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Comparative Structural Analysis of Stainless Steel Shelving Designs Under Static Storage Loads Using ANSYS Workbench 2024 R1

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Abstract

The rapid growth of the manufacturing industry has increased the demand for efficient and reliable storage systems, making the structural strength of iron racks a critical factor in industrial and warehouse environments. This study aims to compare the structural performance of two iron rack designs with different shelf panel configurations, namely a solid flat plate design (Design 1) and a perforated/slat panel design (Design 2), under various static storage loads using ANSYS Workbench 2024 R1. Both designs were modeled in three dimensions using Autodesk Inventor with identical main frame dimensions and Stainless Steel as the material for all components. Finite Element Analysis (FEA) with the Static Structural module was applied by imposing four load variations ranging from 80 kg to 140 kg with fixed support boundary conditions at the rack feet. The parameters analyzed include Equivalent (von-Mises) Stress, Total Deformation, Safety Factor, and Equivalent Elastic Strain. The simulation results show that Design 1 produces a maximum von-Mises stress of 2.6354×10^6 Pa, a total deformation of 9.8967×10^{-6} m, and an equivalent elastic strain of 1.5243×10^{-5} m/m, all of which are lower than Design 2, which recorded values of 2.6894×10^6 Pa, 2.6174×10^{-5} m, and 1.6429×10^{-5} m/m, respectively. Both designs achieved a Safety Factor of 15, indicating a very high level of structural safety. Design 1 is recommended for applications requiring a flat and stable bearing surface, while Design 2 is more suitable for applications prioritizing air circulation and material efficiency.

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INTRODUCTION

The manufacturing industry has grown rapidly in recent years. This has led to an increasing demand for efficient, safe, and reliable storage systems. Steel shelving has become one of the most widely used solutions in warehouses, factories, distribution centers, and the modern retail sector. This is due to their ability to withstand heavy loads, their resistance to corrosion when equipped with appropriate coatings, and the ease of assembly and adjustment. As the volume of stored goods increases, the need for higher load-bearing capacity also rises, making the structural strength of steel shelving a critical factor to consider.

Structural failures in storage racks can have serious consequences, including damage to goods and potential hazards to worker safety. Common failure phenomena include bending of support columns, breakage of load-bearing components, and cracks at joints due to stress concentration. Therefore, a thorough understanding of stress distribution, deformation, and safety factors under various loading conditions is essential as the foundation for designing safe and high-quality steel shelving.

The structural strength analysis in this study was conducted using both theoretical and numerical approaches with Finite Element Analysis (FEA)-based software, namely Ansys

Workbench. The Finite Element Analysis (FEA) method was used to analyze stresses and other characteristics (Lu et al., 2019). Optimizing the design, performing theoretical calculations, accounting for material strength (Lai et al., 2019), (Sner et al., 2021) and confirming loading forces through regression analysis (Azimi-nejadian et al., 2019) are all benefits of Finite Element Analysis (FEA). This analysis provides an overview of the object's actual conditions, eliminating the need for direct physical testing. The analysis is conducted by creating a 3D model of the bicycle frame using CAD software, specifically Autodesk Inventor and applying loads similar to real-world conditions. Additionally, various types of materials are tested to determine which offers the best balance between strength and lightness. From the simulation results, maximum stress, total deformation, and the safety factor will be examined to evaluate the frame's performance.

A study conducted by Kumar & Ramesh (2019) examined the optimization of steel storage rack columns using ANSYS. The results showed that the cross-sectional profile has a significant effect on the column's axial load-bearing capacity. However, there has been little research that comprehensively and systematically compares various steel rack design models against different storage load variations, particularly using Autodesk Inventor 3D modeling and ANSYS Workbench analysis within a structured research framework.

This study aims to deepen our understanding of how design and materials affect the strength of steel shelving frames. The findings from this analysis can serve as a basis for optimization to make the structure stronger, more effective, and more durable. Furthermore, the simulations conducted demonstrate the application of concepts such as normal stress, bending moment, strain, and elastic deformation in the study of mechanics and materials science. By utilizing a numerical approach, this study not only contributes to technological development but also demonstrates that the use of ANSYS software can improve efficiency and accuracy in the design process. The results of this study are expected to serve as a useful technical reference for designers and users of steel shelving in industrial and warehousing environments.

RESEARCH METHODS

The research method may have sub-subs. Avoid using bullets and numbering in the article, it is better to present it in paragraph form. The following is an example of presenting a numbering system in paragraph form.

This study employs a numerical simulation approach based on Finite Element Analysis (FEA) to analyze the structural strength of two stainless steel shelving designs under varying static storage loads. FEA is a numerical method that divides the structural domain into small elements that can be solved mathematically, thereby enabling accurate prediction of structural response without the need for direct physical testing (Al-Yacouby et al., 2022). This approach has proven effective and efficient in evaluating stress distribution, deformation, and safety factors in various steel structure designs (Seul et al., 2023).

In general, the research methodology of this study follows the steps below: (1) 3D geometric design of both rack designs using Autodesk Inventor software, (2) determination of stainless steel material properties, (3) determination of loading conditions and boundary conditions, and (4) execution of FEA simulation using ANSYS Workbench 2024 R1 with the Static Structural module to obtain Equivalent (Von Mises) Stress, Total Deformation, Safety Factor, and Equivalent Elastic Strain.

A. Design of Steel Shelving Geometry

Two variations of metal shelving designs were created using Autodesk Inventor Computer-Aided Design (CAD) software. The 3D modeling was performed with careful attention to the geometric details of each structural component of the shelving, including vertical columns, horizontal beams, shelf panels, and the connections between components. The development of an accurate 3D model is crucial as the basis for static simulation, as geometric accuracy directly affects the accuracy of stress distribution in critical areas of the structure (Gelaziene & Milasiene, 2023).

The main difference between the two designs lies in the configuration of the shelf boards, while the dimensions of the main frame were made identical to ensure a fair comparison in this comparative analysis. The following is a description of each design.

1. Design 1: Shelving Unit with Solid Panel Shelves

This design uses solid flat steel plates as shelving panels on each storage level. This configuration provides a continuous, flat, and even bearing surface for the stored load, ensuring that the load is uniformly distributed across the entire surface of the shelf plate before being transferred to the support beams. The rack components, including the pallet beams and connecting elements, are designed to ensure adequate load distribution throughout the structural system. Storage beams in racks generally have a boxed cross-section defined based on the need to ensure adequate support for pallet units, so that structural integrity at each storage level can be optimally maintained (Bernuzzi et al., 2021). Full steel plate rack designs are generally chosen for storing small or irregularly shaped items that require a flat and stable support surface. The model of Design 1 can be seen in Figure 1.

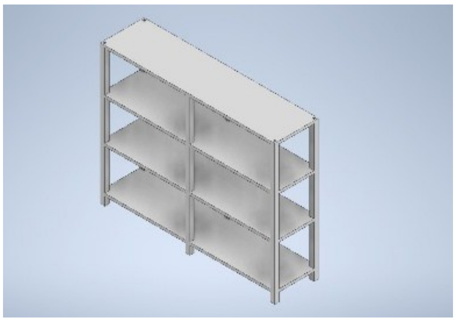

Figure 1. Model of a Flat Plate Shelving Unit

2. Design 2, Shelves with Perforated Panels or Lattice Shelves

This design uses plate-like shelf panels with longitudinal slots that are open at each level. This configuration causes the load distribution to be channeled through the solid sections between the slots, resulting in a different stress concentration compared to a solid-plate design (Wu et al., 2022). Perforated designs are generally chosen for air circulation needs, to reduce the total weight of the shelving, or for storing large items with a sufficiently wide contact area.

Both designs have an identical main frame configuration, consisting of four levels of shelves with dimensions as listed in Table 1. The similarity in frame dimensions serves as a control variable in this comparative study, so that differences in simulation results can be directly attributed to differences in shelf board configuration between the two designs (Ghazali et al., 2021). The model of Design 2 is shown in Figure 2.

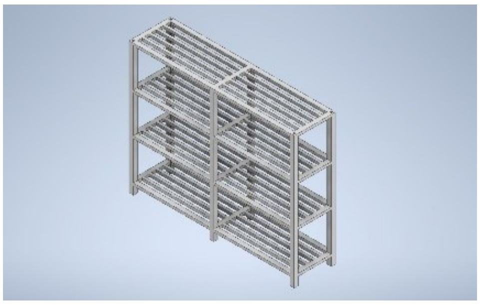

Figure 2. Model of the Lattice Shelving Unit

Table 1. Dimensional Specifications for the Two Metal Shelving Designs

Dimensional Parameters	Description	Value (mm)
Total Shelving Height	From the floor to the top of the post	1600.00
Total Shelving Width	Distance between the outer edges of the left and right posts	2000.00
Shelving Depth	Distance between the outer edges of the front and back posts	500.00
Distance Between Uprights (Internal)	Clear distance between posts (width)	1900.00
Upright Profile Dimensions	Cross-section of vertical posts	50 x 50
Horizontal Beam Thickness	Thickness of shelf support beams	30.00
Distance Between Levels	Clear distance between shelves	465.00
Lower Leg Height	Distance from the floor to the bottom shelf	100.00
Slot Width (Design 2)	Width of the slot openings on the slatted shelves	56.00
Number of Levels	Number of shelf levels	4 levels
Shelf Board Type (Design 1)	Shelf configuration	Solid plate
Shelf Board Type (Design 2)	Shelf configuration	Perforated plate (slat)

B. Determination of Material Parameters

The material used for all components of both shelf designs is stainless steel, which was selected from the built-in material library in ANSYS Workbench. The selection of stainless steel as the sole material for both designs is based on several technical and practical considerations, namely: (1) high corrosion resistance makes stainless steel suitable for use in warehouse and industrial environments that are potentially exposed to moisture; (2) adequate mechanical strength to support heavy storage loads; (3) ease of fabrication and material availability on the market; and (4) its common use as a material for storage racks in the food, pharmaceutical, and logistics industries (Jindra et al., 2021).

The stainless steel referred to in this study is austenitic stainless steel, which contains at least 10.5% chromium and nickel, resulting in excellent corrosion resistance. In the context of FEA simulation, the material's mechanical properties are modeled as a linear elastic isotropic material, meaning the material is assumed to be homogeneous (uniform throughout its volume), isotropic (possessing the same mechanical properties in all directions), and behaves linearly elastically up to its yield strength (Wibowo et al., 2025). This assumption is valid for static load simulations below the material's elastic limit.

The mechanical properties of the stainless steel material used in this simulation are sourced from the ANSYS Workbench material library and are presented in Table 2.

Table 2. Mechanical Properties of Stainless Steel (ANSYS Material Library)

No.	Mechanical Properties	Value	Unit
1	Young's Modulus (E)	1.93×10^5	MPa
2	Poisson's Ratio (ν)	0,31	-
3	Bulk Modulus (K)	$1{,}693 \times 10^5$	MPa
4	Shear Modulus (G)	73,664	MPa
5	Tensile Yield Strength (σy)	207	MPa
6	Compressive Yield Strength	207	MPa
7	Tensile Ultimate Strength (σu)	586	MPa
8	Density (ρ)	7,750	kg/m³
9	Material Model	Isotropic Linear Elastic	-

Young's Modulus (E) represents a material's stiffness against axial elastic deformation; Poisson's Ratio (ν) represents the ratio of lateral strain to axial strain; and Tensile Yield Strength (σy) is the stress threshold at which the material begins to undergo permanent plastic deformation. This yield strength value serves as the primary reference for calculating the safety factor during the post-processing stage of the simulation (Ghazali et al., 2021).

C. Loading and Boundary Conditions

The determination of loading and boundary conditions is a critical step in FEA simulation, as the accuracy in representing actual operational conditions directly affects the validity and accuracy of the simulation results (Wibowo et al., 2025). In this study, the loading conditions were modeled as static equilibrium conditions, i.e., conditions in which the load is applied gradually and the structure is in static equilibrium without inertial components.

1. Boundary Conditions

The boundary conditions applied to the simulation model are fixed supports at the four points where the rack legs contact the floor. Fixed supports restrict all degrees of freedom (DOF) at those points, namely translation in three directions (X, Y, and Z axes) and rotation about those three axes. The use of fixed supports aims to simulate the condition of a rack that is stably mounted on a rigid concrete floor surface, as is the case with operational racks in warehouse and industrial environments (Firouzianhaij et al., 2022).

2. Loading Conditions

The load applied to the model is a uniform static compressive load applied across the entire surface of the shelf panels on each level. This uniform load distribution represents the ideal condition of goods stored evenly across the entire shelf surface. This uniform loading approach for the rack structure aligns with research (S. W. Liu et al., 2021), which applied a uniformly distributed load to beam elements in the analysis of steel storage racks.

The load applied to the structure is converted from the mass of the load in kilograms (kg) to the compressive force in Newtons (N) using Newton's second law:

$$F = m \times g$$

Where F is the compressive force (N), m is the total mass of the stored load per level (kg), and g is the standard acceleration due to gravity of

9.81 m/s². This conversion is important for obtaining an accurate stress distribution at the interface between the shelf boards and the support beams. The load variations tested in this study range from 100 kg to 500 kg, in 100-kg intervals, as shown in Table 3.

Table 3. Variations in Static Loads Applied in the Simulation

No.	Mass Load (kg)	Compressive Force (N)	Description
1	80	784.8	Light load on the top shelf
2	100	981	Light-to-medium load on the third shelf from the bottom
3	120	1,177.2	Medium-to-heavy load on the second shelf from the bottom
4	140	1,373.4	Heavy load on the bottom shelf

The load range of 80–140 kg was selected based on the typical load capacity of commercial steel shelving used in warehouse and industrial settings, while also taking into account the load-bearing limits of the stainless steel material used. Each load variation was simulated separately for each design, resulting in a total of 8 simulation scenarios (4 load variations × 2 designs) that yielded comprehensive comparative data.

D. Data Collection via FEA Simulation

Data collection was performed through numerical simulations using ANSYS Workbench 2024 R1 software with the Static Structural module. ANSYS Workbench was selected for its ability to perform FEA-based structural analysis accurately and efficiently, as well as for its integration with CAD software such as Autodesk Inventor (Firouzianhaij et al., 2022). The simulation procedure followed a standard FEA workflow consisting of three main stages, as described below.

1. Definition of Materials

The material properties for stainless steel are first defined in the Engineering Data module in ANSYS Workbench according to the parameters listed in Table 2. This material is then assigned to all components of the rack's solid body model, as shown in Figure 3.

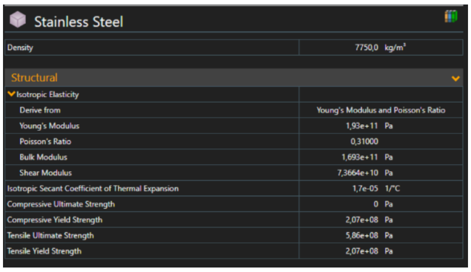

Figure 3. Stainless Steel Material Properties

2. Import geometry

The 3D models of the two shelf designs created in Autodesk Inventor were imported into ANSYS Workbench via the geometry import interface. The geometric models for each design consist of several solid bodies (posts, beams, shelf boards) that are assembled into a single complete structural assembly. Geometric integrity was verified after the import process to ensure there were no geometric errors that could affect meshing accuracy. Figure 4 shows the imported geometry model.

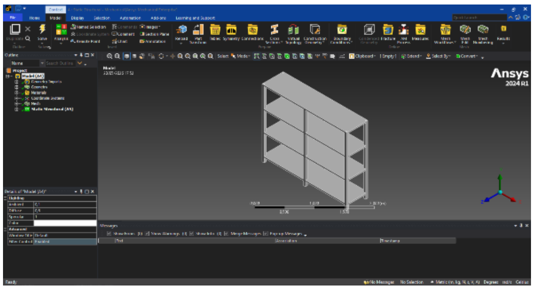

Figure 4. Importing the Shelving Unit Geometry from Autodesk Inventor

3. Meshing Process

Meshing is the process of dividing a continuous geometric domain into small interconnected elements, forming a finite element mesh. Mesh quality significantly affects the accuracy and convergence of FEA simulation results (Gelaziene & Milasiene, 2023). The smaller the mesh size, the more accurate the results will be; however, the simulation will take longer (García Pérez & Vakkilainen, 2019). There are many meshing methods available in ANSYS, such as Hex Dominant, Sweep, MultiZone, and others. In this study, the mesh method used was Tetrahedrons with an element size of 5 mm. The other settings were the ANSYS defaults. A visualization of the meshed model can be seen in Figure 5.

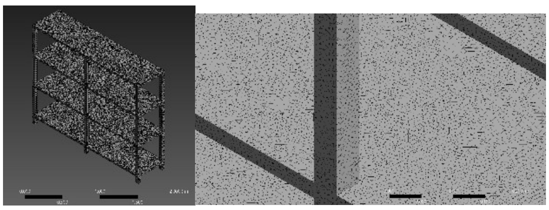

Figure 5. The Meshing Process on the Model

4. Enter Static Structure

At this stage, the geometric model is defined or assigned certain conditions. The shelf is subjected to four types of forces, as shown in Table 3. It is also provided with fixed supports at the base of the shelf.

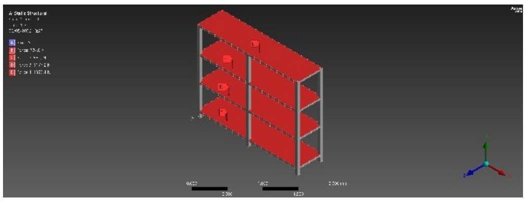

Figure 6. Design conditioning 1

Figure 6 shows the loading conditions, specifically the application of force and fixed supports to the model. The red lines indicate the uniform distribution of force across all surfaces.

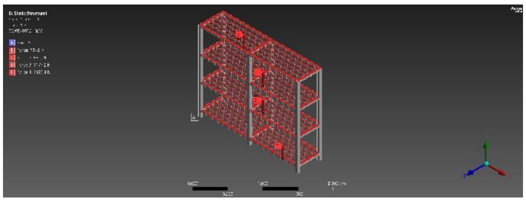

Figure 7. Design conditioning 2

Figure 7 shows the loading conditions, specifically the application of force and fixed supports to the model. As with Model 1, the red color in Model 2 indicates that the force is distributed evenly across all surfaces.

5. Equivalent (von-Mises) Stress

One of the key parameters analyzed and compared between Design 1 and Design 2 in this study is the Equivalent (von Mises) Stress. This analysis is used as the primary indicator of stress distribution in the rack structure. The von Mises criterion states that material failure will occur if the equivalent von Mises stress exceeds the material's yield strength.

6. Total Deformation

Another key parameter analyzed between Design 1 and Design 2 in this study is total deformation. This analysis measures the magnitude of total displacement at each point in the structural model resulting from the applied load. The maximum total deformation value indicates the point on the structure that experiences the greatest positional change due to the load, which serves as an indicator of the overall stiffness of the shelving structure (Wibowo et al., 2025).

7. Safety Factor

The safety factor is also used as an analytical parameter to compare Design 1 and Design 2. The safety factor is a ratio that indicates how strong a lifting device is relative to the maximum load it is permitted to lift. The safety factor is important because it ensures that the lifting device has a sufficient safety margin to handle the load safely. In this study, the safety factor was used as the primary criterion for determining which of the two designs being compared is safer and more reliable.

8. Equivalent Elastic Strain

The final parameter used to analyze and compare Designs 1 and 2 is equivalent elastic strain, a single scalar value that summarizes the various complex strain components resulting from multi-directional loading into a single quantity. This quantity is based on a yield criterion (such as von Mises) and is used to ensure that the material's deformation remains within its elastic limit (i.e., it can return to its original shape). In computer simulations (such as FEA), a material experiences stress and strain in multiple directions simultaneously. Rather than examining numerous strain values separately, Equivalent Elastic Strain provides a single representative number to simplify evaluation.

RESULTS AND DISCUSSION

The conditioned model will then be processed or analyzed by Ansys. The conditioning consists of force and fixed support, as mentioned in the previous subsection. The results of the analysis can be seen in Figures 8, 9, 10, and 11 below.

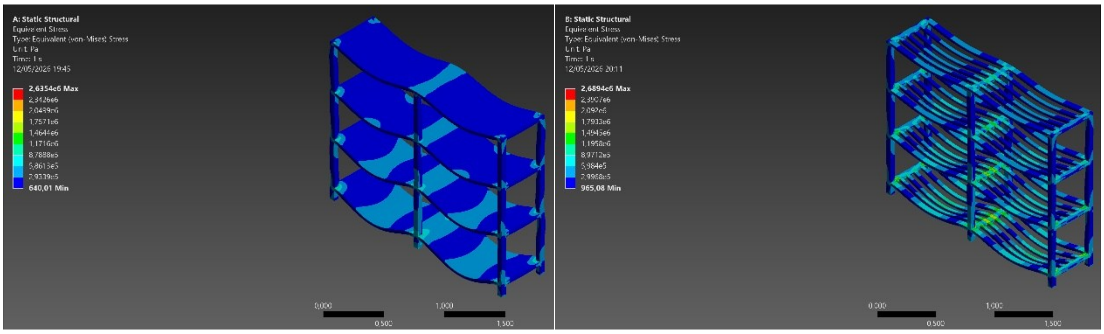

Figure 8. Equivalent (von Mises) Stress Analysis for Designs 1 and 2

Figure 8 shows the distribution of equivalent stress (von Mises) in Design 1 and Design 2 based on the results of the ANSYS simulation. The colors in the model indicate the level of stress concentration caused by the applied load, allowing for a comparison of the two designs' ability to withstand stress.

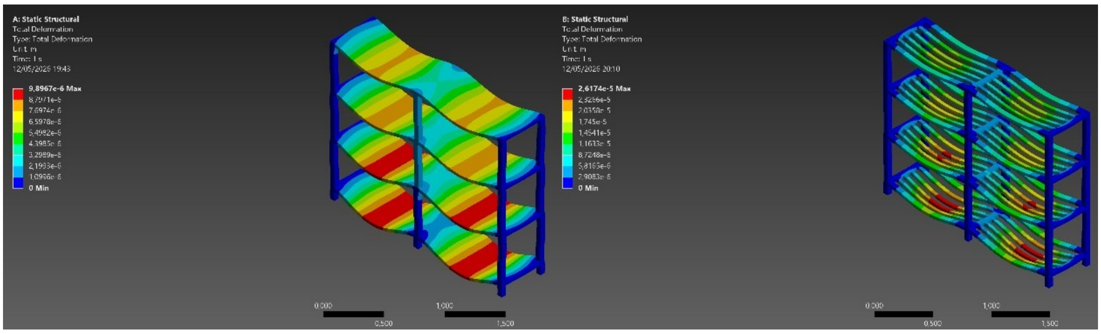

Figure 9. Total Deformation Analysis for Designs 1 and 2

Figure 9 shows the results of the total deformation analysis for Design 1 and Design 2 using ANSYS. The color distribution indicates the magnitude of deformation occurring in the structure due to loading, thereby revealing the stiffness of each design.

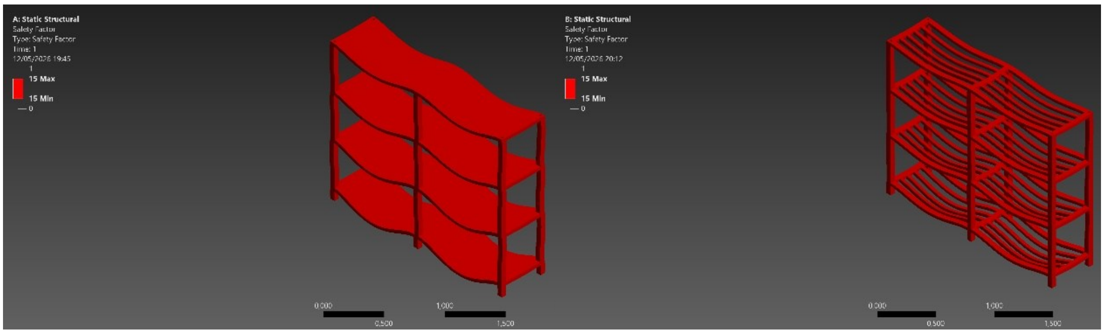

Figure 10. Safety Factor Analysis for Designs 1 and 2

Figure 10 shows the distribution of the safety factor for Design 1 and Design 2 based on ANSYS simulation results. The safety factor is used to evaluate the structural safety margin against material failure caused by the applied load.

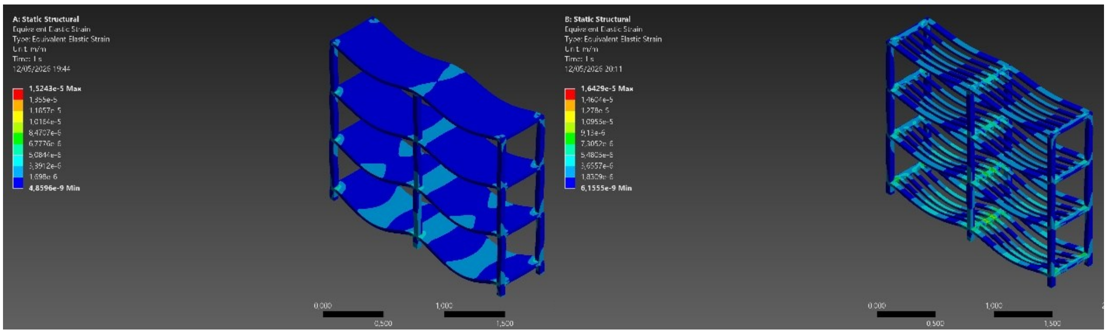

Figure 11. Equivalent Elastic Strain Analysis for Designs 1 and 2

Figure 11 shows the distribution of equivalent elastic strain in Design 1 and Design 2 based on the results of the ANSYS analysis. These results show the level of elastic strain that occurs in the material when it is subjected to loading.

A. Analysis of the Properties of Stainless Steel

This simulation uses stainless steel with isotropic elastic properties. This material has a density of 7750 kg/m^3 and a Young's modulus of 1.93 x 1011 Pa. The selection of this material is based on its superior strength-to-weight ratio and excellent corrosion resistance for structural components (Degtyarev, 2021). The material's elastic limit is determined by a tensile yield strength of 2.07 x 10^8, which serves as a critical parameter to ensure the rack does not fail structurally under load. The use of accurate material data in numerical simulations is crucial for generating structural behavior predictions that closely approximate actual field conditions (Leng et al., 2024).

B. Simulation Results and Comparison of Structural Performance

This study compares two geometrically distinct shelf designs to evaluate their mechanical response to static loads. A summary of the numerical simulation results using Ansys Workbench 2024 R1 is presented in Table 4 below.

Table 4. Summary of Simulation Results

Parameter Analysis	Design 1 (Max)	Design 2 (Max)	Unit
Material	Stainless Steel	Stainless Steel	-
Equivalent (von-Mises) Stress	2.6354 x10^6	2.6894 x 10^6	Pa
Total Deformation	9.8967 x10^{-6}	2.6174 x 10^{-5}	m
Safety Factor	15	15	-
Equivalent Elastic Strain	1.5243 x 10^{-5}	1.6429 x 10^{-5}	m/m

Based on the stress contour visualization, Design 1 produced a maximum stress value of 2.63 MPa, while Design 2 showed a slightly higher stress value of 2.68 MPa. This phenomenon indicates that the differences in profile geometry between the two designs have a direct impact on the stress concentration distribution (Q. Zhang et al., 2023).

In terms of stiffness, Design 1 exhibits more stable performance with a deformation value of 9,89 x 10^{-6}. his contrasts with Design 2, which experiences greater deformation at 2.61 x 10^{-5}. Structural integrity in withstanding vertical loads is significantly influenced by variations in the cross-sectional shape of the profile used (L. Zhang et al., 2022). Overall, despite the difference in deformation values, both designs have a Safety Factor of 15, indicating a very high level of safety (Souto et al., 2022).

C. Comparison of Geometry and Material Properties

This study compares two types of stainless steel shelving units that were modeled using SolidWorks CAD software. The two types are a shelving unit with a solid plate surface, referred to as the Flat Plate Shelving Design, and a shelving unit with a surface consisting of parallel bars (slat/grating design), referred to as the Open Grating Shelving Design. Both feature a four-tier shelf configuration with identical outer frame dimensions, so the primary difference lies solely in the geometric shape of the shelf surface itself. These geometric variations directly influence load distribution patterns, total structural mass, airflow, and the overall mechanical performance of the shelves. Therefore, a thorough understanding of the unique characteristics of each design is a crucial step before determining the most appropriate application for use.

To ensure a fair comparison, both design variants use stainless steel with exactly the same mechanical properties. These properties include a density of 7750 kg/m³, a Young's modulus of 1.93×10^{11} Pa, and a Poisson's ratio of 0,31. Additionally, this material has a tensile yield strength of 2.07×10^{8} Pa (207 MPa) and a tensile ultimate strength of 5.86×10^{8} Pa (586 MPa). These figures indicate that the material used is capable of withstanding extremely high tensile loads before undergoing permanent deformation or total failure. Thanks to these superior properties, stainless steel is classified as a high-strength material that is highly suitable for use in load-bearing structures such as industrial shelving (Arrayago et al., 2015).

The mechanical properties mentioned above are consistent with the characteristics of austenitic stainless steel, such as AISI 304 or AISI 316. These two grades are widely recognized in the industrial sector for their ability to combine good mechanical strength with very high corrosion resistance. The stress-strain curve of this alloy has been extensively studied and documented through various experimental and numerical approaches. Accurate mapping of the curve is crucial when used as a basis for Finite Element Analysis (FEA) in the rack design process. Without a proper understanding of material behavior, simulation results may deviate significantly from actual field conditions (Arrayago et al., 2015).

One of the main reasons for choosing stainless steel is its superior resistance to corrosion. Work environments in the food and pharmaceutical industries, as well as general storage areas, often involve exposure to water vapor, mild chemicals, and routine cleaning processes. With its superior corrosion resistance, this material ensures that the surface of the shelves does not degrade, which could potentially contaminate the products stored on them. In addition, stainless steel also has high mechanical strength, enabling it to withstand both static and dynamic loads over extended periods (Yong et al., 2008). The factor of ease of maintenance (cleanability) is a crucial added value for applications in environments with strict hygiene standards.

According to (Yong et al., 2008), stainless steel offers the advantage of lower life-cycle costs compared to alternative materials such as carbon steel or aluminum. Although the initial cost of stainless steel is generally higher, its low maintenance and replacement costs make it more cost-effective in the long run. In corrosive environments, carbon steel requires periodic recoating or painting, whereas stainless steel does not require such additional treatments. This is particularly relevant for storage racks that are expected to operate for years without requiring major repairs. Thus, the higher initial investment can be recouped through savings in operational and maintenance costs over the product's lifespan.

The open lattice rack design offers a better strength-to-weight ratio compared to flat plate designs. By using parallel bars separated by gaps, the required material volume is significantly reduced without significantly compromising structural rigidity. This design also allows for natural liquid drainage, as water or other liquids can flow directly through the available gaps. Additionally, air circulation is improved, which is a key factor in preventing mold or bacterial growth on products stored on the shelves (Q. Liu et al., 2020). However, the lattice design has the potential to create higher stress concentrations at the support points of the bars, particularly when subjected to concentrated loads in specific areas.

The geometric differences between the two designs also impact the fabrication process and overall production costs. The Flat Plate Shelving design is relatively simpler in terms of material cutting, as it requires only a single sheet of plate cut to the desired dimensions. However, the larger volume of material directly increases raw material costs. Conversely, the Open-Grid Shelving Design requires a more complex process of cutting and assembling bars, but it can reduce material consumption by up to 30–40%. The decision to choose one design over the other must consider not only technical aspects but also the economic aspects of the product's entire lifecycle. A comprehensive evaluation is essential to determine which design is most advantageous for a specific application.

D. The Stress-Strain Relationship and Validation of Hooke's Law

According to (Agrawal et al., 2022) a finite element analysis study of steel structural components emphasizes that an equivalent elastic strain parameter in the order of 10^{-5} m/m indicates that the material is operating well below its elastic limit, so there is no risk of permanent deformation. The elastic strain values obtained for Design 1 (1.5243×10^{-5}) and Design 2 (1.6429×10^{-5}) in this study fall within a range consistent with these findings, confirming that both designs operate entirely within the linear elastic zone of the stainless steel material.

The results of the numerical simulation obtained using ANSYS Workbench 2024 R1 show that the behavior of stainless steel conforms to the basic principles of materials mechanics. In the elastic range, the relationship between stress and strain is described by Hooke's Law, which is expressed as:

$$\sigma = E \times \varepsilon$$

where σ is the equivalent stress in Pascals (Pa), E is the Young's modulus of the material, and ε is the dimensionless equivalent elastic strain.

Research conducted by (Khaleel, 2023), shows that stress analysis of gas turbines made of various materials, including stainless steel, using the finite element method indicates that stainless steel consistently produces lower deformation compared to other materials under equivalent loading conditions. This is due to the high Young's modulus of stainless steel, which allows the material to retain its shape more effectively. This finding aligns with the performance of Design A in this study, which showed minimum deformation on the order of 10^{-6} m.

E. Analysis of Structural Deformation and Stiffness

Total deformation is one of the critical parameters in structural performance evaluation. Simulation results show that Design A produces a maximum deformation of 9.8967 × 10-6 m, while Design B experiences a larger deformation of 2.6174 × 10-5 m. The approximately 2.6-fold difference in deformation between these two designs is closely related to variations in the cross-sectional geometry of each design's profile.

In the theory of materials mechanics, structural stiffness is defined as a structure's ability to resist deformation when subjected to a load. Stiffness is influenced by two main factors: material properties (Young's modulus) and cross-sectional geometry (moment of inertia). Since both designs use identical materials, the significant difference in deformation values between Design A and Design B is solely due to differences in the distribution of the profile geometry, which affects the effective moment of inertia of the cross-section (Machado et al., 2022).

These findings are consistent with the principle described by (Machado et al., 2022) that variations in cross-sectional geometry have a direct influence on a structure's deformation response when subjected to static vertical loads. Designs with a more optimal mass distribution relative to the neutral axis tend to have a higher moment of inertia, resulting in smaller deflections. Deformation values for both designs in the range of 10-5 to 10-6 m indicate that both structures operate well below the material yield limit, indicating structurally safe designs.

F. Structural Analysis and Safety Factor

From a structural engineering perspective, flat-plate shelving designs exhibit a more uniform stress distribution when subjected to evenly distributed loads. This is due to the presence of a continuous bearing surface without gaps or holes on the shelf's surface. Any load placed on the shelf is immediately distributed across the entire plate area before being transferred to the supporting frame at the edges. Consequently, the peak stresses generated in the material tend to be lower compared to a lattice design under an equivalent total load. This characteristic makes the flat plate design a very safe choice for applications requiring the ability to withstand large, evenly distributed loads (Gardner & Nethercot, 2004).

The design of an open-grid shelf distributes the load through the contact points between the parallel bars and the objects placed on top of them. The load does not spread continuously but is concentrated in the areas where the bars come into direct contact with the bottom of the object. As a result, local stresses at the contact points can be significantly higher than the average stress across the entire structure. This condition requires special attention during the finite element analysis process to ensure that these local stresses remain below the material's safe limit. Designs that ignore this stress concentration effect have the potential to cause permanent deformation or even local failure at relatively low load levels.

Under concentrated loading conditions, the Open Lattice Shelving Design generates higher local stresses at the contact points compared to the Flat Plate Shelving Design. Loads concentrated at a single point or in a narrow area, such as those caused by trolley wheels or the legs of heavy equipment cannot be effectively distributed due to the limited contact area with the lattice members. This situation requires local reinforcement measures, such as adding load-distributing plates on top of the grid surface. Another alternative is to modify the grid geometry to have a higher bar density in areas predicted to receive concentrated loads. Without such special treatment, the risk of permanent indentation in the grid bars becomes very high.

The Faktor of Safety (FoS) is a critical parameter in structural design evaluation that represents the ratio of a material's capacity to the maximum actual stress applied. With a yield strength of 207 MPa for stainless steel, flat plate rack designs tend to have a higher FoS by default. This is due to the greater mass of the material, which results in lower actual stresses at the same design load level. However, an excessively high FoS value often indicates over-design or inefficient material usage. Over-design not only wastes material but also increases the structure's weight, which can complicate the installation and relocation of the shelving (Arrayago et al., 2015).

For storage rack systems, the evaluation of static and dynamic loads is a key factor in determining a safe safety factor (FoS). Storage racks are often subjected to cyclic loading due to the repeated daily processes of storing and retrieving goods. Dynamic loads that occur when goods are placed on or removed from the racks can generate an impact factor that increases the instantaneous stress beyond the nominal static load. Therefore, the FoS value for storage racks is generally set higher than that for typical static structures.

G. Evaluation and Recommendations for the Best Design Based on Application

From both a technical and operational cost perspective, the Open Mesh Shelving Design offers clear advantages for general storage applications that prioritize air circulation. Examples of its applications include the storage of dry food products in food industry warehouses, pharmaceutical products that require drying before packaging, and kitchen utensils that have just been washed and are still wet. The gaps in the grid surface allow air to flow freely, preventing moisture from becoming trapped and minimizing the risk of mold or bacterial growth. This design is also ideal for use in frequently wet areas, such as equipment washing rooms, as water can drain directly out through the gaps. With these characteristics, the potential for water pooling, which can cause corrosion or contaminate products is drastically reduced.

In addition, open-shelf designs offer a better strength-to-weight ratio compared to flat-plate designs. Their lighter weight makes them easier to transport, install on-site, and relocate if the room layout changes.

Nevertheless, flat-plate shelving remains the more appropriate choice for certain conditions that cannot be accommodated by grid-style shelving. The first such condition is when the shelves are used to store small items that risk falling through the grid openings, such as microsurgical instruments, miniature electronic components, or precision parts smaller than the width of the openings. Losing such items is not only financially detrimental but can also endanger patient safety (in the case of medical devices) or disrupt production processes. The second condition is when a completely flat and hygienic shelf surface is required, free of gaps that could serve as hiding places for dirt or microorganisms. Several regulations in the pharmaceutical sector explicitly require surfaces that are continuous, easy to clean, and free of gaps or hard-to-reach corners (Gardner & Nethercot, 2004).

The third scenario in which flat-plate rack designs excel is in applications involving extremely high concentrated loads without local reinforcement. A concrete example is the storage of metal drums containing heavy liquids, where the bearing surface consists only of a narrow base ring, causing the load to be concentrated in a very limited area. In such situations, a truss design would experience extreme stress concentrations on the few members directly bearing the load, which could lead to local buckling or even structural failure. In contrast, a flat plate is capable of distributing the concentrated load over a wider area through plate bending mechanisms, resulting in lower maximum stresses. Although this difference can be addressed by adding a load-distributing plate on top of the truss surface for specific applications, the addition of such a component will inevitably increase costs and diminish the material efficiency advantage of the truss design.

The final decision between a flat-plate rack design and an open-grid rack design should be based on the results of a comprehensive finite element analysis (FEA) specific to the actual conditions. Such simulations must account for the loading scenarios the rack will actually experience during its operational lifespan, including variations in load magnitude and loading cycle frequency. By adopting a systematic, evidence-based, and well-documented approach, the most optimal design for each specific application can be determined with a high degree of confidence.

CONCLUSION

This study successfully compared the structural performance of two stainless steel shelving designs using Finite Element Analysis (FEA) simulation via ANSYS Workbench 2024 R1 software. Based on the simulation results, Design 1 (Flat Plate/Solid Panel Shelving) demonstrated superior structural performance compared to Design 2 (Lattice/Perforated Panel Shelving) across all analyzed parameters, namely the Equivalent (von Mises) of 2.6354×10^{6} Pa, Total Deformation of 9.8967×10^{-6} m, and Equivalent Elastic Strain of $1,5243 \times 10^{-5}$ m/m all of which are lower than those of Design 2. The significant difference in deformation, approximately 2.6 times smaller in Design 1, indicates that the solid plate configuration provides a more uniform load distribution and higher structural stiffness. Nevertheless, both designs have a Safety Factor of 15 and operate entirely within the material's elastic range, so both are deemed structurally safe. The selection of the best design ultimately depends on application requirements: Design 1 is more recommended for storing small items or high concentrated loads that require a flat and stable bearing surface, while Design 2 is more suitable for air circulation needs, total weight reduction, and material efficiency in general warehouse environments.

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AUTHORS' CONTRIBUTIONS

Conceptualization: Muhammad Zaky and Nur Rohman. Methodology: Fernanda Regitania and Zaenul Wafa. Validation: Zaenul Wafa. Data Curation: Muhammad Auna Febrian Robani and Razan Hafiz Ghaisan. Writing-Original Draft Article: Muhammad Zaky. Writing-Review and Editing: Zaenul Wafa, Muhammad Auna Febrian Robani, and Razan Hafiz Ghaisan. Visualization: Nur Rohman, Fernanda Regitania, and Zaenul Wafa.

CONFLICT OF INTEREST

The authors declare no conflict of interest that could be perceived as influencing the results and/or discussion reported in this.

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