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Structural analysis of a rope slewing system for loads with a variable center of gravity

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Abstract: Adjustable sling cranes are specialized lifting systems equipped with adaptable sling mechanisms that enhance operational flexibility and efficiency. These systems are particularly advantageous in construction and industrial applications, where adjustable sling tension significantly affects weight distribution and safety. This study presents the design and structural analysis of a rope slewing system for loads with a variable center of gravity. First, the upper and lower lifting groups were designed, and profiles with fixing points according to the load position were mounted on the rails. A sling apparatus was used between the upper and lower groups. For structural analyses, boundary conditions and material properties were defined according to the loads to be carried in the system. Inclined conditions that may occur during transportation were taken into account in the analyses. Loading was performed under transportation conditions with a maximum inclination of 6° and accordingly, the safety of the system according to the material types was observed. According to the Finite Element Analysis (FEA) results, the maximum stress values were obtained as 267.5 MPa in the upper carrying group, 113.4 MPa in the lower carrying group and 66.1 MPa in the sling apparatus. As a result, the structural analyses performed show that the design and material selections of the rope slewing system remained within safe limits during operation. Considering loading conditions and inclined positions, the system's safety and efficiency demonstrate that it provides a practical and safe solution for industrial applications.

Keywords: Sling Cranes; Lifting Systems; Finite Element Analysis; Mechanical Design.

1. Introduction

Sling-based load lifting systems play a critical role in ensuring safety and efficiency in various sectors, particularly in construction and material handling. Adjustable sling cranes are specialized lifting systems that incorporate adjustable sling mechanisms to enhance their operational flexibility and efficiency. These systems have the ability to modify the sling tension which significantly impacts load handling and safety.

Recent studies outline key specifications, functionalities, and implications of adjustable sling cranes. One of the primary advantages of adjustable sling cranes is their ability to accommodate varying load conditions. The principle of adjustable tensioning can be applied to crane systems, where adjustable slings can be tensioned to optimize load support and stability during lifting operations.

The ability to adjust the sling tension dynamically is crucial for maintaining the center of gravity and ensuring that loads are lifted safely without excessive sway or instability. In the context of tower cranes, the integration of adjustable sling systems can enhance the control of payload swing, which is a common challenge in lifting operations. Li et al. highlight the importance of accurately positioning the payload, noting that flexible steel slings can complicate this process [1]. Their research emphasizes the need for effective control strategies to minimize swing and improve operational efficiency. Similarly, Wada et al. discuss the development of a suspended-load rotation-control device that utilizes gyroscopic dampers to stabilize loads during lifting, further illustrating the potential for adjustable systems to enhance crane performance [2].

The dynamic behavior of adjustable sling cranes is also influenced by the design of the crane's structural components. Vasiljević et al. examined the parameters affecting the dynamic behavior of portal cranes, which often feature a rotating boom capable of 360° movement [3]. Their findings suggest that the configuration of the

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sling and boom attachment points plays a critical role in the crane's stability and load handling capabilities. This highlights the need for careful engineering and design considerations when implementing adjustable sling systems in cranes. Moreover, the cost-effectiveness of adjustable sling systems has been analyzed in various studies.

Onur, Devaraj and Krishnaveni et al. investigated the effects of sling angle and size on the reliability of lifting hooks using with stress analyses [4-7]. The researchers utilized computer-aided modeling and finite element analysis to assess the stress on hooks under different sling configurations. The findings indicated that variations in sling size and angle significantly affect the safety factor of lifting hooks, emphasizing the importance of proper rigging techniques to prevent accidents during lifting operations. These studies provided a comprehensive understanding of the mechanical properties and limitations of lifting hooks, which are crucial for material handling systems. The results underscored the necessity of stress testing and modeling to ensure that lifting hooks can withstand the demands of heavy loads without failure. Additionally, mechanical analysis has highlighted the importance of material selection in designing lifting equipment to maintain operational efficiency and load safety [8].

Sydora et al. explored the application of simulation technologies in heavy industrial construction, specifically focusing on lifting processes [9]. Their research developed a real-time interactive simulation that allows users to visualize and understand the complexities of lifting operations. This approach not only enhances training and operational planning but also aids in identifying potential risks associated with sling-based lifting systems. Li analyzed various parameters, including sling length and counterweight position. The research demonstrated how careful design adjustments can enhance the performance of lifting systems [10]. The development of innovative detection methods, such as the anti-lifting detection system based on neural networks used during train loading operations, highlights the ongoing evolution towards intelligent detection and safety mechanisms within crane operations [11]. This reflects a broader trend recognizing the importance of predictive technologies in enhancing the safety and efficiency of crane operations. In the sector of adjustable sling cranes, recent research has shown a trend toward enhancing operational productivity through advanced control systems and ergonomics. A study on the synchronous control of multi-lift overhead cranes highlights the complexities associated with potential loads in crane operations, advocating for robust control mechanisms that adapt to dynamic load conditions [12]. The integration of advanced stability and control systems, such as pulse-width modulation (PWM) technology for lifting platform speed control, showcases innovation in maintaining safety and efficiency during operations [13].

In conclusion, adjustable sling cranes represent a significant advancement in lifting technology, offering enhanced flexibility, safety, and efficiency in load handling. The ability to adjust sling tension dynamically allows for better control of payloads, minimizes swing, and improves operational outcomes. As the literature indicates, careful consideration of design, dynamic behavior, and cost-effectiveness is essential for optimizing the performance of these advanced crane systems. Also the integration of simulation tools in engineering practices represents a significant advancement in ensuring the safety and efficiency of lifting operations.

This study presents a comprehensive structural analysis of a rope slewing system designed to accommodate variations in load center of gravity under transport conditions with a maximum inclination of 6°. Using Finite Element Analysis (FEA), it determines stress values in both the upper and lower carrying groups, evaluating system durability based on material types. Unlike previous studies, this research provides detailed dynamic and static analysis results specifically related to the rope slewing system and inclined loading conditions. Consequently, this study demonstrates that adjustable sling crane systems offer a safe solution under dynamic and inclined loading conditions, making a significant contribution to the existing literature.

2. Materials and Methods

2.1. Design of the System

In sling-based load rotation systems used for handling large and heavy workpieces, sling sideslip during the rotation process can lead to various operational issues. To eliminate these problems and ensure a safer application of the process from both technical and occupational safety perspectives, the sling-centering mechanism must be designed accordingly.

In current systems, the fabric sling may shift laterally along the X-axis across the main drum during load rotation. This slippage causes the sling to climb over the edge flanges of the main drum or, in cases where it cannot, to sag. Such slippage and sagging result in issues during load rotation, causing deformation of the sling and reducing its service life. The proposed design aims to deliver an innovative solution that enhances efficiency, reduces operational costs, and complies with safety standards. ►**Figure 1** shows the overall system design and exploded view of its components. There are upper and lower lifting groups, and profiles with fixing points according to the load position were mounted on the rails. Two triangle sling apparatuses were used between upper and lower lifting profiles.

2.2. Structural Analyses

Defining boundary conditions such as fixed supports,

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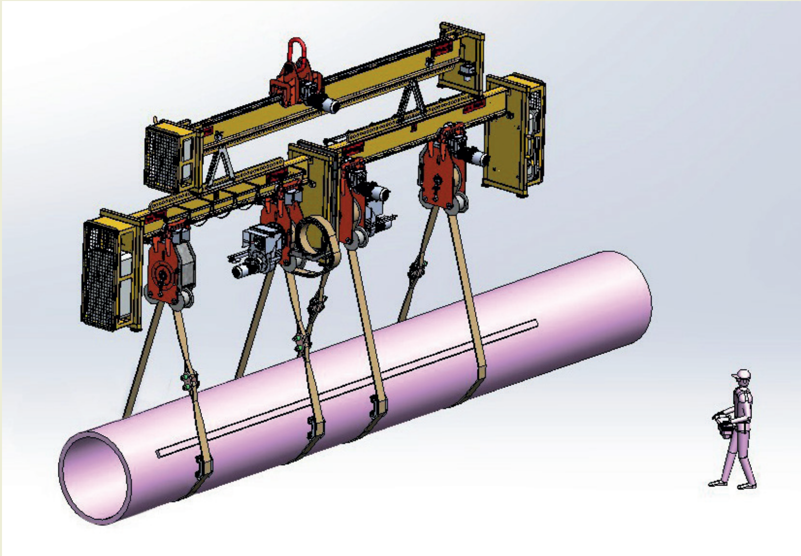

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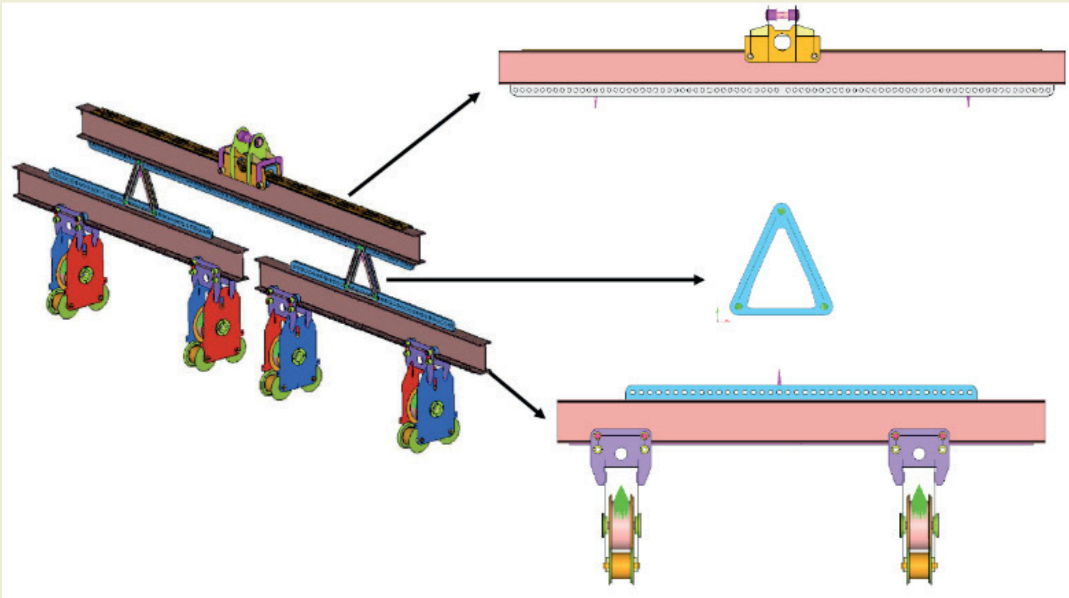


b)

Figure 1. a) Complete system design, b) The design of the rope slewing system.

symmetry conditions, and any constraints that restrict movement in specific directions is critical in structural analysis [14]. Inertia relief analysis is a method used to simulate static loading conditions on a structure that is not fully constrained. By balancing external forces with inertial forces, inertia relief allows for static analysis of systems without fixed boundary conditions. The analyses of the system in ▶**Figure 1** were done according to inertia relief method.

The analyses were done separately for the upper lifting group, lower lifting group and triangle sling apparatus. Since the inertia relief method was used in the analyses, fixing points were not used for the parts. The applied loads for three different analyses are shown in ▶**Figure 2**. Changes in the center of gravity of transported products can cause imbalances in the system, affecting stability during the transport process. To evaluate these potential issues, analyses were conducted to examine how the carrier system behaves at different tilt angles. This approach enables an understanding of the system's performance under inclined operating conditions and provides insights into how imbalances can be minimized.

Loading was performed under transportation conditions with a maximum inclination of 6°. This is the maximum inclination angle that can occur during load transportation, and the boundary conditions were applied based on the worst-case working conditions. All analyses also were done according to maximum loading conditions. For balancing, the loads were applied vertically in opposite directions along the +Y and -Y axes from connection points. RBE2 and RBE3 elements were used to define the connections between the apparatus. While RBE2 creates a fully rigid connection between multiple nodes, constraining all degrees of freedom, RBE3 element distributes loads across the connected nodes, allowing for a more realistic load transfer on the structure.

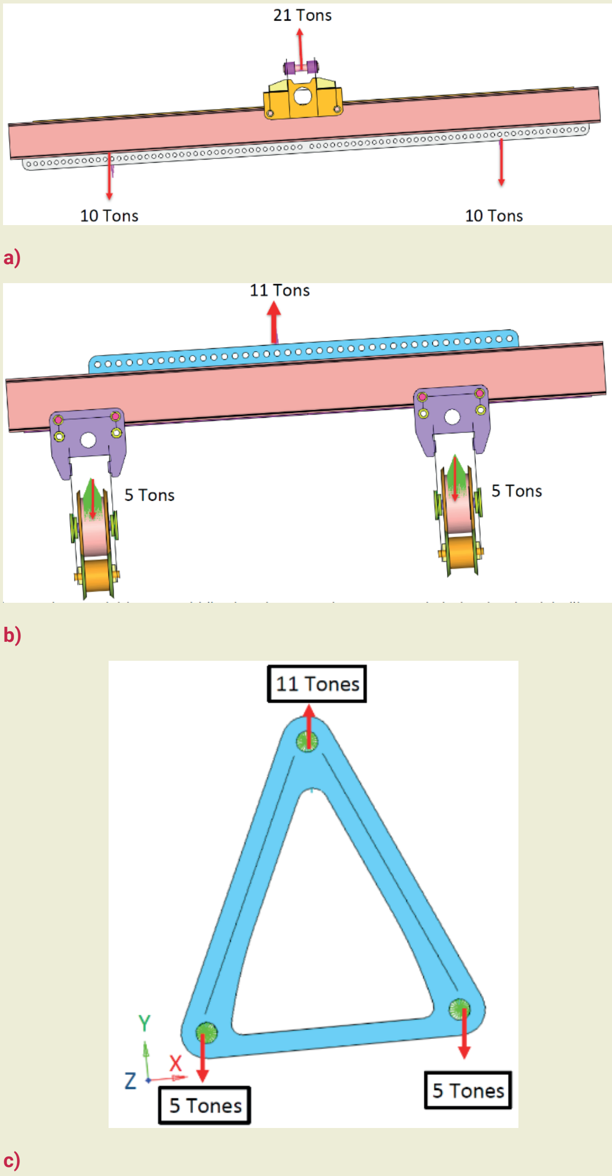


Figure 2. Applied loads with inclination of 6° for three different analyses a) Upper lifting group, b) Lower lifting group, c) Triangle sling apparatus.

Before proceeding with the analysis, the properties of the materials used in the system must be defined. Various materials are used in the production of the system's rails, profiles, connecting pins, and sling apparatus. ▶**Table 1** defines the material types used in the analyses. In the analyses conducted, certain sections exhibited high stress values; therefore, AISI 1050 steel, which has a higher yield strength, was preferred in these areas. In contrast, in sections with lower stress values, St37 steel was selected to reduce the overall system cost.

Table 1. The material types used in analyses.

Connection pins	AISI 1050
Rails, profiles	St37
Sling apparatus	ALU6061-T6

The geometric details of the structure significantly influence the mesh structure selection. Regions with complex or intricate details may require a finer mesh, while simpler, flat regions may be adequately represented with larger elements. Convergence studies were conducted to verify mesh accuracy. By repeating analyses with varying mesh densities, changes in results were observed. Once results stabilized to a certain precision, the mesh density was considered adequate. Mesh convergence for 9 mm, 10.5 mm and 13.5 mm mesh dimensions are shown in ▶**Figure 3**. The maximum stress values obtained according to the mesh numbers and sizes are presented in ▶**Table 2**. As shown in the ▶**Figure 3** and ▶**Table 2**, even though the number of elements was increased and the mesh size was reduced, the difference in stress values decreased. The difference in stress values between the 9 mm and 10 mm mesh sizes is less than 1%. The mesh convergence processes, shown on the suspension apparatus, were applied throughout all the analysis processes.

Table 2. Mesh convergence values.

Mesh Size	Stress Value	Total Elements
13.5 mm	62.4 MPa	2117
10.5 mm	65.8 MPa	2412
9 mm	66.1 MPa	2576

The structural finite element model of the sling apparatus was developed using shell elements, with welds and assembly connections arranged to accurately represent the physical boundary conditions. ▶**Figure 4** illustrates the mesh structures of the system components.

3. Results and Discussions

3.1. Analyses Results

The analysis results for the upper carrying group, lower carrying group, and sling apparatus based on the material, load, and boundary condition definitions are provided in ▶**Figures 5-10**. For the upper carrying group, the maximum Von Mises stress under applied loads is obtained to be 267.5 MPa, which is below the yield strength of the specified connection pin material (550 MPa). Accordingly, the safety factor for the connection pin is calculated as 2.056. Furthermore, the stress levels in the rails and profiles are considerably low, indicating that these components operate well within safe limits. ▶**Figure 5** displays the stress analysis results on the left side and the filtered regions above 155 MPa on

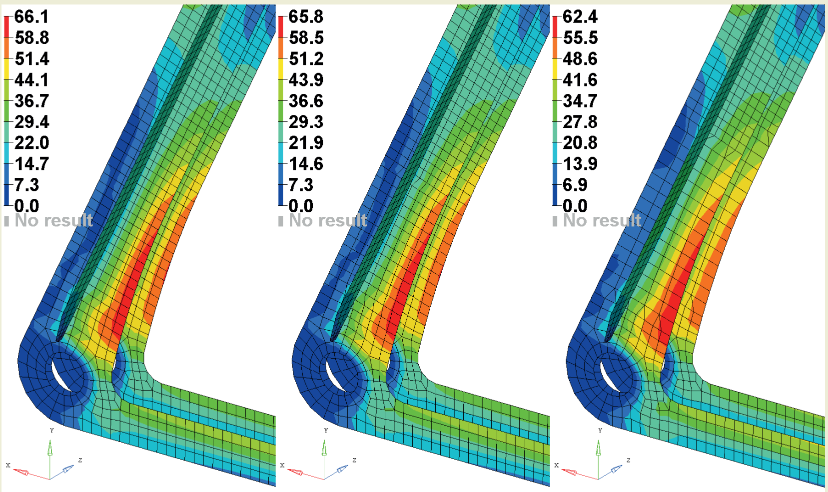
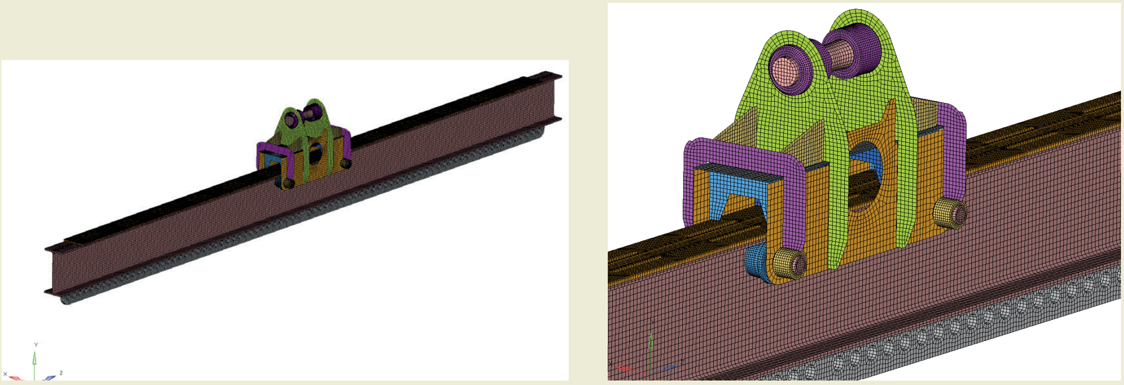


Figure 3. Mesh convergence stress values for 9 mm, 10.5 mm and 13.5 mm mesh sizes.



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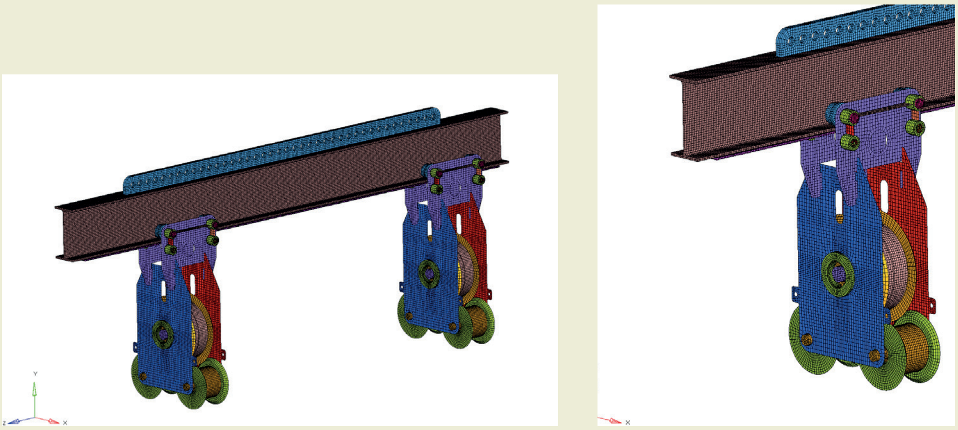

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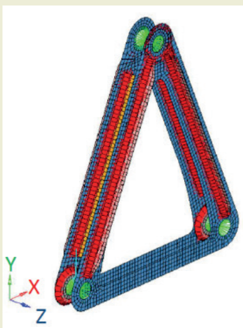

c)

Figure 4. Mesh structures of the system components a) Upper lifting group, b) Lower lifting group, c) Triangle sling apparatus.

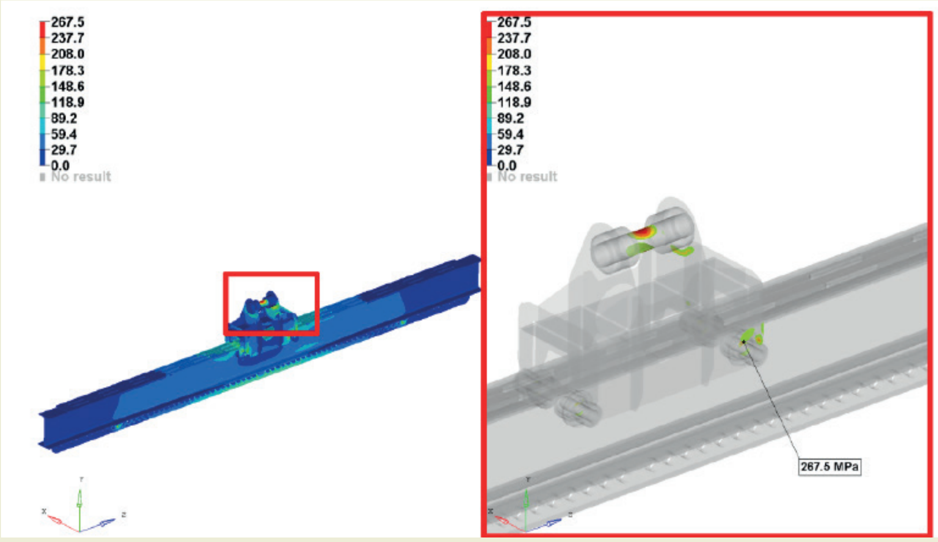

Figure 5. Stress analysis results for upper carrying group.

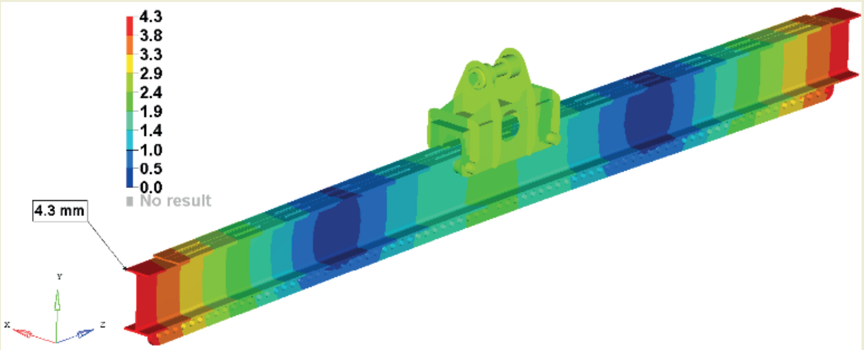

Figure 6. Displacement results for upper carrying group.

the right. Maximum displacement was obtained as 4.3 mm at the end regions of the rails and profiles, as shown in ▶**Figure 6**. Considering the applied boundary conditions and load distributions, it is understandable that maximum displacement occurs at the rail and profile ends.

For the lower carrying group, the maximum Von Mises stress under applied loads is 113.4 MPa, which is less than the specified rail and profile material's yield strength (235 MPa). Thus, the safety factor for the lower carrying group is 2.072. ▶**Figure 7** shows the stress analysis results on the left and the filtered regions greater than 50 MPa on the right. ▶**Figure 8** shows the maximum displacement of 1 mm at the rope connection pulleys.

The maximum Von Mises stress for the sling apparatus under applied loads is 66.1 MPa, which is significantly lower than the yield strength of the specified sling apparatus material (240 MPa). As a result, the safety factor for the sling apparatus is calculated as 3.63. According to the Machinery Safety Regulation (2006/42/EC), the safety factor value in strength calculations for manually operated machines and lifting accessories is 1.5, and this value has been used as a reference in the analyses.

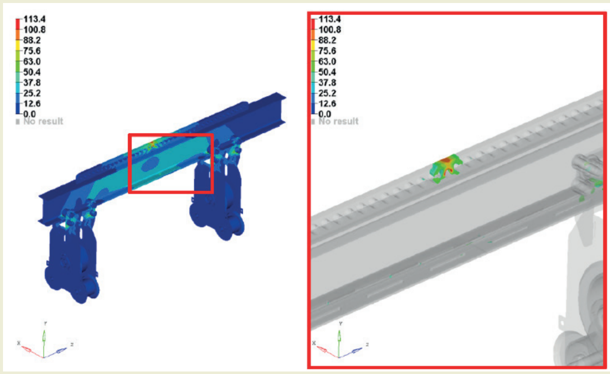

Figure 7. Stress analysis results for lower carrying group

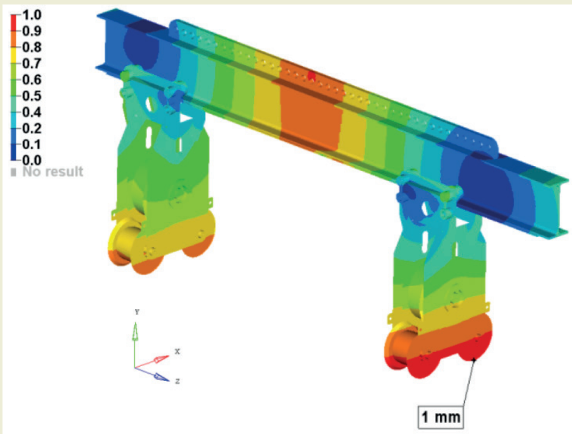

Figure 8. Displacement results for lower carrying group.

▶Figure 9 shows the stress analysis results on the left and the filtered regions greater than 30 MPa on the right. The maximum displacement was 0.4 mm in the middle of the connection pins, as shown in **▶Figure 10**.

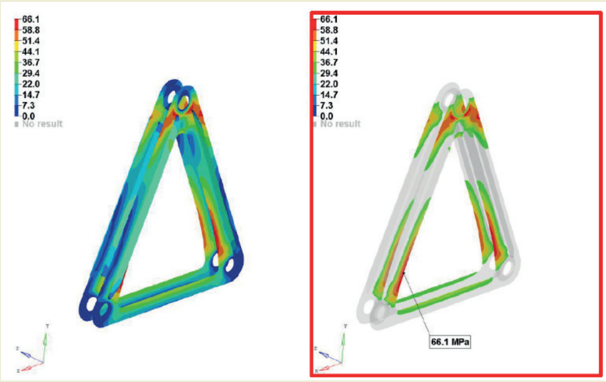

Figure 9. Stress analysis results for sling apparatus.

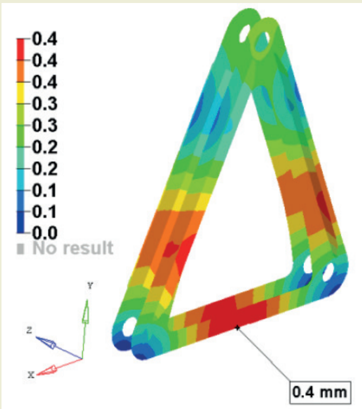

Figure 10. Displacement results for sling apparatus.

3.2. Production of the System

Following the comprehensive design and structural analysis, the adjustable sling crane system was successfully produced, incorporating all the necessary components and ensuring they met the design specifications. The manufacturing process involved precise machining and fabrication of each component, ensuring accurate dimensions and quality standards. The upper and lower lifting groups, as well as the sling apparatus, were fabricated according to the design specifications. Special attention was given to the connection points and the assembly of the profiles to ensure that they would align correctly under operational loads.

The key components were then assembled and tested to verify their functionality. The sling apparatus, which connects the upper and lower lifting groups, was carefully positioned, and the necessary adjustments were made to ensure smooth operation. **▶Figure 11** depicts that the produced system was tested under varying load conditions and inclinations, as predicted in the analysis. During testing, the system demonstrated its ability to function efficiently and safely, with minimal displacement and stress levels within the safe limits.

4. Conclusions

This study presents the design and structural analysis of an adjustable sling crane system, specifically focusing on a rope slewing mechanism that accounts for the varying center of gravity of loads. Through the use of FEA, the system was evaluated under realistic loading conditions, including a maximum inclination of 6°. The results indicate that the designed system remains

Figure 11. Load tests of the produced system

within safe operational limits, with stress values significantly lower than the yield strengths of the selected materials.

The maximum Von Mises stress for the upper lifting group was found to be 267.5 MPa, which is well below the yield strength of the AISI 1050 material (550 MPa), yielding a safety factor of 2.056. Similarly, the lower lifting group and the sling apparatus both demonstrated stress values far below the yield strengths of their respective materials (St37 and ALU6061-T6), with safety factors of 2.072 and 3.63, respectively. These findings confirm the structural integrity of the system, ensuring its durability and reliability under dynamic and inclined loading conditions.

Additionally, the system has been successfully produced, with the final design tested in real-world conditions. The manufactured system demonstrated its ability to safely and efficiently handle loads with varying centers of gravity, validating the analysis results. The successful production and validation of the system further confirm its practical applicability in industrial lifting operations.

This study distinguishes itself from previous research by specifically addressing the effects of inclined loading conditions on a rope slewing system, providing detailed dynamic and static analysis results, and integrating real-world production and testing phases. This research also contributes to the ongoing development of more advanced and reliable lifting systems by offering valuable insights into the performance of adjustable sling cranes under real-world conditions. The combination of appropriate material selection, detailed structural analysis, and consideration of inclined operational conditions allows for a crane system that balances both safety and operational efficiency.

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Research ethics

Not applicable.

Author contributions

Conceptualization: [S. Duzenli, T. Guney, M. Soyaslan], Methodology: [S. Duzenli, T. Guney, M. Soyaslan], Formal Analysis: [S. Duzenli, T. Guney, M. Soyaslan], Investigation: [S. Duzenli, T. Guney], Resources: [S. Duzenli, T. Guney], Data Curation: [S. Duzenli, T. Guney], Writing - Original Draft Preparation: [S. Duzenli, T. Guney, M. Soyaslan], Writing - Review & Editing: [M. Soyaslan], Visualization: [S. Duzenli, T. Guney, M. Soyaslan], Supervision: [M. Soyaslan], Project Administration: [T. Guney].

Competing interests

The author(s) state(s) no conflict of interest.

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Data availability

Not applicable.

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