THE OPTIMUM DESIGN OF THE JIB CRANE BY USING FINITE ELEMENT METHOD

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Abstract

In this experiment, the Finite Element Method (FEM) is employed to simulate von Mises Stress, Displacement, and the Factor of Safety (FOS)across three variations of a swing jib crane. The first variation, referred to as Type-1, incorporated a 12t mm stiffener plate and is characterized by the dimensions H150×150×7×10 mm. The second variation, Type-2, is designed without a stiffener plate and has identical dimensions to Type-1:H150×150×7×10 mm. The third and final variation, Type-3, is similar to Type-1 in its use of a 12t mm stiffener plate but differs in its dimensions, which are H100×100×6×8 mm. This study analyzes these three types of swing jib cranes through simulation and statistical evaluation to identify the optimal design in terms of engineering excellence and cost-effectiveness. The distribution of von Mises Stress and displacement within the jib crane structures are investigated, revealing critical stress concentrations at the bolt holes. However, maximum stress levels remained below yield stress thresholds for all crane types. The factor of safety analysis indicates that the Type-3 jib crane is the most optimal, with a Factor of Safety value of 1.5, exceeding recommended standards. Moreover, considering the mass weight and fabrication cost, the Type-3 jib crane is the most cost-effective choice and helps reduce cost by up to 10%. The statistical significance established through ANOVA reveals the significant impact of design on stress distribution, displacement, FOS, and mass weight. Therefore, the Type-3 jib crane is suggested as the most optimal choice for fabrication. A successful load test of the Type-3 jib crane verifies its performance and matches simulated test results.

Keywords: Crane design, Structure analysis, Simulation, Finite Element, Jib Crane.

1. Introduction

Due to rapid growth in the manufacturing and engineering industry there has been an increased need for equipment to support production line processing. Amongst these pieces of equipment, the crane is of utmost importance. The utilization of cranes in various industries can lead to improved safety and ergonomics. Cranes can provide adjustable heights, omnidirectional movement capabilities, and quick loading of materials. These innovative cranes have the potential to minimize the risk of injury while simultaneously enhancing the efficiency and cost-effectiveness of tasks. In particular, jib cranes have gained significance in the industry due to their flexibility in providing lifting solutions within limited spaces.

To remain competitive in this market, companies must consider both the safety of use and the cost of purchasing cranes as top priorities when formulating market strategies. The application of Finite Element Analysis (FEA) has emerged as a powerful tool that can be applied to the study and design of jib cranes [1-7]. Finite Element Analysis enables engineers to comprehensively investigate the structural behavior of cranes under various loading conditions [8-14]. This facilitates the assessment of factors such as stress distribution, displacement, and factor of safety. Potential weaknesses can be identified and addressed by simulating real-world scenarios, resulting in a more robust and efficient crane design process.

This study aims to investigate three potential crane designs based on standard ISO 8686-1 and ISO/TR 25599:2005 [15-16], including the various aspects related to the analysis and design of jib cranes using the Finite Element Method. By conducting thorough simulations and analyses, our goal is to enhance and optimize some of the various factors considered for a crane design. This involves ensuring that for the optimal design, the jib crane can effectively handle operational requirements while satisfying the following objectives: maintaining safety standards and optimizing cost by using lightweight [6], cost-effective components suitable for the fabrication of the jib crane.

2. Methodology

Modeling of the Jib cranes used in the experiments.

The dimensions of the jib cranes were determined with consideration for the functionality, usability, and comfort of the worker. The modeling of the jib cranes used in the experiments was performed using the 3D modeling software SolidWorks (version 2018), to generate high-fidelity 3D models [3]. The models were designed with the objective of achieving high safety factor scores; each model was designed to have a safety factor greater than 1.25 [15], based on the general recommendation for a safety factor between 1.25 and 2.0 [15]. Each model was designed also to use lightweight, cost-efficient materials and components. Therefore, the goal of these experiments was to analyze these designs and configurations through Finite Element Analysis and to ensure their structural integrity before the fabrication process. Here is a brief summary of each type of jib crane in this experiment:

1) Type-1 Jib Crane (dimension and 3D model shown in Figure 1)

- Column Beam: H-beam 150×150×7×10 mm.
- Swing Arm Beam: H-beam 150×150×7×10 mm with a 12 mm stiffener plate installed at the top of the beam.

2) Type-2 Jib Crane (dimension and 3D model shown in Figure 2)

- Column Beam: H-beam 150×150×7×10 mm.
- Swing Arm Beam: H-beam 150×150×7×10 mm without a stiffener plate.

3) Type-3 Jib Crane (dimension and 3D model shown in Figure 3)

- Column Beam: H-beam 150×150×7×10 mm.
- Swing Arm Beam: H-beam 100×100×6×8 mm with a 12 mm stiffener plate installed at the top of the beam.

Once the 3D models were generated, a Finite Element Analysis was conducted. This analysis aimed to thoroughly examine the structural framework of the cranes and ensure favorable outcomes for the subsequent fabrication process.

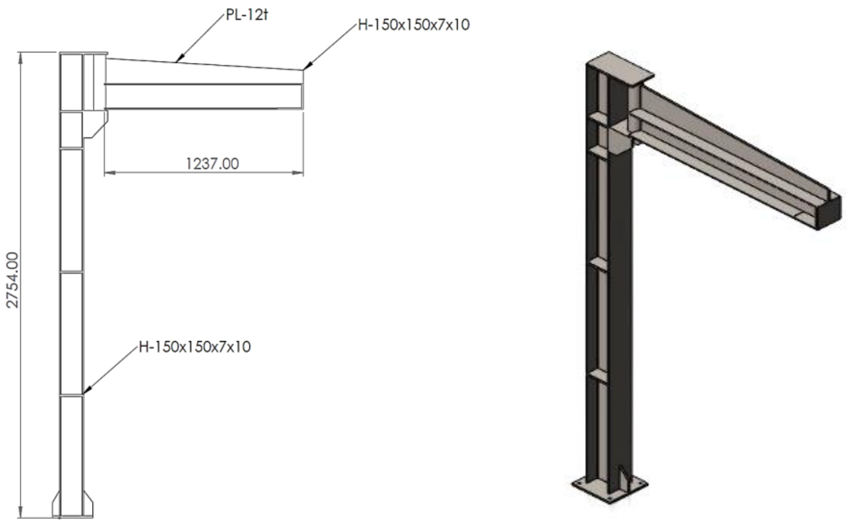

Figure 1 Type-1 Jib Crane; Swing arm beam H-beam 150×150×7×10 mm with a stiffener plate 12t mm.

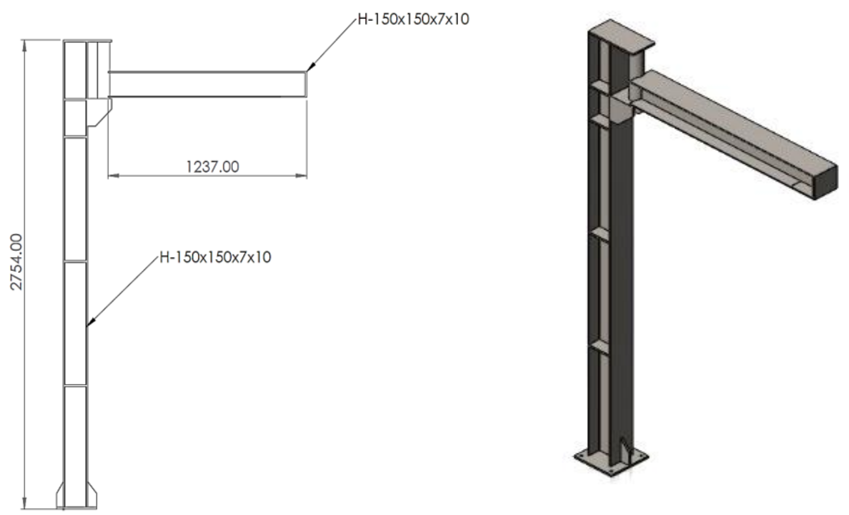

Figure 2 Type-2 Jib Crane; Swing arm beam H-beam 150×150×7×10 mm without a stiffener plate.

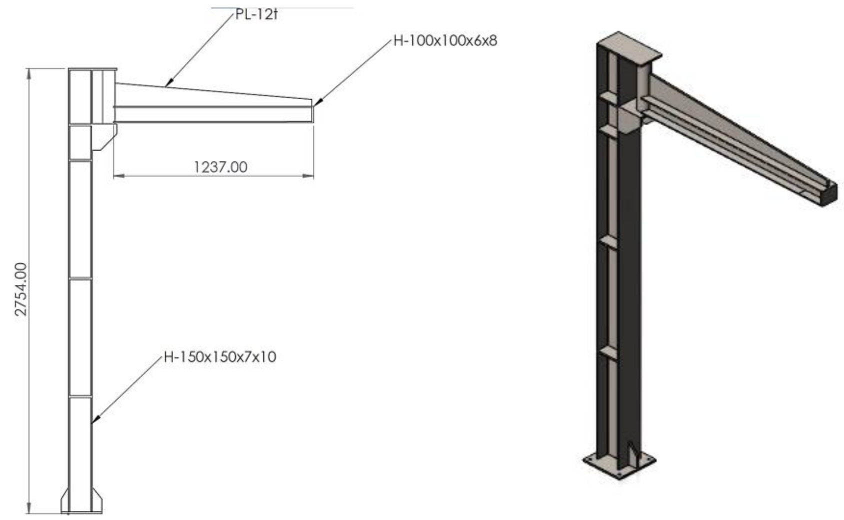

Figure 3 Type-3 Jib Crane; Swing arm beam H-beam 100×100×6×8 mm with a stiffener plate 12t mm.

3. Design and Calculations

The steel design method and standard steel design code were based on the American Institute of Steel Construction (AISC) standards. This design process included calculations for the vertical centroid using formula (1), and moment of inertia for the section of beam using formula (2). The summarized results of these calculations are presented in Table 1.

1) Calculating the vertical (y) centroid of a multi-segment shape:

$$y = \frac{\sum yiAi}{\sum Ai} \tag{1}$$

Where: *Ai* = The individual segment's area

yi = The individual segment's centroid distance from a reference line or datum

2) Calculating the Moment of Inertia of a Beam Section:

$$Itotal = \sum(Ii + Aidi^2) \tag{2}$$

Where: *Ii* = The moment of inertia of the individual segment about its centroid axis

Ai = The area of the individual segment

di = The vertical distance from the centroid of the segment to the Neutral Axis (NA)

Table 1 The results are summarized by Centroid, Moment of inertia, and Modulus of section.

Jib Crane (Swing arm beam)	Centroid (y) (mm)	Moment of Inertia (mm^4)
Type – 1 with stiffener	100	2,939
Type – 2 without stiffener	75	1,641
Type – 3 with stiffener	81	1,108
H-beam 100×100×6×8 mm.	50	383

After analyzing the results (Table 1), it was evident that installing a stiffener plate to the upper section of the swing arm beam on the crane resulted in substantial increases to the moment of inertia of the beam for each type that had a stiffener plate installed. This is apparent in the increase to the moment of inertia from the Type-2 crane to the Type-1 crane, having an increase of 1,298 mm^4. The Type-3 crane also saw a substantial increase when compared with the H-beam, seeing an increase of 725 mm^4 to the moment of inertia. These results are evidence that the addition of the stiffener plate lead to enhancements to the moment of inertia and also the vertical centroid position of the swing arm beam. The increase to the moment of inertia contributes to the heightened strength of the crane, leading to decreased deflection when subjected to various load conditions. The results obtained remained consistent throughout subsequent rounds of Finite Element Analysis.

4. Finite Element Method (FEM)

The jib crane is generally used for lifting heavy factory equipment and has a Safe Working Load (SWL) of 180 kg. Therefore, the intended combined load capacity for the jib crane is 260 kg when considering the design load (considering a safety factor of 1.25 [15]), which accounts for both the live load (190 kg) and the dead load (10 kg) of the crane's hoist chain. This ensures that the crane is designed to handle the combined weight of these loads safely. The structural framework of the jib cranes were studied using FEA for the three model types. All models were subjected to the same simulation conditions for consistency. The static load analysis of the jib crane models was conducted using the SolidWorks Simulation software (2018 version) to study von Mises stress, displacement, factor of safety, and mass weight. The models were treated as solid bodies with a solid body type. The geometry of the base plate was fixed, having all four faces constrained at the bolt hole used for anchor bolt connections to a concrete foundation. This condition of the actual installation is shown in Figure 4(A). The analysis type was set to static, and a standard solid mesh was applied, utilizing four Jacobian points and an element size of 20.9942, 20.3128, and 19.8283 mm, respectively. The tolerance is configured at 1.04971, 1.01564, and 0.991417 mm, respectively. The mesh quality plot indicates high quality; the models were comprised of 68,728, 66,607, and 69,442 nodes and 34,590, 33,438, and 34,872 elements, respectively, and the maximum aspect ratio was 13.887, 20.058, and 20.476, respectively; the created mesh is shown in Figure 4(B). The model and physical jib crane were fabricated using AISI 1015 Steel, known for its 3,314.08 kg/cm^2 yield strength and 7,870 kg/m^3 mass density. At the end point of the swing arm beam, a perpendicular force of 260 kgf was applied (the Safe Working Load of the jib crane is 180 kg). The model considered the earth's gravity to be 9.81 m/s^2 and was applied to each simulation, as shown in Figure 4(C).

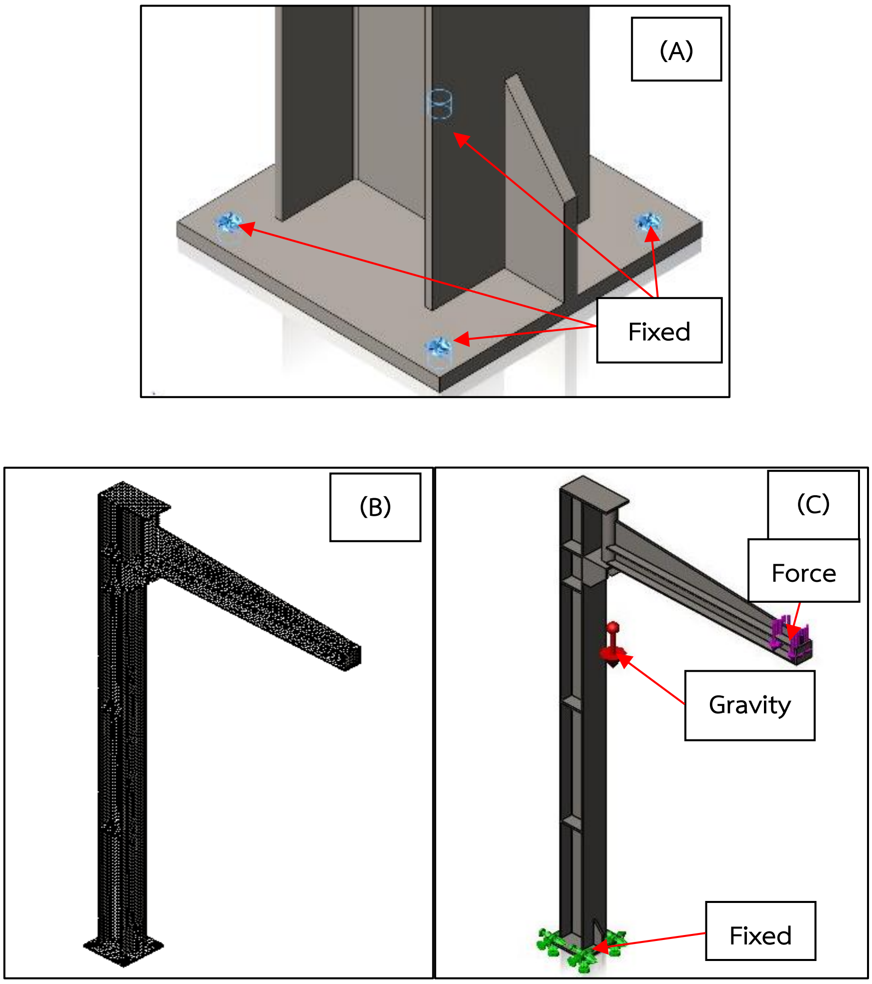

Figure 4 (A) Fixed geometry at the base plate, (B) Create mesh, and (C) Apply force.

5. Results and Discussion

The simulation results are summarized in Table 2, showing the distribution of von Mises Stress within the structural framework of the jib crane, along with the displacement distribution across the same structural framework, as shown in Figures 5-7. These results show that the highest von Mises Stress among all three jib crane types occurred at the base plate end. Further examination of this point revealed that the maximum von Mises Stress was concentrated at the bolt holes. However, it's worth noting that the maximum von Mises Stress value remained below the yield stress for all three types of jib cranes. The specific maximum von Mises Stress values for the three types were recorded as follows: 2375.89, 2297.46, and 2191.37 Kgf/cm^2, respectively, as shown in Figure 8(A). Furthermore, it was observed that the highest displacement within all three types of jib cranes was located at the termination point of the swing arm beam. Notably, the Type-2 jib crane exhibited the most significant displacement, reaching a maximum value of 11.28 mm, as shown in Figure 8(B).

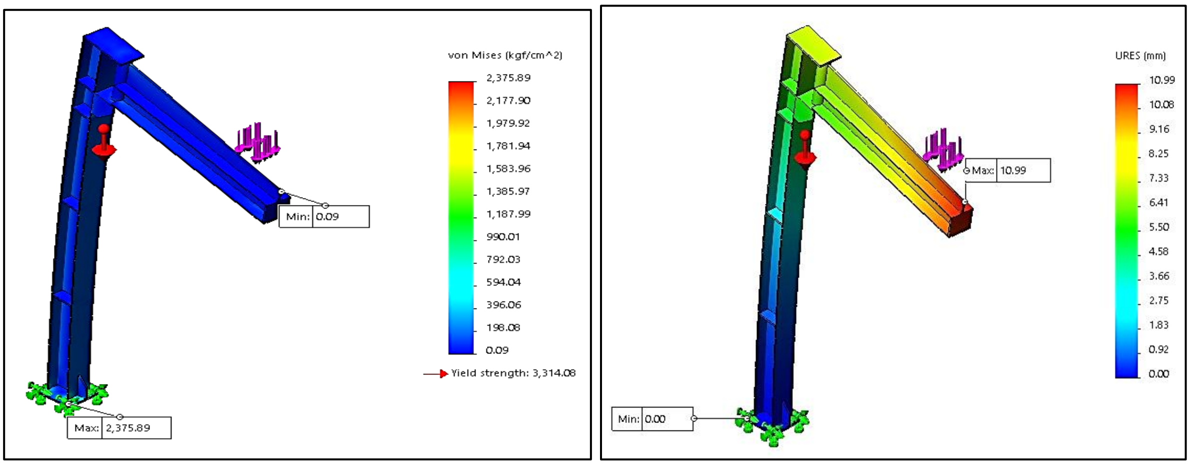

Figure 5 Jib Crane Type – 1; (Left) von Mises Stress, and (Right) Displacement.

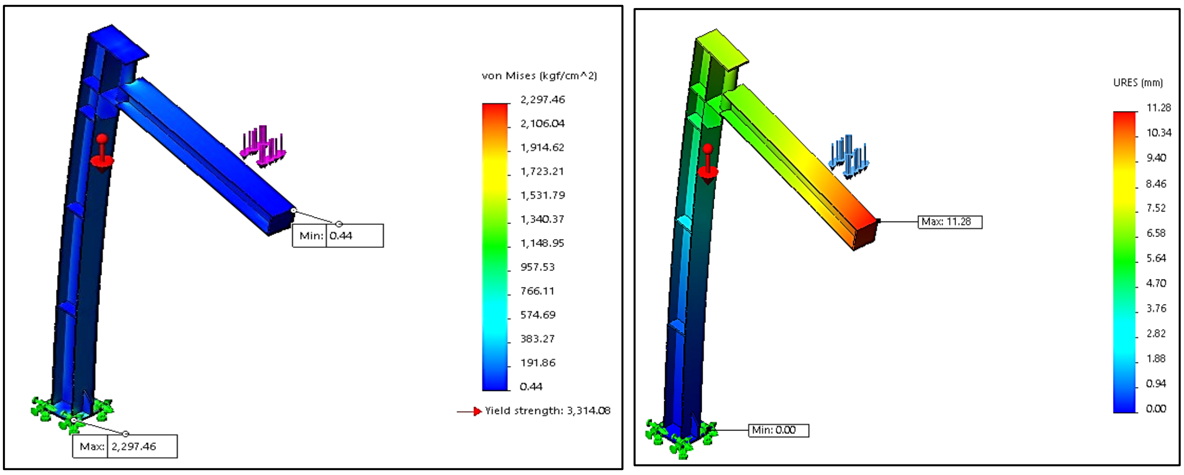

Figure 6 Jib Crane Type – 2; (Left) von Mises Stress, and (Right) Displacement.

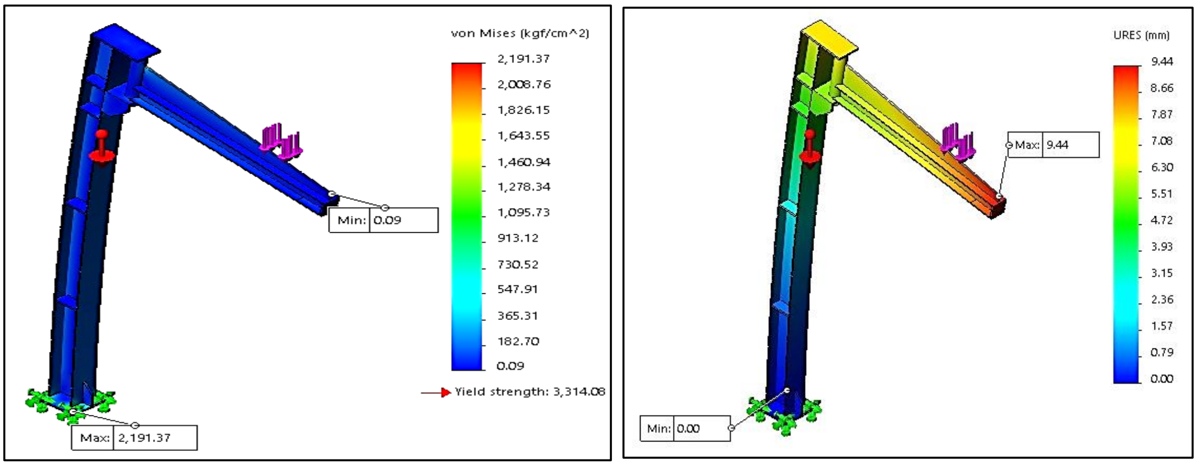

Figure 7 Jib Crane Type – 3; (Left) von Mises Stress, and (Right) Displacement.

Table 2 The results of Stress, Displacement, Factory of Safety, and Mass Weight are summarized.

Jib Crane	von Mises Stress (Kgf/cm^2)	Displacement (mm)	Factor of Safety (FOS)	Mass Weight (Kg.)
Type – 1	2375.89	10.99	1.39	154.0
Type – 2	2297.46	11.28	1.40	140.7
Type – 3	2191.37	9.44	1.50	140.2

When considering the factor of safety, the analysis indicated that the Type-3 jib crane displayed a favorable value of 1.5 FOS, making it the most optimal choice among the three types. This is in alignment with safety factor recommendations that suggest a minimum FOS of 1.2 [15], as shown in Figure 8(C). Considering both the mass weight of the jib crane and the direct cost of fabrication, it was determined that the Type-3 jib crane exhibited a lower mass weight in comparison to the other types. This reduction in mass weight contributed to a more affordable price for fabrication, making the Type-3 jib crane a cost-effective option, as shown in Figure 8(D).

The Type-3 jib crane utilized a swing arm beam constructed from an H-beam with the dimensions of 100×100×6×8 mm, significantly reducing weight per meter. This weight reduction contributes to an improved load-bearing capacity and is further enhanced by incorporating a 12 mm stiffener plate at the beam's upper section. This addition improves the moment of inertia and centroid of the swing arm beam. Increasing the Moment of Inertia increases the crane's strength, leading to reduced deflection under various loading conditions. Therefore, the Type-3 jib crane offers a favorable combination of structural integrity, safety, cost-effectiveness, and fabrication feasibility. However, before making a final decision, it's important to consider any additional project-specific requirements, specific operational considerations, and any other additional constraints that may not have been covered in the provided information.

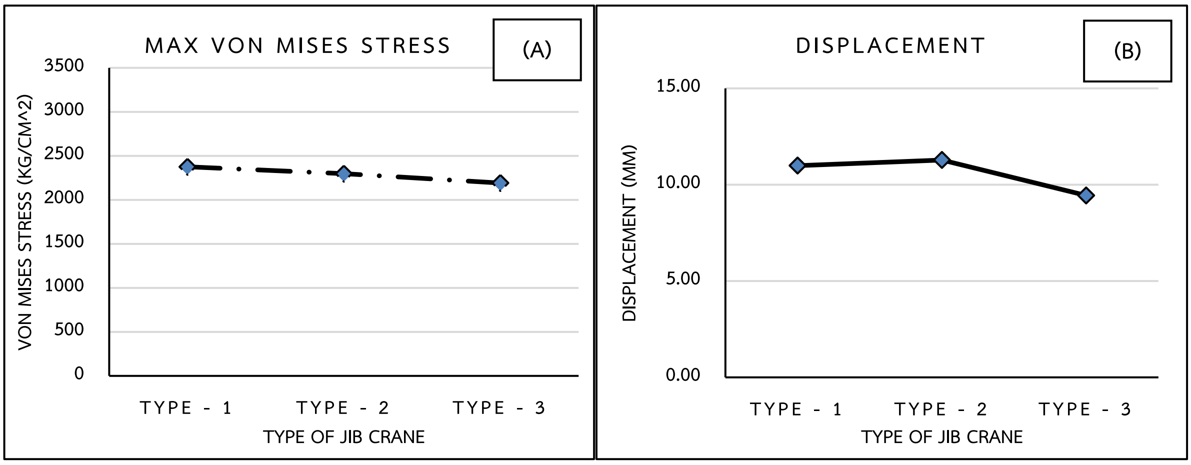

Figure 8 (A) Max Von Mises Stress, (B) Displacement, (C) Factor of Safety, and (D) Mass Weight.

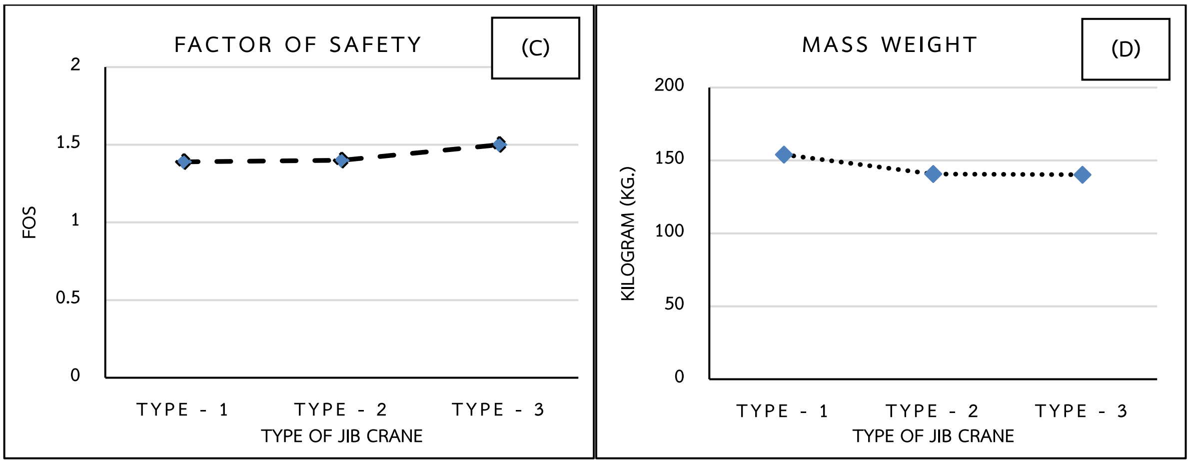

Figure 8 (A) Max Von Mises Stress, (B) Displacement, (C) Factor of Safety, and (D) Mass Weight.

The results presented in Table 3 indicate that when utilizing one-way analysis of variance (ANOVA) to assess the maximum von Mises Stress, Displacement, Factor of Safety, and mass weight across the three jib crane types, the p-value was less than 0.05 in the results for each type of jib crane. As can be seen from the results, the design of the jib crane has a significant impact on various aspects of the structural framework, including stress distribution, displacement, safety factor, and mass weight, which has optimal outcomes on both usability and the cost of fabrication. This underscores the importance of careful consideration of these factors when determining the type of jib crane to fabricate that satisfies project requirements. The statistically significant differences observed in the ANOVA results further support earlier recommendations of the Type-3 jib crane due to its balanced stress, safety, and cost-effectiveness.

Table 3 ANOVA: Single factor

Source of Variation	SS	df	MS	F	P-value	F crit
Max von Mises Stress	34117.3	3.0	11372.4	15163.3	6.6E-05	19.2
Displacement	3.9	2.0	1.9	12908.3	1E-06	9.6
Factor of Safety	0.0	2.0	0.0	63.5	0.004	9.6
Mass Weight	382.8	2.0	191.4	179.0	4E-06	5.1

After fabricating the Type-3 crane, performing a load test on the Type-3 jib crane was essential to validate its structural integrity and ensure that it performed as expected under real-world conditions. The load test, conducted with a 200 kg load (SWL 180 kg. x SF1.1), assessed how the crane responds to the applied load and confirmed that it meets safety and performance requirements; the real-world load test results found the Type-3 jib crane safe to use, as shown in Figure 9.

Figure 9 Shows the Type-3 Jib Crane; The actual load testing.

6. Conclusion and Recommendation

In summary, after performing simulations and analyzing the results for three different jib crane types, the results revealed that the Type-3 jib crane, with the 12 mm stiffener plate installed, offers the most optimal balance of structural integrity, safety, and cost-effectiveness. With optimal stress distribution, displacement (9.44 mm), and factor of safety (FOS1.5), this design also allows for a low cost for fabrication, reducing cost by up to 10%. These findings provide evidence, supported by statistical significance, that the Type-3 jib crane is the most optimal choice among the three tested for theoretical and practical consideration. Furthermore, this study shows that Finite Element Analysis is a powerful tool that can be used to study and design jib cranes before starting fabrication. This study showed the application of Finite Element Analysis in proving and testing a design and suggested an optimal jib crane design with favorable results. This study can serve as a guide for applying Finite Element Analysis to a potential crane design and in the fabrication of new designs. It aims to assist in achieving optimal designs that balance engineering excellence and cost-effectiveness, providing valuable insights for the industry to enhance efficiency and economic viability in engineering.

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