c) Safety Factor

Table 4. Displacements results based on load applied

Load (N)	Displacement Maximum (mm)	Displacement Minimum (mm)
110,82	0,396496	0
73,880	0,264331	0
36,940	0,130555	0

Safety Factor

The safety factor is an essential criterion for determining the structural integrity of the linear guide rail. A system is considered safe when the safety factor exceeds a value of 1. As observed in Figure 8(c), the maximum safety factor remains at 15 for all load conditions. However, the minimum safety factor decreases as the applied load increases. At 110.82 N, the lowest safety factor recorded is 10.595, whereas at 73.88 N and 36.94 N, the minimum remains at 15. Table 5 outlines the safety factor values for different loading conditions, showing that higher loads reduce the safety margin, though the structure remains within acceptable limits.

Table 5. Safety factor results based on load applied

Load (N)	Safety Factor Maximum (ul)	Safety Factor Minimum (ul)
110.82	15	10.595
73.880	15	15
36.940	15	15

MATLAB linear regression model

Following the simulation results, a numerical approach was employed to analyze the data using a linear regression model in MATLAB R2018a. This method allows for the establishment of a mathematical relationship between the applied loads and the corresponding stress, displacement, and safety factor values. By implementing a regression analysis, trends in the data can be identified, providing insights into the mechanical behavior of the linear guide rail under different loading conditions.

As shown in Figure 9, a MATLAB script was developed to execute the regression analysis. The program takes the numerical results obtained from the simulations as input and applies the regression formula to generate predictive equations. These equations help in estimating the expected mechanical responses under varying conditions, facilitating further analysis and optimization of the guide rail design.

```
>> % Input data
F = 36.940; % N
A = 0.01; % m^2
L = 1.6; % m
deltaL = 0.001; % m

% Calculation
sigma = F / A;
epsilon = deltaL / L;
E = sigma / epsilon;

% Output
disp(['Tegangan = ', num2str(sigma), ' N/m^2']);
disp(['Regangan = ', num2str(epsilon)]);
disp(['Modulus Young = ', num2str(E), ' N/m^2']);
Tegangan = 3694 N/m^2
Regangan = 0.000625
Modulus Young = 5910400 N/m^2
```

```
>> % Data Simulasi
x = [7.769, 15.370, 23.595];
y = [36.940, 73.880, 110.82];

% Regresi linear
p = polyfit(x, y, 1);

% Plot data dan garis regresi
figure;
plot(x, y, 'o', x, polyval(p, x), 'r');
xlabel('Variabel X');
ylabel('Variabel Y');
title('Regresi Linear pada Bahan Mekanik');
legend('Data', 'Regresi Linear');
```

Figure 9. Values of stress, strain and Young's modulus, and stress linear regression script in MATLAB

Figure 9 presents the linear regression analysis of stress versus strain, obtained using MATLAB. The coefficient of determination (R^2=0.9994) indicates a strong correlation between the variables, signifying that the linear model accurately describes the relationship between stress and strain [18], [19]. The positive slope of 4.6523 suggests that as strain increases, stress increases proportionally, which aligns with Hooke's Law for linear elastic materials. The intercept of 1.3617 MPa indicates a minor initial stress, potentially due to preloading or residual stress in the material.

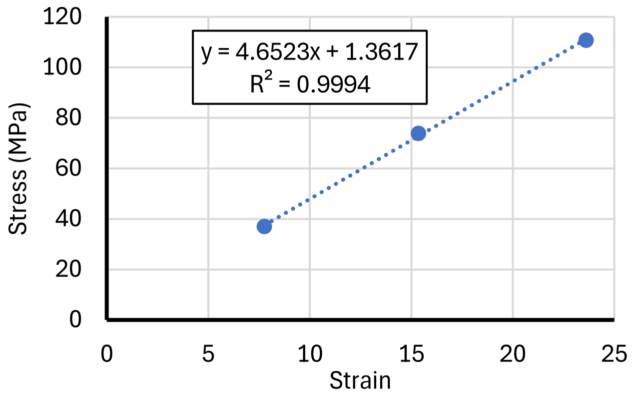


Figure 10. Linear regression plot

4. Conclusion

This study examined the mechanical properties of a stainless steel 304 linear guide rail using Autodesk Inventor and MATLAB. The design modeling and finite element simulation in Autodesk Inventor provided essential insights into stress distribution, displacement, and safety factors under varying loads. The results indicated that under the highest applied load, the maximum von Mises stress reached 23.595 MPa, while the maximum displacement was 0.396496 mm. Despite these values, the linear guide rail remains structurally sound, as the safety factor exceeds 1, with a minimum value of 10.595, ensuring reliable performance in practical applications. The simulation results confirmed that the von Mises stress remained well within the material's yield strength, preserving structural integrity under operational conditions. Additionally, the displacement analysis demonstrated minimal deformation, further validating the stability and durability of the linear guide rail. A MATLAB-based linear regression model was applied to assess the stress-strain relationship, yielding a high correlation coefficient (R^2=0.9994), reinforcing the accuracy of the numerical approach. Statistical validation further confirmed the reliability of the regression model in predicting material behavior. For future research, a more comprehensive analysis could be conducted by incorporating different load conditions, alternative materials, and comparisons with other simulation software. Such studies would enhance the optimization of linear guide rail designs, ensuring improved efficiency and longevity in Platform Screen Door (PSD) systems.

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