Structural Integrity Analysis of the Guard Filter Cap Lifting Structure Using Finite Element Analysis

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Abstract - **This study investigates the efficiency and safety of a guard filter cap lifting system that has traditionally relied on a mobile crane. The objective is to analyze the structural integrity of an alternative lifting structure using the Finite Element Analysis (FEA) method implemented in SolidWorks software. Data were obtained through numerical simulations under three load scenarios to determine the maximum stress, maximum deformation, and buckling load factor (BLF) values. The results reveal that the maximum stress of 72.26 MPa remains well below the yield strength of SS400 and SS41 steels, while BLF > 1 indicates structural stability without buckling. With a minimum safety factor of 4.843, the structure is confirmed to be safe and efficient as a permanent lifting system. This research reinforces the reliability of FEA as a tool for assessing structural integrity in industrial applications.**

Keywords: Filter cap lifting system, structural integrity, Finite Element Analysis, Buckling Load Factor.

I. INTRODUCTION

In modern industrial operations, efficiency and safety during equipment maintenance are critical factors, particularly in high-pressure fluid filtration systems such as the *guard filter*. This component features a guard filter cap, which serves as the primary access point for periodic filter replacement. The lifting process for this component typically involves the use of a *mobile crane*, which requires a wide operational area and incurs high operational costs (Pomares *et al.,* 2021). Consequently, it is necessary to develop an alternative lifting system with a fixed structure equipped with a pulley and trolley mechanism to improve maintenance efficiency without compromising safety. The primary challenge in developing this system lies in ensuring that the lifting structure possesses sufficient structural integrity to withstand dynamic loads and prevent failures such as *buckling* or excessive deformation (Bölükbaş & Mete, 2020). Therefore, a precise structural analysis using modern numerical methods such as Finite Element Analysis (FEA) becomes highly relevant to ensure both safety and design efficiency (Qasim & Al-Zaidee, 2020).

A review of the literature indicates that, although extensive research has been conducted on *buckling* behavior and steel structural strength, most studies have focused on conventional columns or large-scale structures, while analyses of smaller industrial lifting systems remain limited (Arrayago & Rasmussen, 2022). Studies such as (Fieber, Gardner, & Macorini, 2020) demonstrated that advanced inelastic analysis improves the accuracy of steel structure strength assessments, yet such methods are rarely applied to small-scale lifting frames subjected to localized loads. Furthermore, geometric imperfections, joint conditions, and dynamic load variations, factors often neglected in conventional simulations, can lead to unrealistic predictions (Yao *et al.,* 2023). Hence, a comprehensive approach that integrates FEA-based numerical modeling with material property validation is essential to ensure structural integrity under various loading conditions (Possidente, Tondini, & Battini, 2021).

This research aims to analyze the structural integrity of the guard filter cap lifting structure using Finite Element Analysis as the main analytical approach. The analysis seeks to evaluate stress distribution, strain, deformation, and potential *buckling* under actual loading conditions. The outcomes are expected to provide a scientific foundation for designing efficient and safe lifting structures applicable in industrial filtration maintenance systems. Furthermore, these findings can serve as a reference for the development of similar lifting systems in other industrial sectors with comparable load and structural configurations (Fu *et al.,* 2021).

The significance of this research lies in the necessity to ensure that the guard filter cap lifting system operates safely, efficiently, and economically without relying on external heavy equipment such as mobile cranes. Theoretically, the FEA-based approach enables a more comprehensive analysis of the nonlinear behavior of steel structures, including stress distribution and potential failures due to local *buckling* (Kristijanto *et al.,* 2022). Practically, this study reinforces the theoretical framework for lightweight structure design focused on material efficiency and operational safety. By combining numerical validation and empirical data, this research contributes significantly to the advancement of adaptive and

reliable design standards for industrial equipment support structures (Yao *et al.,* 2025).

II. LITERATURE REVIEW

The concept of structural integrity refers to a structure's ability to withstand external loads and stresses without experiencing failure or deformation that could compromise its functionality and safety (Walport, Gardner, & Nethercot, 2020). In the context of mechanical and civil engineering, structural integrity involves understanding material behavior, stress distribution, and structural response to combinations of static and dynamic loads. This principle emphasizes the balance between material strength and geometry to prevent failures such as cracking, fatigue, or buckling (Possidente, Tondini, & Battini, 2021). In modern design practices, structural integrity also includes predictive aspects through numerical analysis methods like Finite Element Analysis (FEA), allowing engineers to estimate strength limits and deformation behavior before real-world application (Fieber, Gardner, & Macorini, 2020). Thus, structural integrity serves as a fundamental principle to ensure the safety and reliability of engineered structures across various industrial applications.

The manifestations of structural integrity can be categorized into three main aspects: strength, durability, and stability. Strength refers to the material's ability to withstand loads without reaching its yield point, durability pertains to the structure's capacity to maintain performance against environmental influences or fatigue from cyclic loading, and stability involves the structure's resistance to geometric failure such as buckling or unwanted lateral deformation (Fu, Dai, Zhang, & Shang, 2021). In modern analyses, these three aspects are evaluated collectively through finite element simulations to ensure structures meet safety criteria under all loading stages (Yao *et al.,* 2023). This integrated approach enables designers to predict potential failures during the design stage and make necessary modifications in geometry or material selection to improve reliability (Bölükbaş & Mete, 2020).

Finite Element Analysis (FEA) is a numerical method used to solve structural and material mechanics problems by discretizing a continuous system into small, interconnected finite elements (Kristijanto *et al.,* 2022). This method allows for analyzing stress, deformation, and strain distributions in structures with complex geometries that are difficult to solve analytically.

The application of Finite Element Analysis can be categorized into several types based on the analysis objectives: linear static analysis, nonlinear analysis, dynamic analysis, and buckling analysis (Benincá & Morsch, 2020). Linear static analysis investigates a structure's response to constant loads within the elastic range, while nonlinear analysis accounts for material plasticity and geometric changes. Dynamic analysis evaluates the structure's behavior under time-dependent loads such as vibration or impact, whereas buckling analysis focuses on evaluating stability under axial or lateral compression (Akshara M., 2020).

Buckling is defined as a structural instability phenomenon characterized by a sudden lateral deformation when an element is subjected to axial compression exceeding its critical limit (Arrayago & Rasmussen, 2022). In structural engineering, buckling represents one of the most critical failure mechanisms, particularly for slender elements such as steel columns, plates, and thin-walled beams. The phenomenon is nonlinear and strongly influenced by geometry, boundary conditions, and the elastic properties of the material. Traditionally, buckling analysis is explained through Euler's theory for ideal columns; however, the development of numerical methods such as FEA allows for more realistic studies of local buckling, distortional buckling, and post-buckling behaviors in modern steel structures (Qasim & Al-Zaidee, 2020). Understanding this concept is essential for ensuring the integrity and safety of structures subjected to high compressive loads.

III. METHODOLOGY

The main object of this research is the guard filter cap lifting structure, a component used to lift the cover of a filtration system during periodic maintenance and filter replacement. The primary problem addressed is the dependence on mobile cranes for the lifting process, which is inefficient in terms of operational space and cost. Therefore, this study focuses on designing and analyzing an alternative fixed lifting structure equipped with a trolley and pulley system, expected to replace the mobile crane while maintaining the same level of safety and functionality. The structural performance was evaluated using the Finite Element Analysis (FEA) method to assess its ability to withstand load forces and verify that no failures—such as buckling or excessive stress—occur under maximum loading conditions.

The research process began with the design of the lifting structure model, developed in SolidWorks according to the actual dimensions and configuration of the guard filter cap system. This was followed by a meshing process, dividing the model into discrete finite elements for numerical analysis. Then, boundary conditions were applied to represent realistic field conditions, including supports, lifting forces, and load distributions. The analysis involved both static structural and linear buckling approaches. The static structural analysis

generated results for von Mises stress, strain, and displacement, which were used to evaluate the structural strength under maximum applied loads. The buckling analysis was conducted to calculate the Buckling Load Factor (BLF), serving as an indicator of the structure's stability under compressive loading (Zewudie & Zerfu, 2024). The simulation results were compared against material strength thresholds to determine whether the structure experienced failure. The interpretation was based on von Mises failure theory for plastic deformation and Euler's theory for column stability, ensuring that the lifting structure's structural integrity remained within safe operational limits (Fieber, Gardner, & Macorini, 2020).

IV. RESULTS AND DISCUSSIONS

Figure 1 presents the principal geometric configuration of the filter guard cover lifting structure. The primary load-carrying members employ RHS $150 \times 150 \times 6$ mm sections, while the diagonal bracing elements utilize RHS $80 \times 80 \times 4$ mm profiles. SS400 steel is applied in the lower structural region, whereas SS41 is adopted for the upper assembly. All structural joints are executed using bolted connections.
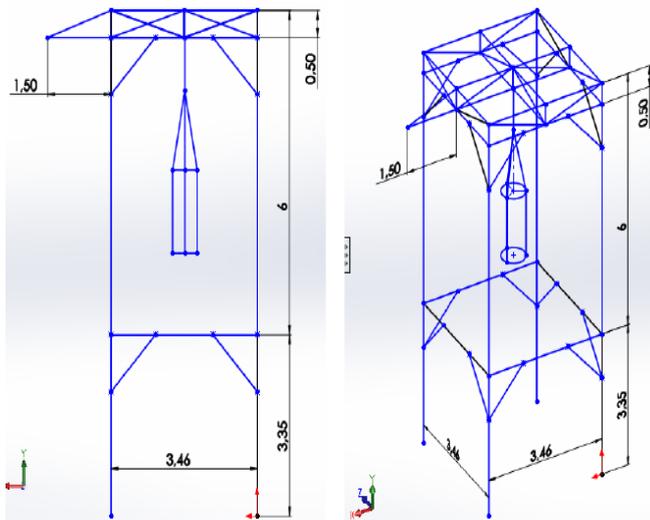

Figure 1: principal geometric of the guard filter cap lifting structure

The structural integrity of the guard filter cap lifting framework was evaluated through a series of Finite Element Analysis (FEA) simulations performed in SolidWorks. The model was examined under three distinct loading configurations—designated as Static 1, Static 2, and Static 3—which represent realistic lifting conditions, as illustrated in Figure 2.
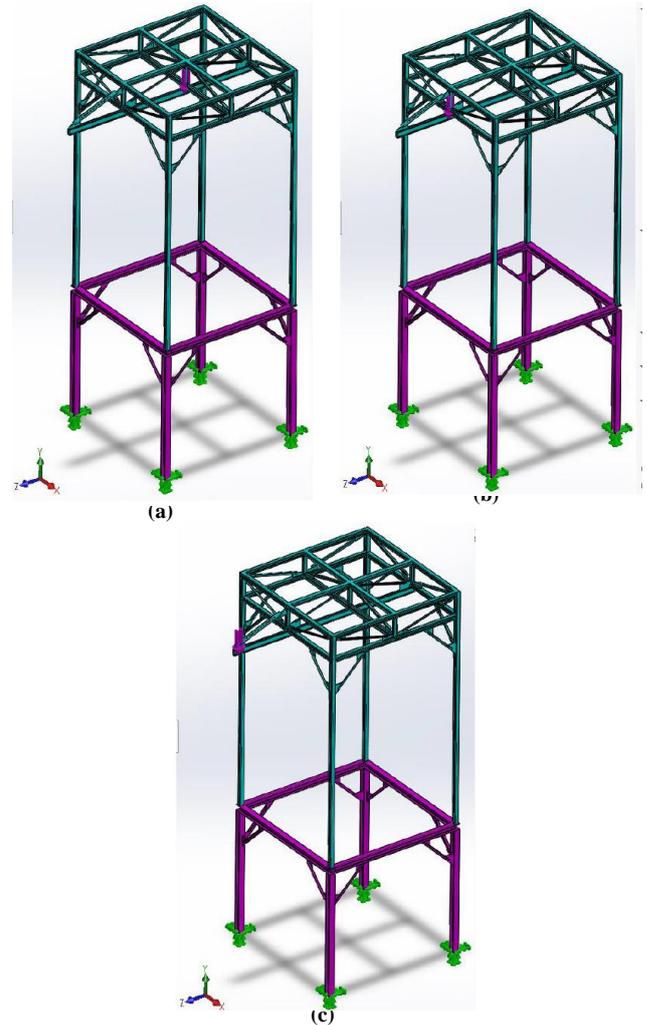

Figure 2: Load simulation of (a) Static 1, (b) Static 2 and (c) Static 3

The results revealed that the maximum von Mises stress values were 42.49 MPa, 29.70 MPa, and 72.26 MPa for Static 1, Static 2, and Static 3 conditions, respectively. These values are significantly below the yield strength of SS400 steel (205 MPa) and SS41 steel (350 MPa), indicating that the structure operates safely within its elastic range. Hence, no signs of failure or plastic deformation were detected, confirming the excellent structural integrity of the lifting framework.

The distribution of stress across the structure showed a consistent pattern, where stress concentration was mainly located at the junctions between the vertical columns and the beam supports. However, even at the highest recorded stress of 72.26 MPa, the region remained well within the safety margin, demonstrating that the design possesses sufficient stiffness and load-bearing capacity (Fieber *et al.,* 2020). The deformation profile also indicated uniform load transfer, with no local weaknesses or unstable zones, which further emphasizes the structure's balanced load distribution. Therefore, the analysis verifies that the guard filter cap lifting structure maintains its

structural integrity under realistic operating conditions (Fu *et al.,* 2021).

The results of the structural integrity analysis correlate directly with the operational demands of the guard filter cap maintenance process. In real-world applications, lifting operations often involve asymmetric loads due to uneven filter weight distribution or off-center pulling forces. The results demonstrate that the structure is capable of maintaining stability and safety even under such uneven loading conditions (Yao *et al.,* 2023). This finding validates the structure's suitability for replacing mobile cranes, offering a more compact and cost-efficient solution while ensuring compliance with industrial safety standards.

The Finite Element Analysis (FEA) conducted in this study proved effective in accurately predicting structural behavior. The model employed solid tetrahedral meshing with a fine mesh density to ensure accurate stress gradients across the structure (Kristijanto *et al.,* 2022). Simulation results revealed that the highest deformation values were 0.43 mm, 0.61 mm, and 2.13 mm across the three static conditions, respectively. These small displacement values confirm that the structure has high rigidity and minimal deflection under maximum loading. The strain analysis also yielded a maximum strain value of 1.746×10^{-4}, indicating that the material operates well within its elastic limit, with negligible risk of permanent deformation (Pomares *et al.,* 2021).

Detailed FEA post-processing results indicated that areas with the highest stress intensity were concentrated at bolt holes and joint interfaces between the primary beams and support columns. However, the maximum stresses remained significantly lower than the yield threshold, confirming the adequacy of the design in terms of safety and load transfer efficiency (Benincá & Morsch, 2020). This demonstrates that the FEA model can effectively simulate complex stress paths and provides accurate numerical representation of real loading behavior. Consequently, the study validates the effectiveness of using Finite Element methods in the optimization of small-scale lifting structures with varying geometric configurations (Akshara M., 2020).

The results from the FEA correlate well with theoretical predictions from structural mechanics. The analysis confirms that the load distribution, stress flow, and deflection patterns align with expected behavior for steel frame structures under concentrated loading conditions (Arrayago & Rasmussen, 2022). This consistency reinforces the accuracy of FEA as a numerical method for assessing small-scale mechanical systems. Moreover, the findings emphasize that modern design verification using FEA can reduce the need for full-scale

testing while maintaining high safety and precision standards (Fieber *et al.,* 2020).

The buckling analysis results revealed a Buckling Load Factor (BLF) of 67.947 for the first mode and −76.322 for the second mode. These values indicate that the structure is highly stable and will not experience buckling under the applied loading conditions. The positive BLF value greater than 1 confirms that the structure can withstand compressive loads many times greater than the operational load. The negative value on the second mode represents an unloaded or non-critical deformation mode, confirming that no instability occurs in practical operation.

The buckling mode shapes illustrated in Figure 3 indicate that deformation is concentrated along the upper beam segment where the load is applied. Nonetheless, no substantial displacement or notable geometric instability is detected. The structure's stiffness and proper bracing configuration contribute to its strong resistance to buckling. The simulation demonstrates that the structural design efficiently distributes compressive forces, minimizing the potential for localized instability or secondary bending effects. Thus, the overall buckling analysis confirms the structure's robustness and reliability for repeated operational use.

In practical industrial conditions, buckling failure often arises from improper loading, misalignment, or material fatigue over time. The high buckling load factor obtained in this study shows that the guard filter cap lifting structure possesses a substantial margin of safety and long-term operational stability (Pomares *et al.,* 2021). This result highlights that even when subjected to repeated use, the structure is unlikely to undergo geometric instability, ensuring a safe and reliable maintenance process. Consequently, this design can effectively replace traditional lifting systems while enhancing both operational efficiency and industrial safety standards.

The findings of this study demonstrate that the guard filter cap lifting structure exhibits exceptional performance in maintaining structural integrity under operational loads. The maximum von Mises stress recorded at 72.26 MPa remains far below the yield strength of the materials used, ensuring elastic performance and structural safety. The displacement values, ranging between 0.43 mm and 2.13 mm, indicate high rigidity and minimal deflection. Moreover, the buckling load factor (BLF) exceeding 1 in all modes confirms that the structure is highly stable and free from instability risks. These outcomes confirm that the structure can replace conventional mobile crane system.
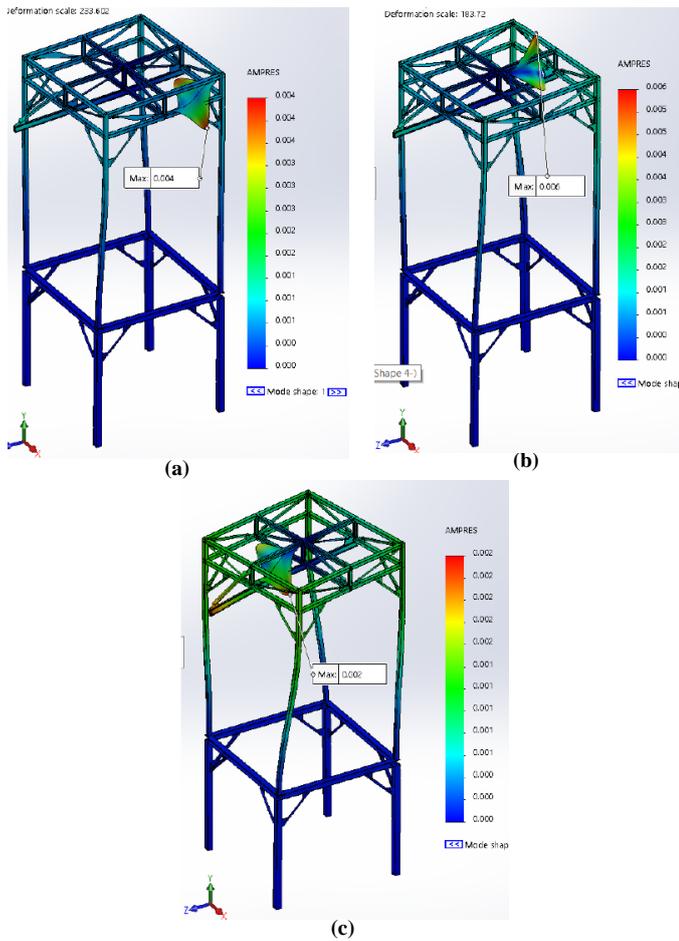
Figure 3: Buckling mode, (a) mode 1, (b) mode 2 and (c) mode 3

Compared to previous research, this study offers notable improvements in predictive accuracy and design validation. For instance, prior studies by (Arrayago & Rasmussen, 2022) primarily focused on the influence of imperfection directions on global stability, whereas the present work integrates multi-positional load conditions, offering a more realistic simulation framework. Similarly, (Kristijanto *et al.*, 2022) concentrated on shear buckling in corrugated plates but did not consider the integrated effect of load distribution and geometry on smaller industrial systems. The inclusion of three loading configurations in this research enhances the robustness of the evaluation and demonstrates the versatility of FEA for assessing stability in compact lifting frameworks. These findings highlight the innovation of this study in bridging the gap between theoretical modeling and practical application in mechanical lifting systems.

This research provides substantial insight into the practical and theoretical aspects of structural integrity analysis, particularly for lightweight industrial structures. By employing Finite Element Analysis, engineers can predict critical stress zones, deformation tendencies, and possible buckling points prior to fabrication. Such predictive modeling significantly

reduces the likelihood of design errors and enhances safety during operation. Furthermore, this study underlines the importance of integrating numerical validation in maintenance equipment design, offering a systematic framework for developing self-supporting lifting systems that are both safe and sustainable.

The implications of this study extend to industrial maintenance, design optimization, and safety management. From an engineering standpoint, the findings affirm that fixed lifting structures can replace mobile cranes, resulting in reduced space requirements and improved lifting efficiency. In addition, the analytical framework applied here can be utilized to evaluate other industrial support systems, such as maintenance gantries, overhead rails, and filter replacement stations. From an industrial safety perspective, the adoption of FEA-based verification ensures that such structures comply with safety standards while minimizing human risk exposure during lifting operations.

The favorable outcomes of this study can be attributed to three key factors: optimized structural geometry, accurate simulation configuration, and appropriate material selection. The geometry of the lifting frame was designed to distribute loads symmetrically, minimizing stress concentrations at joint interfaces (Zewudie & Zerfu, 2024). The FEA model incorporated realistic boundary conditions and refined meshing, enhancing the precision of stress and deformation predictions. Moreover, the selection of SS400 and SS41 steels, both possessing high ductility and yield strength, contributed to superior resistance against deformation and buckling. These factors collectively resulted in a structure capable of maintaining stability under diverse loading scenarios (Yao *et al.*, 2025).

Based on the results, several recommendations are proposed for practical application and future research. First, the guard filter cap lifting structure design should be adopted as a standard solution for filter maintenance systems in compact industrial facilities, as it enhances efficiency without compromising safety (Qasim & Al-Zaidee, 2020). Second, future studies should extend the analysis by incorporating nonlinear and dynamic loading conditions, as well as fatigue evaluation, to simulate long-term operational performance. Lastly, optimization techniques such as topology optimization and parametric analysis could be employed to further reduce structural weight while maintaining stability. Through these follow-up studies, the present research may serve as a foundational model for developing more adaptive, efficient, and sustainable industrial lifting systems.

V. CONCLUSION

The most striking finding of this research is that the guard filter cap lifting structure, analyzed through FEA, can withstand a maximum load of 10,200 N without exhibiting any signs of mechanical failure. The highest recorded stress, 72.26 MPa, remains far below the yield strength limits of SS400 and SS41 steels, demonstrating that the structure operates safely within its elastic region. This result confirms not only the structural soundness of the design but also reveals that the system achieves a safety margin exceeding four times the conventional design threshold. The discovery challenges the common assumption that structural efficiency must be achieved through complex geometries, proving instead that a simple, well-modeled structure can deliver comparable strength and performance to large-scale industrial lifting systems.

The principal contribution of this research lies in enhancing the scientific understanding and practical application of structural integrity analysis using FEA. Theoretically, it strengthens the relationship between stress distribution, geometric configuration, and overall stability in steel structures subjected to varying loads. Practically, this study provides a reliable framework for developing efficient, safe, and compact lifting structures that eliminate dependence on mobile cranes. The resulting design offers a cost-effective and space-saving solution for industrial maintenance operations. This work thus contributes both to the advancement of mechanical design theory and to the optimization of maintenance practices in the manufacturing and energy industries.

The limitation of this research lies in its focus on static and linear buckling analyses, without incorporating dynamic loading or fatigue effects that could occur during long-term operation. However, this limitation presents opportunities for future exploration. Subsequent studies should extend the analysis to include nonlinear buckling, fatigue life assessment, and vibration response under varying operational conditions. Furthermore, the implementation of topology optimization can help achieve lighter yet equally robust designs. These directions would expand the current research into a more comprehensive framework for developing adaptive, efficient, and sustainable lifting systems for future industrial applications.

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