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Development and Structural Analysis of a Hydraulically Driven Coil Tilting Machine for Heavy Steel Coils

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ABSTRACT

The safe transportation of steel coil sheets within a factory is of vital importance for the machinery manufacturing sector. This study aims to design and structurally analyze a hydraulically driven coil tilting machine to ensure safe and efficient handling of steel coils weighing up to 10 tons. The machine was developed to position coils in both horizontal and vertical orientations to improve operational flexibility in manufacturing. Considering the industry's demand for positioning a wide range of coil sizes, design criteria were established, and a 3D model was developed. Structural analysis was performed using the finite element method to evaluate the machine's performance under various loading and operational conditions. The results showed a maximum stress of 125.5 MPa and a maximum displacement of 7.9 mm, demonstrating compliance with the Turkish Machinery Safety Directive. This research provides an effective approach for improving industrial safety and productivity in coil handling operations.

Keywords: Finite element analysis; machine design; rotation machine; steel coil

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1 Introduction

The safe and efficient handling of heavy steel coils is critically important, particularly for production processes in the machinery manufacturing sector. The transportation and positioning of these coils, which weigh several tons, require the development of specialized equipment capable of managing the risks associated with such heavy loads. In addition, the ability to move steel coils in different orientations (such as horizontal or vertical) during manufacturing processes is also of great significance.

Hydraulic systems are frequently utilized for transporting and positioning heavy loads. These systems stand out in handling heavy weights due to their ability to generate significant forces with relatively compact components. As Rybak et al. stated, the efficiency of hydraulic drives can be significantly improved through careful design and analysis, which is vital for applications involving heavy machinery [1]. Furthermore, the performance of hydraulic systems is closely related to the design of their components. The study by Andrenko et al. emphasizes the importance of establishing a definitive evaluation criterion at the design stage to ensure reliability and efficiency [2].

Finite element analysis (FEA) has become an important tool in the design of machines operating on hydraulic principles. This computational method simulates the behavior of structures under various loading conditions, providing insights into stress distribution and potential failure points. The sensitivity study conducted by Fraas et al. demonstrates the significance of numerical and geometrical parameters in structural mechanical analyses and highlights the necessity of FEA in the design process of hydraulic machines [3]. The operational requirements of hydraulic machines also demand an understanding of fluid dynamics and mechanical interactions within the hydraulic system. Zhang's research on hydraulic control systems emphasizes the role of fluid transmission in determining the overall performance of hydraulic machines [4]. This understanding is highly critical for the design of a coil tilting machine, which must effectively manage the hydraulic forces involved in tilting and positioning heavy steel coils. Furthermore, the study by Rustamov et al. underlines the importance of experimental studies in understanding the operational processes of hydraulic equipment, offering valuable data for design improvements [5]. The integration of advanced control strategies into hydraulic systems can further enhance performance. Hwang et al., in their work on dynamic analysis and control of hydraulic machine systems, stated that effective control mechanisms are essential for optimizing the operation of hydraulic machines [6]. In this context, precise control of the tilting mechanism is required to ensure the safe handling of heavy coils.

To the best of our knowledge, no dedicated system has been developed specifically for coil tilting applications. However, several recent studies have investigated the rotation and handling of heavy loads using hydraulic mechanisms [7–9, 13–15]. These studies collectively highlight the importance of adaptable designs and motivate the development of the coil tilting system presented in this paper.

A review of the literature reveals that no system has been developed specifically for coil tilting. However, there are several studies focused on the rotation and positioning of heavy loads. For example, Zheng et al. designed a high-precision hydraulic rotation mechanism for handling heavy loads, and their study demonstrated that the system was resistant to high load capacities [7]. However, the limited analyses on energy consumption optimization and the long-term performance of the mechanism indicate areas that still require improvement. In another study, Vieira et al. developed a fully automated device for rotating and lifting pallets, showing its potential to optimize material flow in supply chain processes. Nevertheless, the adaptability of the system to loads of different sizes needs to be enhance [8]. Finally, Li et al. focused on stress analysis of mechanical systems used in transporting heavy industrial equipment. Their study highlighted the effectiveness of modeling techniques developed for accurately predicting deformations under load, while also pointing out the importance of producing more general solutions for different geometries and material types [9].

In conclusion, the existing systems developed for transporting and rotating heavy loads offer significant advantages in terms of operational efficiency and safety. However, there is a need for the development of cost-effective systems that provide design flexibility, particularly for rotating steel coils. In this study, the development process and structural analysis results of a hydraulically driven coil tilting machine designed for positioning steel coils weighing up to 10 tons are presented. The developed machine is designed to rotate and position coils both horizontally and vertically, aiming to meet various handling requirements of the manufacturing sector. Using Finite Element Analysis (FEA), the structural integrity of the machine under different loading conditions was evaluated, and its design was optimized to meet safety and performance criteria. While several studies have addressed rotation and lifting systems for heavy loads, a dedicated solution for coil tilting remains unexplored. Therefore, this study focuses on developing and analyzing a hydraulic coil tilting machine that bridges this gap.

2 Materials and Methods

This section covers the design, load distribution, finite element analysis, and prototype manufacturing stages of the developed coil tilting machine.

2.1 Design of the Coil Tilting Machine

The design criteria of the system were determined in accordance with the needs of companies operating in the manufacturing industry. The dimensions and features of the system were identified through field observations. The main components of the system, designed to meet these requirements, are shown in Figure 1. The primary components of the system consist of the lower chassis (1), the hydraulic system (2), and the upper chassis (3). Part (4) represents the coil to be positioned.

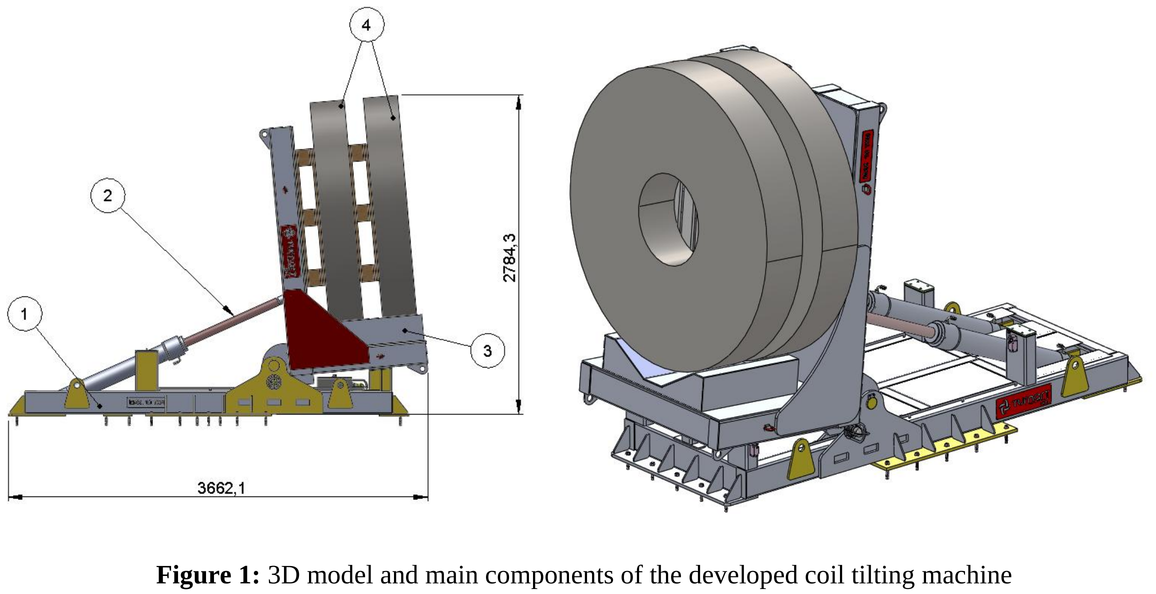

Figure 1: 3D model and main components of the developed coil tilting machine

In industrial processes, the transportation of materials sometimes needs to be carried out vertically and sometimes horizontally. Taking operational processes and the proper functioning of the machine into account, an operation scenario was developed. Figure 2 shows the details of the system's operation scenario. Initially, steel coils weighing up to 10 tons are placed horizontally onto the machine with the help of a forklift. Then, the coil tilting operation is performed using two hydraulic pistons. The coil, now in a vertical position, is lifted and handled using a C-hook. This operation scenario can also be configured in reverse. The coil can first be loaded onto the tilting machine with the help of the C-hook and then returned to a horizontal position via piston actuation. The hydraulic system provides the necessary power for all these operations. The two pistons are driven by the hydraulic unit to perform the positioning tasks.

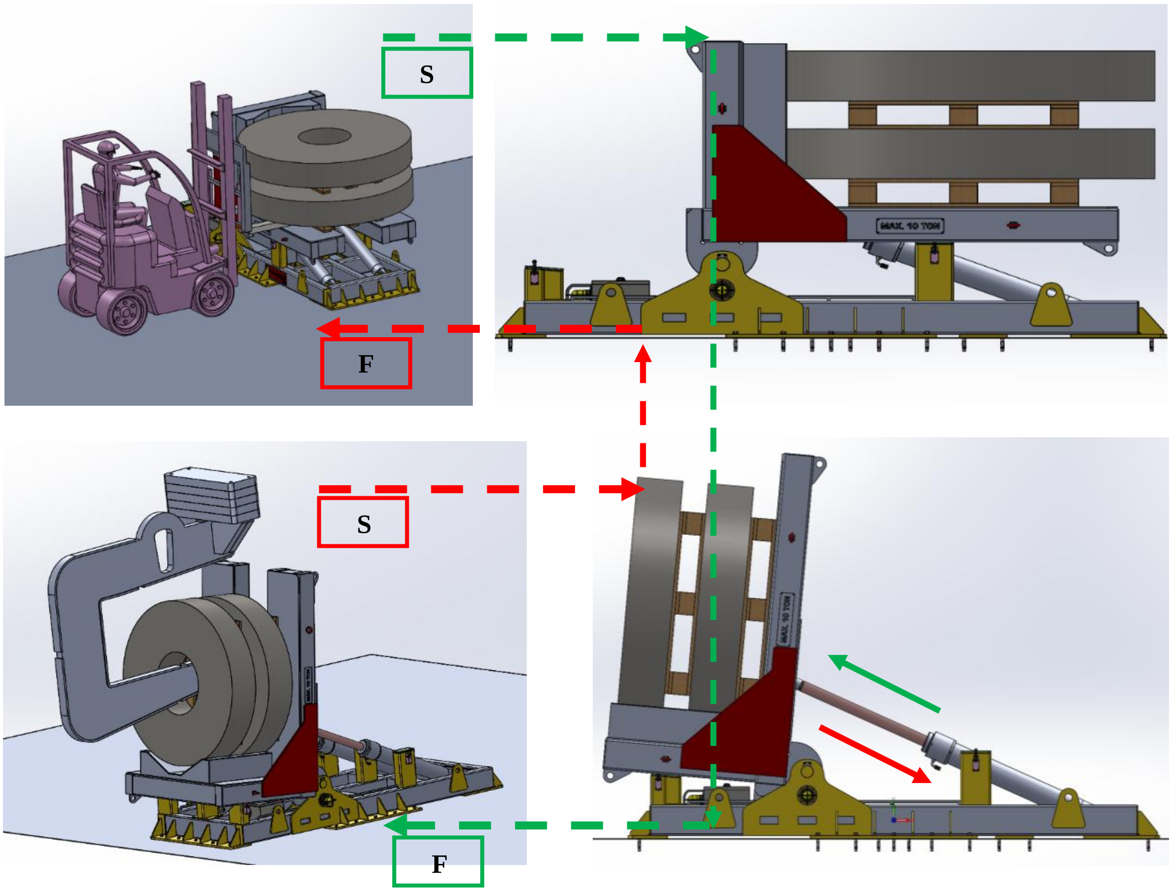

Figure 2: System operation scenario. S: start position, F: final position

2.2 Determination of Critical Loads

A The limit positions occurring in the vertical and horizontal orientations during the operation of the system are shown in Figure 3. To calculate the maximum forces generated in these situations, Eq. 1 and Eq. 2, based on the principle of conservation of momentum, were utilized [10].

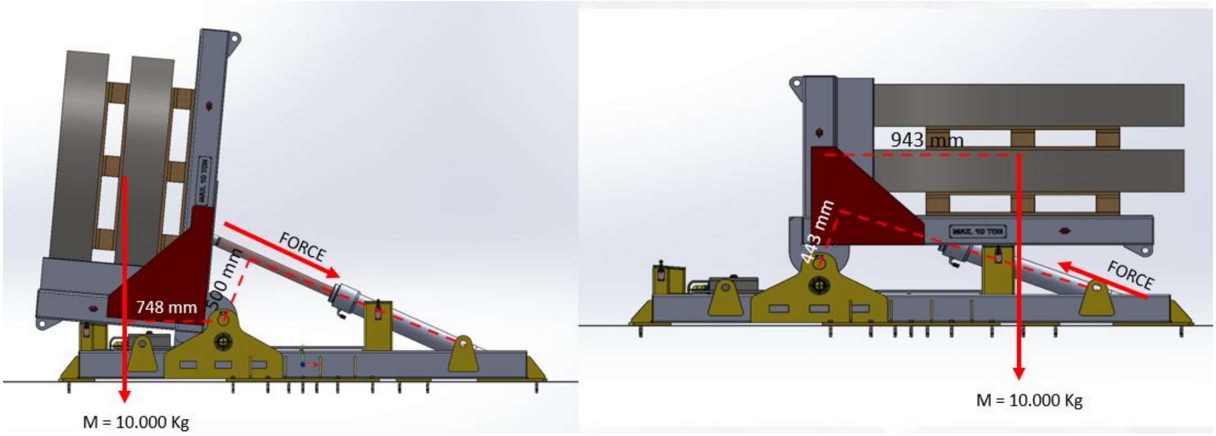

Figure 3: Vertical (left) and horizontal (right) limit positions and critical loading conditions

$$\boldsymbol{F}_{ij} + \boldsymbol{F}_{jk} + \sum \boldsymbol{F}_{ext,j} = m_j \boldsymbol{a}_{G,j} \tag{1}$$

$$(\boldsymbol{R}_{ij} \times \boldsymbol{F}_{ij}) + (\boldsymbol{R}_{jk} \times \boldsymbol{F}_{jk}) + \sum \boldsymbol{T}_j + (\boldsymbol{R}_{ext,j} \times \sum \boldsymbol{F}_{ext,j}) = I_{G,j} \boldsymbol{\alpha}_j \tag{2}$$

where F represents the force, m the mass, a the linear acceleration, R the reaction force, T the torque, I the moment of inertia and α the angular acceleration.

2.3 Structural Analysis of the System Using Finite Element Analysis

Finite element analysis was conducted based on the critical loading condition identified in the previous section. Since the highest force value occurs under horizontal loading, the FEA was performed with this position as the reference. While creating the finite element model, all structural components of the machine were evaluated according to their thickness, and the mesh structure was generated using shell and solid elements. Quadrilateral elements were primarily used for meshing, while triangular elements were occasionally employed to connect nodes in specific part geometries.

The most critical component of the coil tilting machine is the load-bearing profile located on the upper chassis. For this specific profile, a regional mesh convergence study was conducted (Table 1). As shown in Table 1, the stress difference between mesh sizes of 7.5 mm and 5 mm is less than 1%. Therefore, it was deemed appropriate to use a 5 mm mesh size in the analyses. This mesh optimization was applied to all other structural components as well.

Table 1: Mesh and stress variations for the model

Mesh size (mm)	Max. Stress (MPa)	Number of elements
10	106.8	7866
7.5	124.5	9154
5	125.5	11684

The finite element model of the system, created according to the mesh optimization, is shown in Figure 4. The structural analyses of the system were performed using a nonlinear finite element model. The Second Piola-Kirchhoff stress method was utilized to model deformations. The Piola-Kirchhoff tensor represents stress in the reference configuration for finite deformations. The force in the reference configuration is expressed according to the relative orientation between the direction of the force and the normal vector of the surface. The Second Piola-Kirchhoff stress is expressed as shown in Eq. 3.

$$S = \frac{FL_0}{A_0 L} = \frac{\sigma_E}{(1+\epsilon_E)} = \frac{\sigma_E}{\lambda} \quad (3)$$

where F represents the force, L_0 denotes the original length of the part, L represents the final length of the part, A_0 indicates the initial cross-sectional area, σ_E refers to the engineering stress, ε_E represents the engineering strain, and λ denotes the stretch ratio.

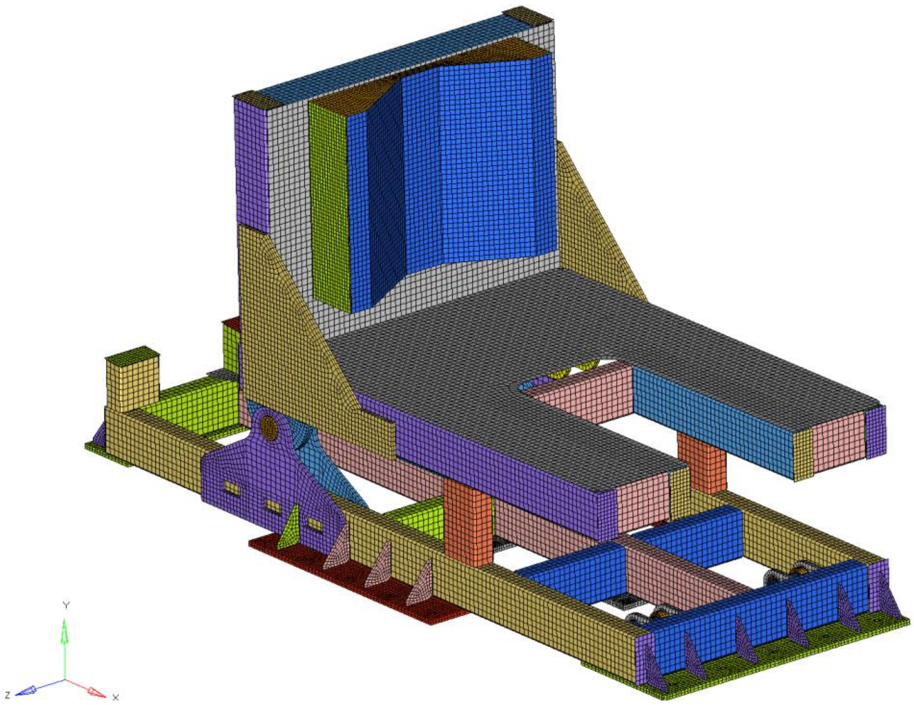

Figure 4: Finite element model and mesh types

A distributed load of 10,000 kg was applied to the contact areas of the workpiece to be positioned on the coil tilting machine. During the application of the distributed load, RBE3 elements were used, and Beam elements were employed for piston modeling. Since the coil tilting machine will be fixed to the ground via the lower chassis, all degrees of freedom in the connection areas were constrained to represent real conditions. RBE2 rigid elements were used in these connection regions for this purpose. The loading and boundary conditions are shown in Figure 5.

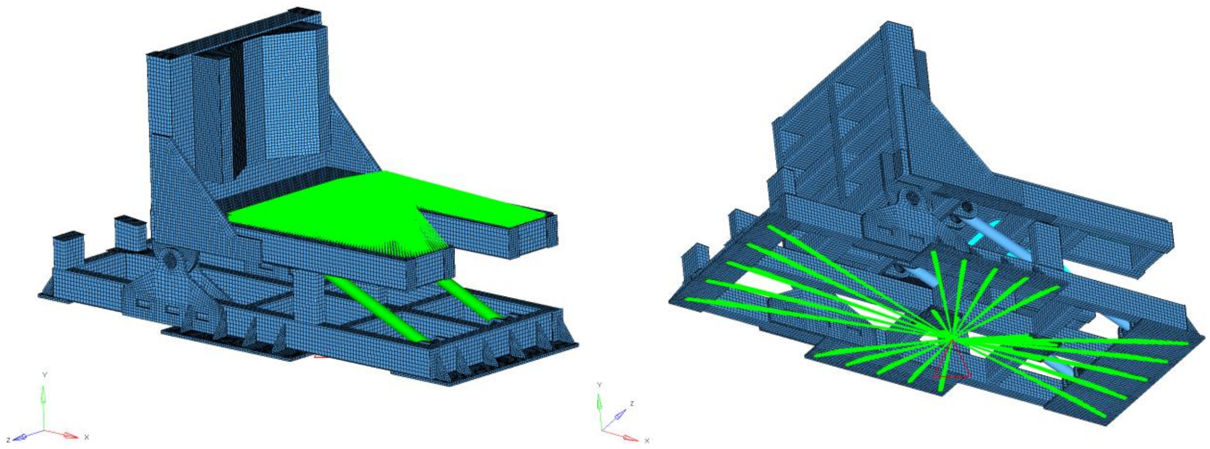

Figure 5: Loading and boundary conditions

In the analyses, the standard gravitational acceleration (9.81 m/s²) was applied to simulate real-world loading conditions. The modulus of elasticity was set to 210 GPa, and the density to 7850 kg/m³, according to structural steel used in heavy machinery applications. The Poisson's ratio was taken as 0.3 [11].

2.4 Prototype Manufacturing

The prototype of the developed coil tilting machine was manufactured in accordance with the criteria determined during the design phase. Images of the system prototype are shown in Figure 6. An electric motor with a power of 11 kW, a speed of 1450 rpm, B5 flange type, three-phase, and 50 Hz frequency was selected to drive the system. This motor provides the necessary energy to the hydraulic power unit, ensuring the reliable operation of the system. A gear pump with a pressure of 300 bar was used for hydraulic power transmission. The mechanism responsible for load handling and positioning operates with two double-acting hydraulic cylinders with diameters of Ø125/80 mm and stroke lengths of 900 mm. These cylinders enable the coil to be safely rotated between horizontal and vertical positions. To enhance operational safety, a counterbalance valve, hose burst valve, pressure relief valve, and directional control valve were incorporated into the hydraulic circuit. These components ensure safe operation during sudden load changes and unexpected pressure fluctuations. The mechanical components were manufactured using machining methods and welded assembly techniques. The chassis and load-bearing profiles were made of high-strength structural steel, and precise measurements and inspections were carried out during assembly to ensure correct positioning and maintain structural integrity. Following all these manufacturing processes, the system assembly was completed. During prototype assembly and testing, minor alignment adjustments were required to ensure smooth piston movement. Additionally, slight hydraulic pulsations were observed at high load conditions but remained within acceptable operational limits. These observations provided practical feedback for improving future designs.

Figure 6: Images of the prototype

After prototype manufacturing, a series of tests were conducted to determine whether the system met the design objectives. First, the hydraulic system was checked for leaks, and it was confirmed that there were no leaks at connection points or hoses. Then, no-load tests were performed to observe the synchronization of the motor, pump, and pistons. During load tests, steel coils of varying weights were placed on the machine, and horizontal–vertical positioning operations were carried out. Throughout these tests, the system's maximum load capacity, hydraulic pressure stability, and piston movement accuracy were evaluated. The results showed that the prototype operated in accordance with the design objectives and met the anticipated safety requirements. This validation process demonstrated the machine's reliability for industrial use.

3 Results and Discussion

Hydraulic components were selected and the electric motor was chosen to meet the operational requirements of the developed coil tilting machine. Accordingly, an 11 kW, 1450 rpm, 50 Hz, asynchronous electric motor with a gearbox was selected to drive the main components of the hydraulic system. The hydraulic system consists of two double-acting cylinders (⌀125/80 mm with 900 mm stroke), a directional control valve, a hose burst valve, a counterbalance valve, and a pressure control valve. The operating pressure of the hydraulic system was set to 300 bar to ensure the safe movement of the coils, precise positioning, and operational efficiency.

The horizontal and vertical forces of the system at the limit positions (see Figure 3) were calculated through analyses (see Eq. 1 and Eq. 2). During the machine's operation in the vertical position, it was determined that the hydraulic cylinders and the load-bearing profile would be subjected to a force of 149.60 kN. In the horizontal position analyses, due to the weight of the coil and the machine's geometry, the machine was found to experience a force of 212.86 kN. These results indicate that the horizontal loading conditions generate a higher force on the machine, potentially causing increased stress in critical areas of the upper chassis. Therefore, the horizontal position, where the maximum force occurs, was taken as the reference for the structural analysis.

According to the FEA results, the highest Von-Mises stress of 125.5 MPa occurred on the upper chassis (Figure 7). As shown in Figure 7, the stress distribution is generally concentrated on the main load-bearing elements and connection areas of the upper chassis. This indicates that these regions require careful consideration in the design and highlights the importance of reinforcing them. Nevertheless, the calculated stress value remains within the yield strength limits of the structural steel used, demonstrating that the design is safe. The stress distribution results are consistent with previous studies on heavy-load rotation mechanisms. Similar stress concentration behavior was reported by Zheng et al. [7] and Vieira et al. [8], confirming the validity of the design and finite element modeling approach used in this study.

The maximum stress and displacement values obtained from the analyses indicate that the machine's design remains within safe limits. Accordingly, the developed system complies with the Turkish Machinery Safety Directive [12]. However, these results also suggest that certain improvements could be made to enhance the machine's performance and increase its durability. In future design optimization studies, measures can be implemented to reduce these stress and displacement values.

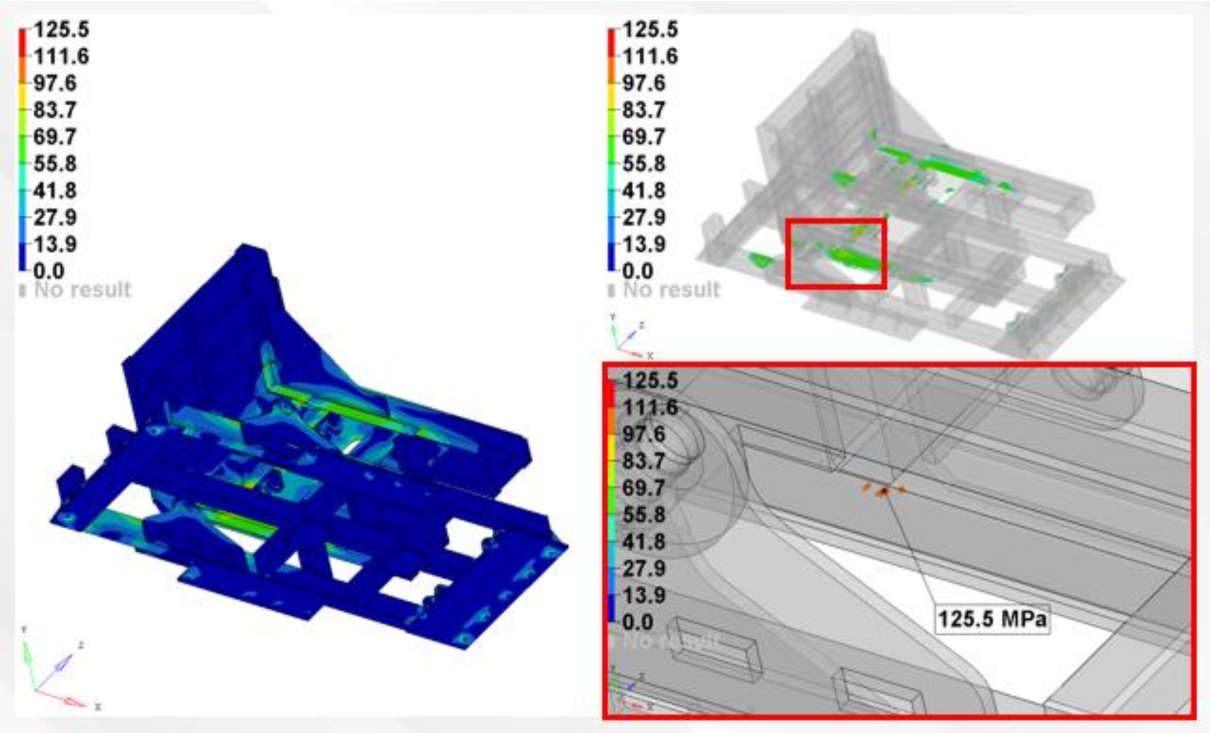

Figure 7: Stress distribution on the upper chassis

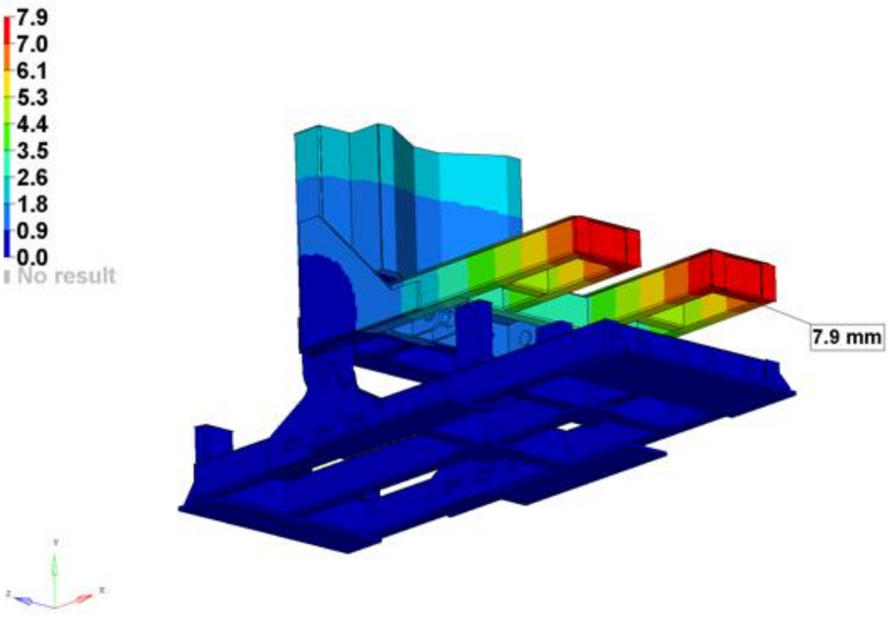

Figure 8: Displacement distribution on the upper chassis

4 Conclusions

In this study, a hydraulically driven coil tilting machine was designed, analyzed, and tested to improve the safety and efficiency of steel coil handling. The system successfully achieved stable operation under both horizontal and vertical load conditions. The finite element analysis confirmed the structural integrity of the design with a maximum stress of 125.5 MPa, while the prototype met all safety requirements and demonstrated stable performance under 10-ton loads. Minor hydraulic fluctuations were observed during testing but did not affect the operational performance. Future studies will focus on dynamic analysis and the integration of automated control strategies to further enhance precision. Overall, the results indicate that the developed system complies with the Turkish Machinery Safety Directive and can be effectively implemented in industrial environments.

5 Declarations

5.1 Acknowledgements

This study was conducted at the design center of YEKTAMAK Engineering and Machinery Co. Inc.

5.2 Competing Interests

There is no conflict of interest in this study.

5.3 Authors' Contributions

Ömer Buğra Seymen: Contributed to the conceptualization and methodology of the study, participated in formal analysis, took responsibility in the investigation process, contributed to the writing of the original draft, participated in the review and editing of the manuscript, and was involved in the preparation of visualizations.

Tolga Güney: Contributed to the conceptualization and methodology of the study, participated in formal analysis, took responsibility in the investigation process, and contributed to the writing of the original draft.

Sinan Düzenli: Contributed to the conceptualization and methodology of the study, took responsibility in the investigation process, and contributed to the writing of the original draft.

Emre Küçük: Contributed to the conceptualization and methodology of the study, took responsibility in the investigation process, and contributed to the writing of the original draft.

Kasım Serbest: Contributed to the conceptualization and methodology of the study, participated in formal analysis, contributed to the writing of the original draft, was responsible for the review and editing of the manuscript, contributed to the preparation of visualizations, and provided overall supervision of the study

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