TSSA Journal of Tomography System & Sensors Application Vol. 9, Issue 2, 2026
www.tssa.com.my e-ISSN: 2636-9133

Finite Element Analysis and Design Optimization of Heavy-Duty Storage Systems for Automated Palm Oil Harvesting

Yunus Othman [2], Nurul A'in Nadzri [1*], Nur Alya Hannani Binti Roslan [2], Muhammad Syukri Bin Hayattudin [2], Wan Muhamad Aqiff Zahid [2], Siti Aisyah Binti Kamarul Bahrom[2]

[1]Faculty of Electrical & Electronics Engineering Technology, Universiti Malaysia Pahang Al- Sultan Abdullah, 26600 Pekan, Pahang, Malaysia
[2]Department of Mechanical Engineering, Universiti Teknologi Petronas, 32610 Seri Iskandar, Perak, Malaysia

Corresponding author* email: nurulainadzri@umpsa.edu.my
Available online 01 July 2026

ABSTRACT

The palm-oil industry remains heavily dependent on manual labour for harvesting fresh fruit bunches (FFB), which creates challenges in productivity, cost, and worker safety. To support the move toward automation, this study focused on the design and validation of a square-shaped storage unit for an automated palm-oil harvester. A 3.0 m³ detachable storage bin with a maximum rated capacity of 900 kg was specified, reinforced with a steel frame and mesh walls. Analytical flexural strength checks were carried out on two representative faces of the bin, and finite element analysis (FEA) was performed in Autodesk Inventor to assess structural performance under a worst-case load of 10.4 kN. The results indicated that the maximum von Mises stress was 35 MPa, which remained below the allowable stress of 45.7 MPa, while the maximum displacement was limited to 1.695 mm at the centre of the panel. The safety factor analysis confirmed a minimum value of 15, matching the design target. These findings validate the structural adequacy and reliability of the proposed storage design and highlight its potential to reduce labour dependency in palm-oil harvesting.

Keywords: Palm oil harvesting, Storage design, Finite element analysis

1. Introduction

Palm oil is one of the most important agricultural commodities in Southeast Asia, contributing significantly to both local economies and global food and energy supply chains [1][2]. Harvesting fresh fruit bunches (FFB) is, however, highly labour-intensive [3] and physically demanding, requiring workers to cut bunches at height and transport them manually to collection points [4], [5]. This reliance on manual labour presents increasing challenges in terms of workforce shortages [6], productivity, and occupational safety [7]. The growing demand for palm oil, coupled with these labour issues, has created an urgent need for mechanisation and automation in harvesting systems [8].

In recent years, researchers and industry players have explored a variety of mechanised and semi-automated solutions to improve harvesting efficiency[9], [10], [11] . These include mechanised cutting tools, mobile platforms, and integrated transport systems. While these efforts have reduced dependence on manual labour, many prototypes have faced limitations in field application, such as high operating costs, bulky designs, and difficulties in adapting to plantation terrain. One critical challenge that remains under-addressed is the handling and temporary storage of FFB once harvested. Without an efficient storage solution integrated into the machine, significant delays occur as workers must transfer bunches multiple times before final collection[12], [13].

Previous studies in agricultural mechanisation have emphasised cutting technology, machine mobility, and energy efficiency. However, comparatively fewer works have examined the structural design of on-machine storage systems, despite their importance in ensuring reliability, safety, and productivity during harvesting operations. A poorly designed storage bin not only reduces efficiency but also risks structural failure due to the heavy and irregular loads imposed by FFB [14]. Therefore, storage design is not just an auxiliary component but a core element that determines the practicality of an automated harvesting system.

To address this gap, this study focuses on the design and evaluation of a square-shaped storage unit for automated palm oil harvesting. The design was developed based on practical specifications of capacity, weight limit, and safety requirements, and then validated through finite element analysis (FEA). The analysis considered worst-case loading conditions, evaluating von Mises stress distribution, displacement, and safety factor to ensure that the storage design could withstand field operation demands. By narrowing the focus to storage, this paper provides detailed insights into one of the most structurally critical yet underexplored aspects of harvesting automation.

The objective of this paper is therefore twofold: first, to contribute to the broader field of palm oil harvesting automation by highlighting the role of storage in reducing labour dependency, and second, to validate the proposed storage design through analytical and numerical analysis. The results demonstrate that the chosen design offers sufficient strength, stability, and safety margins, thereby supporting its feasibility for integration into future mechanised harvesting systems.

2. Methodology

2.1 Study design

The study was conducted as a design-and-analysis investigation of an onboard storage unit for a palm-oil harvester. The objective was to specify the storage geometry, materials, and operating features, then verify structural integrity using finite element analysis under a full fresh-fruit-bunch load. Acceptance criteria were that simulated stress remained below the allowable stress and that the computed safety factor met the target.

The design of the storage subsystem was guided by specific criteria to ensure that it could operate effectively in field conditions. These criteria focused on capacity, weight handling, mobility, and safety, which are summarized in Table 1.

Table 1. Criteria, specifications, and overall design features of the storage unit

Criteria	Remarks
Maximum volume capacity	1x2x1.5m = 3m^2
Maximum weight capacity	900 kg
Mobility	Detachable and can be opened at the bottom
Safety aspects	Safety lock

The maximum volume capacity was set at approximately 3 m³, derived from the bin dimensions of 1 m × 2 m × 1.5 m. This allowed the storage to accommodate enough fresh fruit bunches (FFB) per trip, improving efficiency compared to manual collection. The maximum weight capacity of 900 kg was chosen based on the expected load of 30–40 bunches, each weighing between 20 and 30 kg. This ensured that the bin would not be overloaded under normal harvesting cycles.

For mobility, the unit was designed to be detachable and incorporated a bottom-release mechanism. This feature allowed rapid unloading in the field and reduced the need for manual handling. The safety aspect was addressed by fitting locks at the sides and hinge. These prevented accidental opening during operation and also acted as a physical barrier against unauthorized access.

2.2 Specifications and materials

Based on these criteria, the storage was configured with a square planform. This geometry provided several advantages, it stored at least 25% more than circular containers of the same span, offered higher volumetric efficiency than triangular containers, and simplified fabrication due to its straight sides and 90° corners. Structurally, the square layout improved stability by ensuring flat contact with the chassis frame, reducing sliding, and lowering the center of gravity when fully loaded. The final configuration is illustrated in Figure 1. The model shows the reinforced steel frame, mesh wall panels, and critical features such as the corner pillar, which resists bending and carries vertical loads, and the base panel, which distributes fruit weight evenly. This figure demonstrates how the chosen square shape satisfied the criteria while providing structural reliability for subsequent finite element analysis.

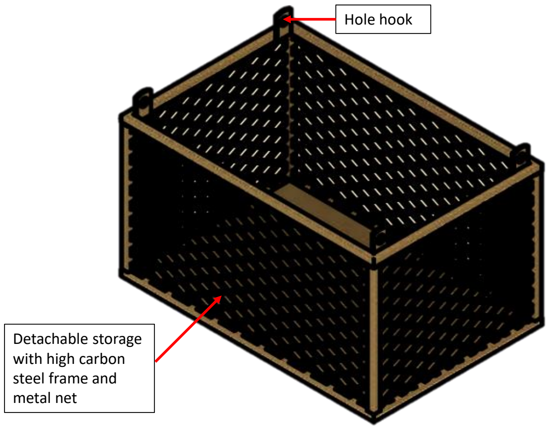

Figure 1. CAD model of the storage unit showing the reinforced steel frame and mesh walls. Arrows indicate the reinforced corner pillar and the base panel used in the finite element analysis.

The storage unit was designed with an internal volume of approximately 3.0 m³, achieved through the dimensions of 2.0 m × 1.5 m × 1.0 m. These proportions allowed the bin to fit securely within the chassis of the harvester while providing sufficient clearance to maneuver between palm trees. The chosen size also optimized the balance between capacity and stability, ensuring that the center of gravity remained low when fully loaded. Table 2 summarizes the key dimensional specifications of the storage unit.

Table 2. Dimensional specifications of the storage unit

Features	Dimensions (m)
Length	2
Width	1.5
Height	1
Metal mat thickness	0.0127
Frame thickness (area)	0.04 × 0.04

To facilitate structural analysis, the storage geometry was divided into two main faces, as illustrated in Figure 2. Side A corresponds to the larger panel measuring 2.0 m × 1.5 m, while Side B represents the smaller panel measuring 1.0 m × 1.5 m. These faces were selected for flexural strength evaluation since they are the primary load-bearing surfaces subjected to pressure from stacked fresh fruit bunches.

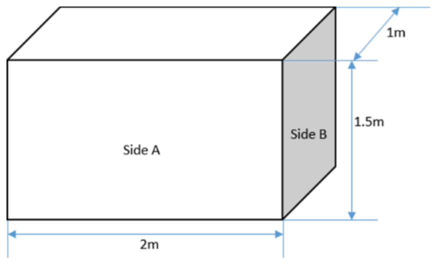

Figure 2. Storage geometry showing Side A (2.0 m × 1.5 m) and Side B (1.0 m × 1.5 m) used in flexural strength analysis.

2.3 Capacity and design loads

The frame was constructed from high-carbon steel with a square cross-section of 0.04 m × 0.04 m. This material was selected for its high yield strength and toughness, making it suitable for resisting bending moments and impact forces when bunches are dropped into the bin. The walls were formed from a metal net with a thickness of 0.0127 m. Compared to solid sheet panels, the netting reduced material cost, increased airflow, and provided a degree of flexibility while still confining the fruit securely. Reinforced steel pillars at each corner provided additional stiffness to prevent excessive lateral deflection under load.

The base panel was designed to withstand the greatest stress concentration, as it directly carried the weight of the fresh fruit bunches. For proof-of-concept analysis, the base was modeled using AISI 304 stainless steel with a thickness of 0.5 mm, chosen for its corrosion resistance and reliable mechanical performance. Operational features included a detachable design and a bottom-release mechanism, which allowed quick unloading in the field. Safety locks were incorporated at the sides and at the hinge to secure the storage during operation. These locks also reduced the risk of accidental opening and protected the harvested fruit from damage or unauthorized access. Overall, the specifications and material selections ensured that the storage unit was structurally robust, cost-effective, and practical for continuous field operation. The chosen configuration also provided a reliable basis for finite element analysis, where the structural integrity of the walls and base was further verified under simulated full-load conditions.

The storage unit was designed to carry a sufficient number of fresh fruit bunches (FFB) per harvesting cycle without exceeding the allowable weight capacity. In the nominal case, calculations showed that the bin could hold around 30 bunches, each weighing between 20 and 30 kg. This corresponded to a total load of 600–900 kg, which remained within the specified maximum capacity of 900 kg.

A more conservative proof-of-concept scenario was also considered using volumetric estimation. Based on the bin dimensions (2.0 m × 1.5 m × 1.0 m), the internal volume was approximately 3m³. The design load was established by estimating the number of fresh fruit bunches (FFB) that could be accommodated within this volume. Multiplying the average mass of one bunch by the total number of bunches provided the total weight:

$$W_{FFB} = n \times m_{avg} \qquad (1)$$

where n is the number of bunches and m_{avg} is the average mass per bunch.

By comparing the internal volume to the average size and mass of an FFB, the storage was estimated to hold about 46 bunches with an average mass of 23 kg. This gave a total weight of approximately 1,058 kg. The value was then converted into an equivalent gravitational load of about 10.4 kN for use in finite element analysis.

The second scenario intentionally exceeded the rated capacity to provide a worse-case design condition. By testing the structure against this higher load, the analysis ensured that the storage unit would remain structurally sound even in the event of overfilling during field operation. This load was therefore applied in the finite element model to evaluate the resulting stresses, displacements, and safety factors.

2.4 Numerical model and boundary conditions

Before conducting the finite element analysis (FEA), the storage base was simplified into a two-dimensional representation of its main load-bearing surfaces. As shown in Figure 3, the geometry was divided into two critical faces: Side A, representing the larger panel, and Side B, representing the smaller panel. These faces were identified as the most important structural elements because they are directly subjected to the distributed pressure generated by stacked fresh fruit bunches (FFB). Defining the surfaces in this manner allowed both analytical checks and numerical simulation to be carried out systematically, with Side A and Side B serving as the basis for evaluating bending response, stress distribution, and displacement.

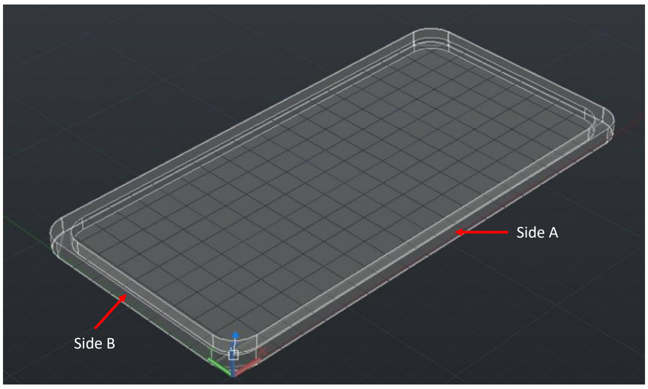

Figure 3. Geometric representation of the storage base showing Side A (2.0 × 1.5 m) and Side B (1.0 × 1.5 m) used in analytical checks and finite element analysis

To verify their structural adequacy, flexural stress was calculated using the standard relation

$$\sigma = \frac{3FL}{2bd^2} \qquad (2)$$

where F is the applied force, L is the span length, b is the breadth, and d is the thickness. Substituting the design dimensions for Side A resulted in an estimated force of approximately 0.024 N, while Side B produced a value of about 0.05 N. These values were small relative to the allowable stress of the material, confirming that the mat thickness was sufficient to resist bending under the expected load.

Following this analytical validation, a proof-of-concept finite element model was developed to assess the detailed structural performance. One wall panel was represented as a sheet supported along its edges to simulate the welded connection between the metal net and the surrounding steel frame. The base of the storage was modelled separately using AISI 304 stainless steel with a thickness of 0.5 mm, as this component carried the greatest share of the applied load. The analysis focused on three output parameters: the maximum von Mises stress, the maximum displacement in the vertical direction, and the safety factor distribution across the evaluated surfaces.

The safety evaluation followed the standard relation

$$FoS = \frac{UTS}{\sigma eq} \tag{3}$$

where UTS is the ultimate tensile strength of the material and σ_{eq} is the von Mises stress from FEA. The allowable stress was obtained by rearranging this relation as

$$\sigma allow = \frac{UTS}{FoS} \tag{4}$$

For high-carbon steel with a tensile strength of 685 MPa and a target safety factor of 15, the allowable stress was calculated as approximately 45.7 MPa. The stress obtained from the simulation was then compared against this allowable limit to determine whether the design was structurally adequate.

Boundary conditions were applied by fixing the lower frame edges to replicate the rigid attachment of the storage to the harvester chassis. The finite element mesh was refined around welded joints and the base panel to capture stress concentrations more accurately. By combining analytical checks with detailed simulation, the methodology ensured that the storage design was verified against both simplified calculations and numerical modelling under worst-case loading conditions.

3. Results and Discussion

This section presents the outcomes of the finite element analysis (FEA) performed on the storage unit to evaluate its structural performance under the applied design load of 10.4 kN. The analysis was carried out in Autodesk Inventor using a static structural environment, and the results are discussed in terms of von Mises stress distribution, displacement behaviour, and safety factor validation. Validating the storage design is essential because it represents the primary load-bearing component of the automated harvester, and its structural adequacy directly affects both the safety and efficiency of palm-oil harvesting operations.

Figure 4 illustrates the von Mises stress distribution of the storage base subjected to the applied load of 10.4 kN. The contour plot shows that the highest stress, approximately 35 MPa, occurred near the welded joints at the edges of the panel, while the central region of the base experienced considerably lower stresses, generally below 10 MPa. This pattern indicates that the load was primarily resisted at the fixed supports, where the welded frame provided stiffness and restraint against deformation. The gradual transition of stress from the edges towards the centre follows the behaviour predicted by plate bending theory, in which stresses are greatest at constrained boundaries and diminish toward free spans. The stress remained below the allowable limit of 45.7 MPa, calculated from equation (4), confirming that the storage could withstand the applied load safely.

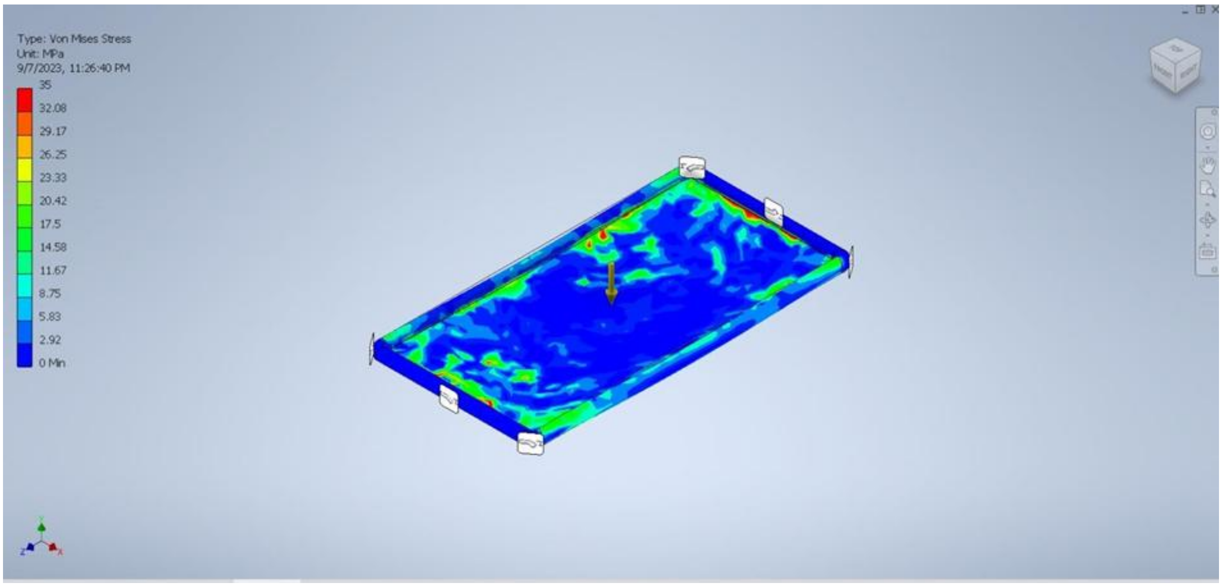

Figure 4. Von Mises stress distribution of the storage base under a 10.4 kN applied load, showing maximum stresses concentrated near the welded edges and lower stresses at the central span.

The observed distribution occurred because the welded boundaries created zones of high bending moments, concentrating stresses along the edges. In contrast, the central span acted more flexibly, spreading the load across a wider area and resulting in reduced stress intensity. The presence of localized peaks around the weld fillets is consistent with the principle of stress concentration, where abrupt geometric transitions amplify local stresses beyond the average values. Fundamentally, this behaviour can be explained using the bending stress relation

$$\sigma = \frac{My}{I} \tag{5}$$

Where bending moment M is largest at the supports, and the second moment of area I of the welded frame controls the resistance to bending.

This explains why stresses accumulated at the panel boundaries while remaining lower in the mid-span region. Overall, the von Mises stress results demonstrated that the storage structure was capable of withstanding the design loading condition without exceeding material limits. The stress patterns were consistent with theoretical expectations of plate bending and welded joint behaviour, thereby validating both the numerical model and the structural adequacy of the design.

Figure 5 illustrates the displacement distribution of the storage base when subjected to the design load of 10.4 kN. The analysis shows that the maximum displacement reached approximately 1.695 mm, located at the center of the panel, while the edges remained fixed with negligible movement. The displacement contours followed a concentric pattern, gradually reducing from the center toward the boundaries, which is consistent with the behavior of a plate supported along its edges. The smooth gradient of deformation indicates that the load was uniformly transferred across the surface, with no signs of localized instability or buckling.

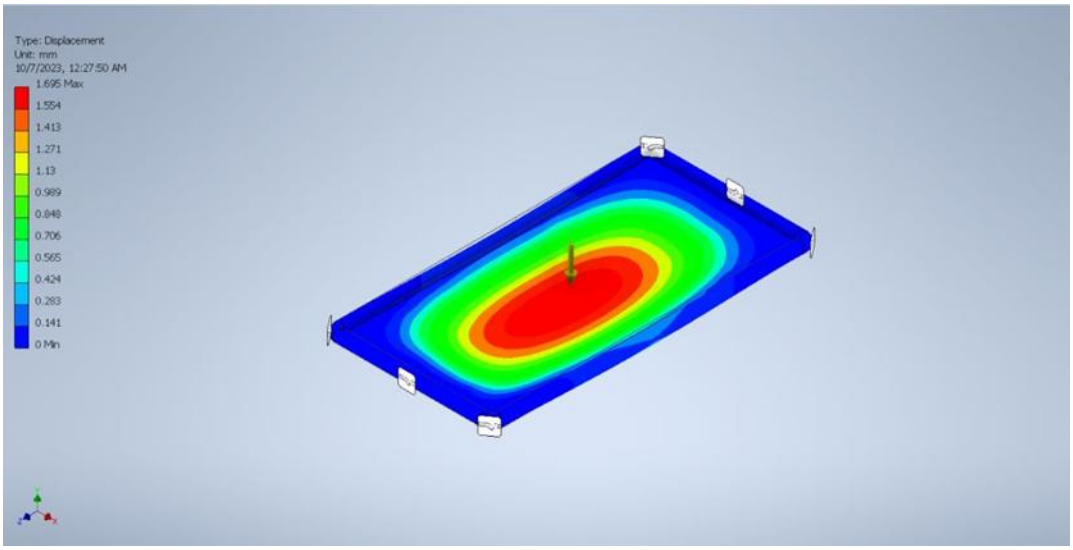

Figure 5. Displacement distribution of the storage base under a 10.4 kN applied load, showing a maximum central deflection of 1.695 mm with symmetric reduction toward the fixed edges.

The central deflection pattern observed is typical of bending in rectangular plates, where the maximum deflection occurs at the midpoint of the span, and the displacement decreases symmetrically toward the supports. This behaviour is explained by classical plate theory, where displacement is proportional to the applied pressure and inversely proportional to the flexural rigidity of the plate, expressed as

$$\delta = \frac{qL^4}{Eh^3} \qquad (6)$$

Here, q is the distributed load, L the span length, E the modulus of elasticity, and h the plate thickness. Because the storage base had a relatively thin wall section supported by stiff welded edges, the center experienced greater deformation while the boundaries constrained movement.

Despite the deflection, the magnitude of less than 2 mm is small compared to the overall dimensions of the storage (2 m × 1.5 m), representing less than 0.1% of the span length. This confirms that the deformation was within the elastic range and would not compromise the serviceability or functionality of the storage during operation. The result also supports the adequacy of the chosen material and thickness, as the structure maintained its integrity under worst-case loading conditions.

Figure 6 illustrates the safety factor distribution of the storage base under the design load of 10.4 kN. The simulation showed that the minimum safety factor reached approximately 15, which corresponded exactly to the design target established in the methodology. Across the surface of the panel, the safety factor was uniformly distributed, with no regions dropping below the threshold. This indicates that the stresses developed in the structure remained consistently within the allowable limits of the material.

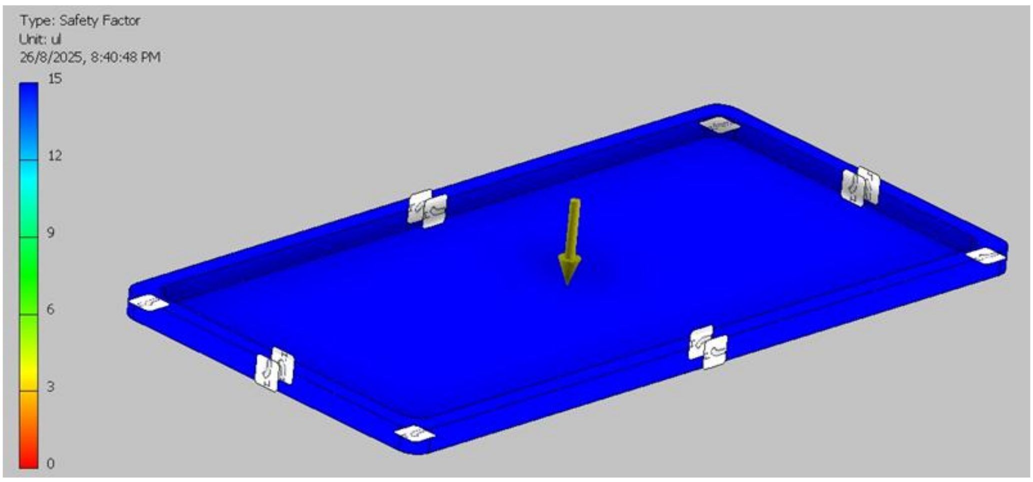

Figure 6. Safety factor distribution of the storage base under a 10.4 kN applied load, showing a minimum factor of 15 uniformly maintained across the structure.

The uniform distribution can be explained by the balance between the applied load and the structural stiffness of the welded frame. Since the von Mises stresses, as shown previously in Figure 4, remained well below the allowable stress of 45.7 MPa, the calculated factor of safety remained high across the entire model. This reflects that the storage base did not experience any localized overstressing or instability that could reduce structural reliability.

From a theoretical perspective, the factor of safety is defined as the ratio of the material's ultimate tensile strength to the equivalent stress obtained from simulation, expressed as in equation (3). With an ultimate tensile strength of 685 MPa and a maximum stress of only 35 MPa, the resulting value produced a factor of safety around 15. This result is consistent with the input design requirement and demonstrates that the storage structure has a considerable margin of safety under worst-case loading conditions.

Overall, the safety factor analysis confirms that the storage design is highly reliable. The large margin ensures that even if variations occur in field loading, material imperfections, or fabrication quality, the structure will remain secure during operation. This strengthens the conclusion that the storage unit is not only adequate but also robust for integration into automated palm oil harvesting.

4. Conclusions

This study investigated the design and structural validation of a square-shaped storage unit intended for integration into an automated palm-oil harvesting system. The design was specified based on a 3.0 m³ capacity, a maximum weight limit of 900 kg, and reinforced safety features, including a detachable configuration and bottom-release mechanism. Finite element analysis (FEA) was employed in Autodesk Inventor to evaluate the suitability of the storage under a worst-case load of 10.4 kN. The results demonstrated that the maximum von Mises stress of 35 MPa was well below the allowable stress of 45.7 MPa, indicating that the structure remained within safe operating limits. The displacement analysis showed a maximum deflection of only 1.695 mm at the central span, confirming that deformation was minimal relative to the storage dimensions and did not compromise serviceability. The safety factor analysis further verified the robustness of the design, with a minimum value of 15 uniformly distributed across the structure. These findings confirm that the proposed storage unit is structurally adequate, reliable, and capable of withstanding the loads associated with fresh fruit bunch handling in plantation operations. By validating the design through both analytical checks and simulation, this work highlights the importance of storage as a critical component in reducing labour dependency and improving efficiency in palm-oil harvesting automation. Future work could extend this study by evaluating the full harvester assembly, incorporating dynamic loading conditions, and conducting field trials to validate performance under real harvesting environments.

Acknowledgment

The authors would like to acknowledge the support of their university and research center for providing facilities and resources to carry out this study.

References

[1] K. I. Muhammad, A. H. Sharaai, M. M. Ismail, R. Harun, and W. S. Yien, "Social implications of palm oil production through social life cycle perspectives in Johor, Malaysia," *Int J Life Cycle Assess*, vol. 24, no. 5, pp. 935–944, May 2019, doi: 10.1007/s11367-018-1540-y.

[2] E. Meijaard *et al.*, "The environmental impacts of palm oil in context," *Nat Plants*, vol. 6, no. 12, pp. 1418–1426, Dec. 2020, doi: 10.1038/s41477-020-00813-w.

[3] M. Mosquera-Montoya, D. E. Munévar Martínez, E. Ruíz Álvarez, C. A. Fontanilla-Díaz, Ó. H. Salamanca, and J. M. Obregón Esguerra, "Labor productivity assessment of three different mechanized harvest systems in Colombian oil palm crops," *OCL*, vol. 30, p. 15, Aug. 2023, doi: 10.1051/ocl/2023014.

[4] S. Mohamaddan, M. Andrew-Munot, S. J. Tanjong, S. Z. M. Dawal, K. Case, and A. Hanafusa, "Investigation of the Usage of Oil Palm Harvesting Tools on Work Related Musculoskeletal Disorders of Lower Limb," in *2021 IEEE 3rd Eurasia Conference on Biomedical Engineering, Healthcare and Sustainability (ECBIOS)*, IEEE, May 2021, pp. 41–44. doi: 10.1109/ECBIOS51820.2021.9510258.

[5] S. Mohamaddan *et al.*, "Investigation of oil palm harvesting tools design and technique on work-related musculoskeletal disorders of the upper body," *Int J Ind Ergon*, vol. 86, p. 103226, Nov. 2021, doi: 10.1016/j.ergon.2021.103226.

[6] E. Meemken *et al.*, "Policy for Decent Work in Agriculture," *Agricultural Economics*, vol. 56, no. 3, pp. 401–418, May 2025, doi: 10.1111/agec.70009.

[7] M. Ekmekci and S. Yaman, "Occupational health and safety among farmers: a comprehensive study in Central Anatolia, Turkey," *BMC Public Health*, vol. 24, no. 1, p. 2732, Oct. 2024, doi: 10.1186/s12889-024-20249-7.

[8] N. Ramasenderan, V. Thiruchelvam, U. Saeed, K. Ravinchandra, C. K. Ze, and S. K. Sivanesan, "Autonomous navigation system with weight detection for autonomous loose fruit collector," 2024, p. 020136. doi: 10.1063/5.0229308.

[9] Y. Hua *et al.*, "Recent Advances in Intelligent Automated Fruit Harvesting Robots," *Open Agric J*, vol. 13, no. 1, pp. 101–106, Aug. 2019, doi: 10.2174/1874331501913010101.
[10] Y. Hua and K. Nagasaka, "Recent patents on intelligent automated fruit harvesting robots for sweet pepper and apple," *The Journal of Applied Horticulture*, vol. 25, no. 01, pp. 65–68, Mar. 2023, doi: 10.37855/jah.2023.v25i01.11.
[11] M. M. Foglia, A. Gentile, and G. Reina, "Robotics for Agricultural Systems," in *Mechatronics and Machine Vision in Practice*, Berlin, Heidelberg: Springer Berlin Heidelberg, pp. 313–332. doi: 10.1007/978-3-540-74027-8_27.
[12] J. Liu, S.-Y. Liew, B. Y. Ooi, and D. Qin, "Efficient Order-based Scheduling Algorithms for Automated Retrieval System (ARS) in Smart Warehouses," in *2020 20th International Conference on Control, Automation and Systems (ICCAS)*, IEEE, Oct. 2020, pp. 839–844. doi: 10.23919/ICCAS50221.2020.9268419.
[13] M. Woschank, D. Steinwiedder, A. Kaiblinger, P. Miklautsch, C. Pacher, and H. Zsifkovits, "The Integration of Smart Systems in the Context of Industrial Logistics in Manufacturing Enterprises," *Procedia Comput Sci*, vol. 200, pp. 727–737, 2022, doi: 10.1016/j.procs.2022.01.271.
[14] J. C. Sagarnaga and A. D. Kulkarni, "The Need for a Comprehensive Standard/Code for the Design of Bins and Silos in the USA," in *Structures Congress 2019*, Reston, VA: American Society of Civil Engineers, Apr. 2019, pp. 349–360. doi: 10.1061/9780784482230.034.