Turkish Journal of Engineering
https://dergipark.org.tr/en/pub/tuje
e-ISSN 2587-1366

Design sustainability of rollover protective structure in tractors

Sakthivel Murugesan[1], Elamvazhudi Balasubramaniyan*[2], Kulothungan Subramaniyan[3]

[1]*Department of Mechanical Engineering, IFET College of Engineering, Villupuram, Tamil Nadu, India,* sakthivel@ifet.ac.in
[2]*Department of Mechanical Engineering, IFET College of Engineering, Villupuram, Tamil Nadu, India, elamvazhudib@gmail.com*
[3]*Department of Mechanical Engineering, IFET College of Engineering, Villupuram, Tamil Nadu, India, kulo.rajan@gmail.com*

Cite this study: M. Sakthivel, B. Elamvazhudi, S. Kulothungan. (2025). Design Sustainability in Rollover Protective Structure for Tractors. Turkish Journal of Engineering, 9 (3), 402-408.

https://doi.org/10.31127/tuje.1523230

Keywords

ROPS, Tractor, Prototype; static analysis, Finite Element Analysis

Research Article

Received:27.07.2024
Revised:26.08.2024
Accepted:28.08.2024
Published:01.07.2025

Abstract

Rollover Protective Structure (ROPS) design is becoming more important in tractors. Static analysis in accordance with the SAE J2194 standard is necessary for the designing ROPS prototypes that maximize safety while minimizing environmental impact. Using renewable and recyclable materials, energy-efficient production techniques, and sound design concepts to increase lifetime and durability are important tactics. In order to promote cradle-to-cradle design principles, the lifecycle assessment approach is utilized to examine environmental implications from material extraction to end-of-life disposal. The study shows how sustainable ROPS can be achieved by maximizing material consumption, putting modular designs into practice, and making sure that regulations are followed. To promote economic and social sustainability, factors like worker safety, local production, and recyclability are also taken into account. This analysis is a framework for designing ROPS that not only ensure operator safety but also contribute to broader sustainability goals, supporting a more sustainable agricultural sector. In this study, static load analysis on ROPS frame with different cross sections and loading conditions was performed using Finite Element Analysis (FEA). Three different cross sections were investigated: square, circular, and hollow circular. The produced stress, strain, and deformations under combined loading circumstances can be used to assess ROPS performance. The post-processing results reveal that the material qualities, shape, and loading conditions have a direct impact on the static load behaviour of ROPS. In comparison to other cross sections, the circular cross section has a high load bearing capacity and minimum deformation.

1. Introduction

Rollover Protective Frames are fixed structures designed to withstand rollovers and protect the operator. Folding ROPS are hinged structures that can be folded down and offers flexibility. Rollover Protective Enclosures are more comprehensive structures that include protective frames and enclose the operator within a cabin. Roll Over Protective Structure (ROPS) is a system designed to protect operators of vehicles, particularly heavy machinery and agricultural equipment, in the event of a rollover. ROPS are engineered to withstand significant impact forces and prevent collapse during rollovers, using high-strength materials and robust structural design. In challenging environments like mining tunnels, where space is confined and conditions are harsh, ROPS are compact and robust. ROPS mitigate these risks by providing a protective structure that maintains integrity during a rollover, reducing the likelihood of injury. ROPS typically consists of a robust framework made from materials such as steel, designed to withstand the forces generated during a rollover. These structures are securely mounted to the vehicle's frame to ensure stability and integrity. Rust, wear, and tear can significantly affect the efficiency of ROPS by weakening the material and compromising structural integrity. ROPS is crucial in preventing fatalities and serious injuries. During a rollover, the structure helps maintain a safe zone around the operator, preventing the vehicle from crushing the occupant. It significantly reduces the likelihood of head injuries and other trauma by preventing contact with the ground or other harmful objects.

ROPS design is becoming more important these days in order to meet the operator's expectations in terms of comfort and safety. There is a risk of big pieces of earth masses falling over the operator compartment in mining tunnels. The tractor rolls over due to uneven ground surfaces, tractor speed, and tractor load. The compartment design must be carefully considered in order to avoid serious accidents and save the operators' life. High yield strength of steel ensures that the structure can withstand large forces without permanent deformation. Good ductility allows the steel to absorb and distribute impact energy without fracturing. This combination helps ROPS to effectively absorb and dissipate the energy during a rollover, reducing the risk of failure and enhancing operator protection. ROPS structures are subject to rigorous testing and must meet specific standards to be certified as effective. These tests simulate rollover scenarios to verify the protective capability of the structure. Vehicles equipped with ROPS can return to service more quickly after an incident, reducing downtime and maintaining productivity. ROPS must be designed specifically for each type of vehicle, considering the vehicle's size, weight, and typical operating conditions. Proper installation by certified professionals is critical to ensure that the ROPS performs as intended during an accident. ROPS effective design protects operators from major injury during tractor rollovers in extreme scenarios. Rollover protective structures are divided into three categories: rollover protective frame, folding ROPS, and rollover protective enclosure. Because the top half of the ROPS folds down, less overhead clearance is required in folding ROPS constructions. A metal and glass frame, as well as seatbelts, are sup-plied in rollover protective enclosures. The cabin is protected from dust, chemicals, noise, and vibration with this style of enclosure. When the frame is damaged, the ROPS's efficiency is reduced. Rust, wear, and tear are typical examples of these damages. It is extremely difficult to predict the strength of a damaged rollover protection structure. In the presence of apparent defects such as fractures, bends, and so on, the strength of weldments in ROPS structures can be examined by the designer. Many attempts at ROPS design for agricultural tractors have been proposed, according to literature reviews. Computer based ROPS design was developed based on weights of the tractor components [1]. The roof structure and beams, such as a four-post column shown in Figure 1 was modeled according to SAE J2194 standard [2]. Non-foldable ROPS for tractors was designed for tractors to maintain the safety of the structure and to make more profitable [3]. FEA was performed on SD190 full ROPS structure as per ISO 3471 and optimization study was also performed to predict the load carrying ability of the structure [4]. The ROPS model was developed using solid works software [5-6]. In which, tractor and ramp was modelled based on the scale 1:16. The design of rollover protective structure is designed using FE model based on the maximum lateral force. The produced stress and strain was calculated using elastic and plastic theories [7-8]. The failure analysis of rollover structures under combined horizontal and vertical loading is still a relatively unknown issue that requires a great deal of more investigation. The goal of this project is to use FEA to develop an effective rollover protective structure with square, circular, and hollow circular sections, as well as to investigate the behavior of tractors under static loading conditions. The performance of the ROPS assessed by maximum stress, total strain energy, and from the total deformations under combined loading conditions [9-10].

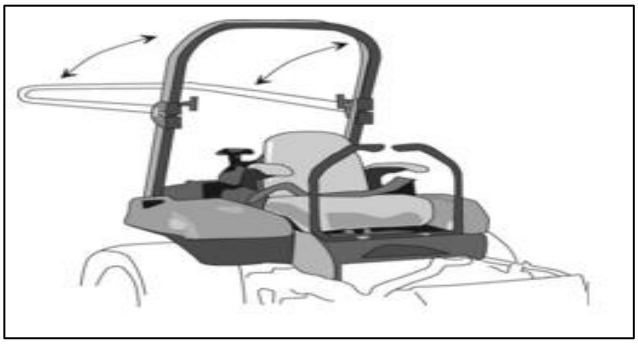

Figure 1. ROPS structure

2. Materials and Methods

The material used for Roll Over Protective Structures (ROPS) is typically high-strength steel due to its excellent combination of durability, toughness, and ability to absorb impact energy during a rollover. Aluminum and composite materials offer different mechanical properties compared to steel. Aluminum is lightweight but generally has lower yield strength compared to steel. This steel must possess properties such as high yield strength and good ductility to ensure it can withstand significant forces without failing. Sometimes, other materials like aluminum or composite materials are considered for specific applications, where weight reduction is critical, but these must still meet stringent safety and performance standards [11]. The manufacturing process of ROPS involves several steps to ensure the structure's integrity and performance. The ROPS manufacturing process involves several steps including material selection, design, fabrication, assembly and testing. It begins with precise cutting and shaping of the steel components, often using CNC machines for accuracy. These components are then welded together, with special attention to the quality and strength of the welds, as they are critical to the overall strength of the structure. After welding, the ROPS may undergo heat treatment to enhance its mechanical properties. Finally, the structure is often subjected to surface treatments like powder coating or galvanization to prevent corrosion, ensuring durability in various environmental conditions. Throughout the manufacturing process, rigorous quality control measures are implemented to ensure that the final product meets all safety and regulatory standards. In most cases, the tractor industry prefers structural steel as a material for manufacturing ROPS. High-stress areas such as mounting points, corners, and bends are identified through stress analysis techniques. Table 1 summarizes the mechanical properties of the steel material. The SAE J2194 tractor part of a combination earth-moving equipment was used to design the rollover protecting structure. Three ROPS were created, each with a different cross section: square, circular, and hollow circular. The dimensions are 150 cm x 140 cm x 116 cm. The bar's cross section is 5 x 5 cm^2 and the section thickness is 1 cm.

Table 1. Mechanical properties

Properties	Structural Steel
Tensile Strength	276-1882 MPa
Yield Strength	186- 758 MPa
Modulus of Elasticity	2 x 105 MPa
Elongation %	10-32
Density	7870 kg/m^3

3. Finite Element Analysis

Finite Element Analysis is a sophisticated computational technique extensively utilized in engineering, physics, and various scientific domains to simulate and understand the behavior of complex systems [12-13]. It operates on the principle of dividing intricate structures or systems into smaller, more manageable components known as finite elements, which are interconnected at nodes to represent the overall behavior of the system [14]. FEA employs mathematical formulations based on principles from continuum mechanics to describe the behavior of materials and the interactions between different components [15]. Engineers create digital models of the systems under study, specifying parameters such as geometry, material properties, boundary conditions, and applied loads. These models are then discretized into finite elements through meshing processes. Once the model is prepared, specialized software is used to solve the system of equations governing the behavior of each finite element and their interactions [16-17]. Through iterative numerical methods, the software converges to a solution, providing detailed insights into various aspects such as stress distribution, deformation, vibration modes, thermal effects, and more. FEA has widespread applications across industries, including aerospace, automotive, civil engineering, biomechanics, and manufacturing, enabling engineers to optimize designs, analyze performance, and enhance reliability while minimizing development time and costs [18-19]. Pre-processing, processing, and post-processing are the three essential procedures that must be followed in finite element analysis. Selecting the element type, establishing the material properties, modelling the component, and adding boundary and loading conditions as input parameters are all done during the pre-processing stage.

Figure 2(a) shows the 3D CAD model created with Creo 5.0 and the dimensions of the ROPS. The CAD model was imported for analysis meshed using eight nodded tetrahedron elements for getting accurate results, as well as a colour gradient contour pattern for a better comprehension of the results. Figure 2 (b) depicts the meshed model of ROPS structure. The meshed model helps identify potential weaknesses and optimize the design for improved performance and safety. For achieving the better connectivity between the elements and to avoid singularity error, fine meshing is preferred. Explicit impact analysis was done to predict the deformation, unknown variable and time. The applied loading conditions are lateral, longitudinal and vertical loading. The ROPS subjected to side transverse load of 17.5 kN, longitudinal load of 14 kN, and vertical load of 40 kN.

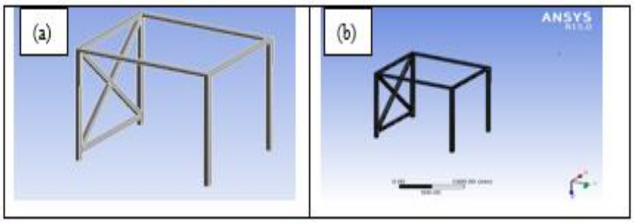

Figure 2. (a) Modeling (b) Meshed model

4. Simulation

Predicting the stress and strain energy distributed in ROPS is critical for ensuring their defensive performance during rollover incidents. High stress areas typically include mounting points, corners, bends, and impact zones, where forces are concentrated due to load transfer and geometric discontinuities [20]. Analysis techniques like von Mises stress and principal stresses are used to identify potential failure points. Strain energy, representing the energy stored due to deformation, should be distributed as uniformly as possible to maximize energy absorption and minimize the forces transmitted to the operator. Finite Element Analysis (FEA) simulates rollover scenarios to visualize and optimize stress and strain energy distribution, ensuring materials with high ductility and toughness are used, and the ROPS design incorporates smooth curves and strategic reinforcements [21-22].

This comprehensive analysis ensures the ROPS is robust and reliable, providing maximum protection in rollover events. Cross-sectional designs influence how forces are absorbed and transmitted through the ROPS during a rollover, affecting its effectiveness in protecting the operator. The stress analysis was performed on meshed model to predict the behavior of these sections using finite element analysis. The post-processing results summarized the values of total deformation, directional deformation along x, y and z-axis, total strain energy and equivalent stress [23-24]. The post-processing results of the ROPS for circular cross-section is shown in Figure 3. The total deformation along x, y, and z directions is 0.847 mm, 7.654 mm, and 8.651 mm respectively. The results revealed that the total deformations along the z-axis is maximum compared to all other directions. Which indicates that the structure can withstand maximum load in z-direction. The total strain energy of 161.68 MJ and the equivalent stress of 162.11 MPa was observed under combined loading conditions. This phenomenon is related to the total amount of strain energy stored per its unit volume which indicates that the plastic deformation is maximum in the structure under the given loading conditions [25-26].

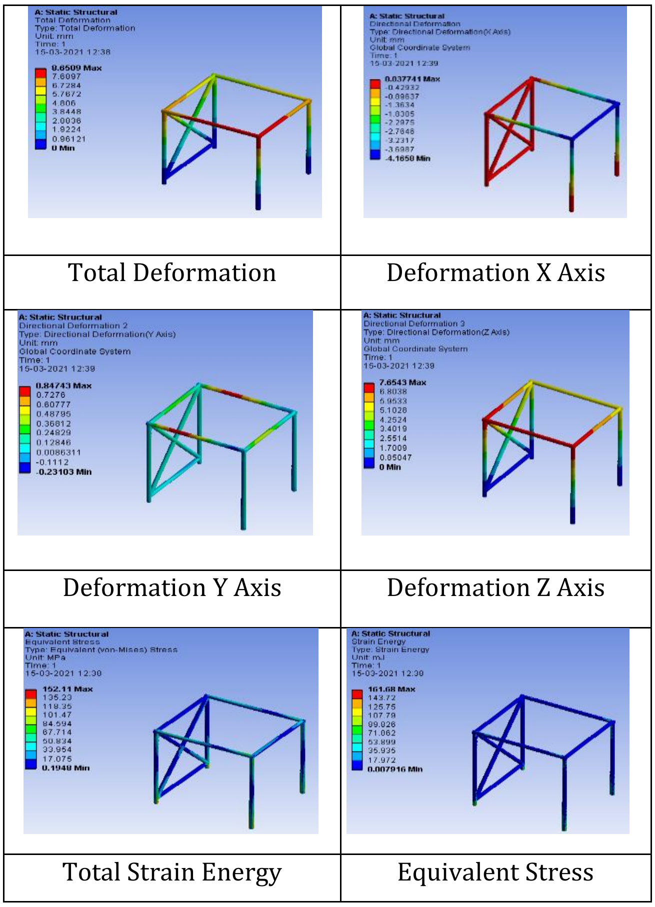

Figure 3. Stress and strain energy distribution of ROPS with circular cross-section

Variations in loading conditions significantly affect the stress and deformation results of the ROPS design. We have considered different loading scenarios to evaluate the structural integrity of the design. Figure 4 presented the post-processing results of ROPS with square cross-sectioned members. The deformation in x, y, and z-directions are 0.021 mm, 8.414 mm, 0.797 mm respectively. The total deformation is 9.14 mm. this results showed that the maximum deformation obtained in y-direction. Which revealed that square cross sectioned members can withstand the maximum load in y-direction under given loading and boundary conditions. The total strain energy was 179.76 MJ and the corresponding stress was 159.54 MPa observed under combined loading conditions. Maximum strain energy was stored with minimum stress values which reveals that the square cross sectioned members in ROPS can withstand maximum load with minimum deformation [27-28]. The deformation along x, y, and z axis and total deformation of ROPS with hollow circular cross-section is summarised in the Fig. 5. The values of deformation is 0.009 mm, 7.654 mm, 0.847 mm in x, y, and z directions respectively. The total volume deformation is 13.03 mm. According to the deformation values, the highest deformation occurs along the y-axis, which indicates that hollow circular cross sectioned members can deform more in y-directions compared to other two directions. The total strain energy stored in ROPS designs indicates how much energy the structure can absorb before failure. The total strain energy of 239.22 MJ and an equivalent stress of 152.62 MPa were reported under the combined loading conditions. The strain energy is stored is maximum under minimum stress conditions. Which indicate that the hollow circular cross sectioned members can absorb maximum strain energy under minimum deformation. This phenomenon is because of higher rigidity and stiffness of the structure [29-30].

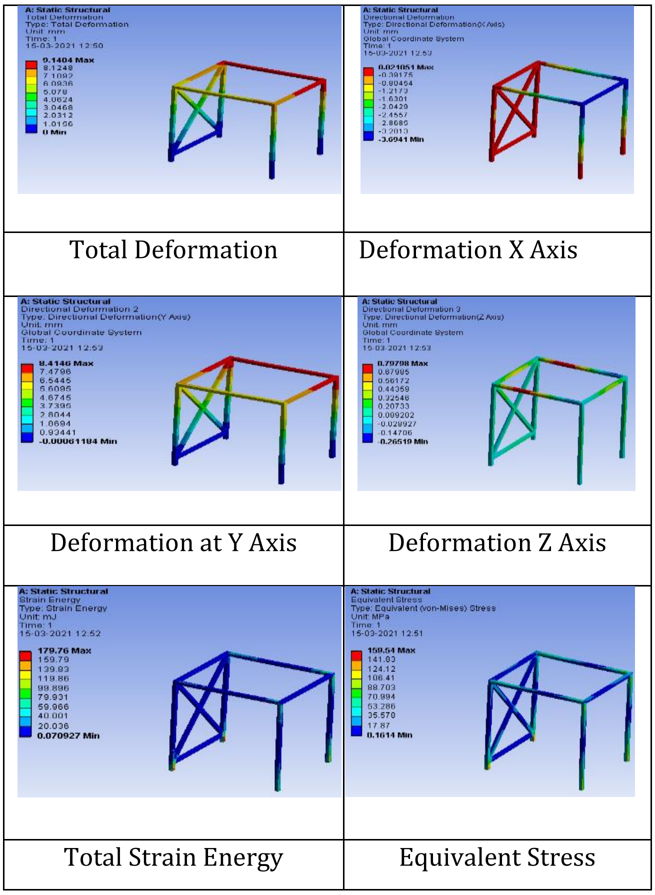

Figure 4. Stress and strain energy distribution of ROPS with square cross-section

In the Figure 6 the total deformation values of all cross-sections were compared. In the hollow-circular cross-section, the overall deformation value is highest (13.01 mm). Circular section bars have the least amount of distortion (8.65 mm). The total deformation of a hollow circular section is 50.4 % more than that of a square and 42.3 % higher than that of a circular section. This is owing to the hollow-circular section's larger section modulus. In the Figure 7, the total strain energy of all cross-sections was compared. In a hollow-circular cross section, total strain energy is at its lowest (152.62 MJ). Square section bars have the most strain energy (179.76 MJ). In comparison to the other two portions, the hollow circular section has the lowest strain energy. In the Figure 8, equivalent stress levels for all cross-sections were compared. In a hollow-circular cross section, the equivalent stress is 239.22 MPa. Circular section bars have a minimum stress of 152.11 MPa. The total deformation of a hollow circular section is 50.4 % more than that of a square and 42.3 % higher than that of a circular section. This is owing to the hollow-circular section's larger section modulus. Deformation in X, Y, Z identifies horizontal bending or twisting forces, vertical compression and lateral forces.

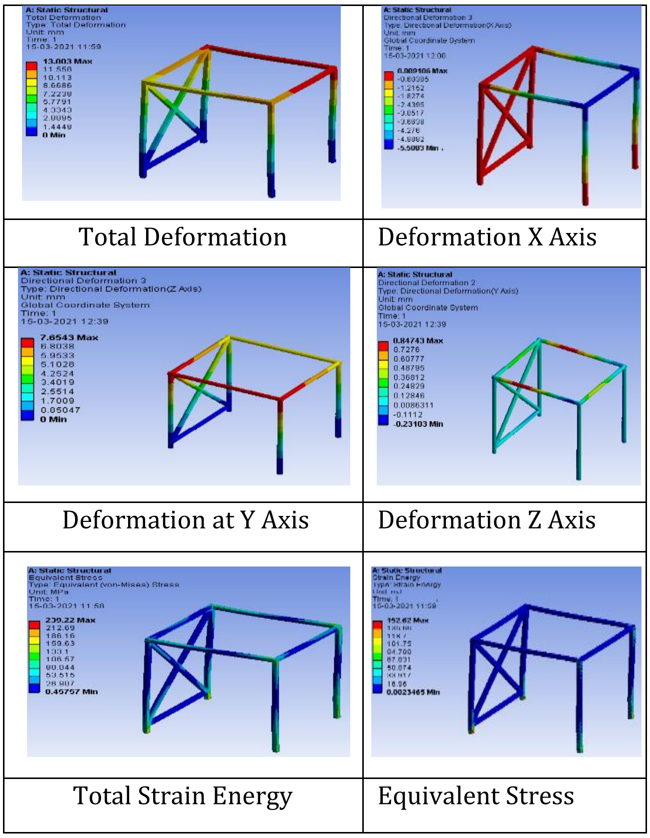

Figure 5. Stress and strain energy distribution of ROPS with hollow cross-section

The results obtained from the FEA are correlated with the field data. Comparison between total deformation, strain energy, and equivalent stress across different cross-sections is summarized in Table 2. The correlation between stress and deformation in ROPS is a key factor in determining the overall safety and effectiveness of the structure [31-32]. The square sections offers high torsional stiffness and resistance to bending. Circular sections provide excellent resistance to buckling and evenly distribute stress. Hollow circular sections provides combine strength with weight reduction to ROPS.

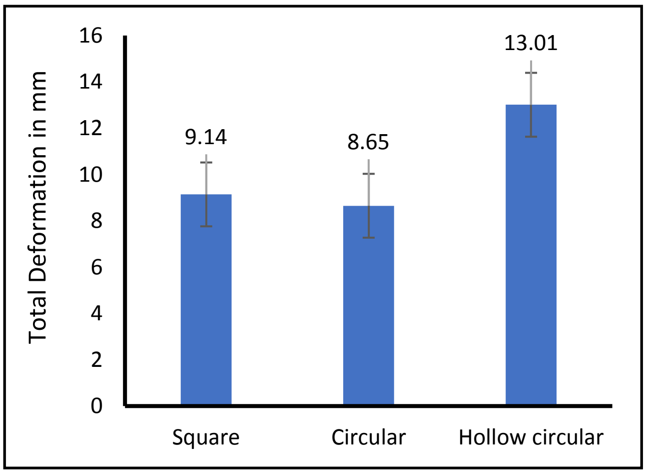

Figure. 6 Total deformation comparison

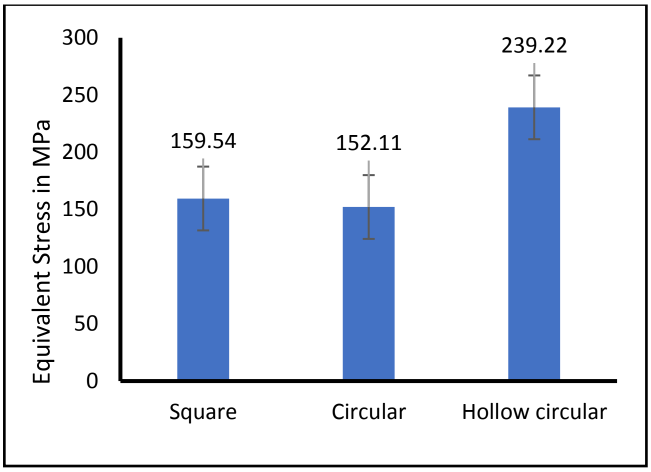

Figure 7. Total strain energy comparison

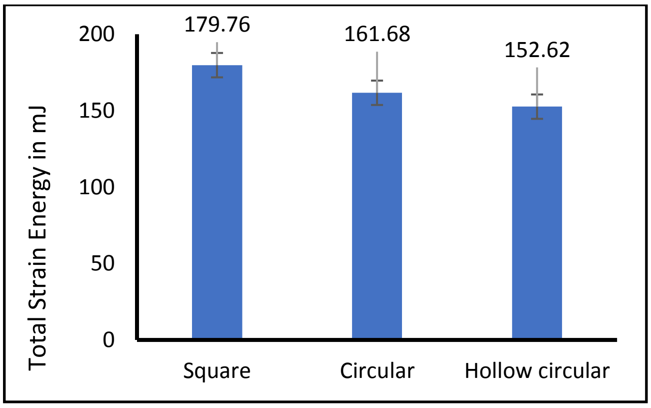

Figure 8. Equivalent stress comparison

Table 2. Comparison of Results

Results	Square	Circular	Hollow Circular
Total Deformation (mm)	9.14	8.65	13.01
Total Strain Energy (MPa)	159.54	152.11	239.22
Equivalent stress (MJ)	179.76	161.68	152.62

5. Conclusion

The comparative analysis of proposed ROPS in terms of performance, cost, and sustainability have been done. Our design aims to enhance performance by improving the structural strength and energy absorption capacity, while also focusing on cost-effectiveness through optimized material usage and manufacturing processes. Engineers are able to forecast and maximize the performance of ROPS through the painstaking creation of intricate 3D models, the application of precise material properties, the definition of realistic boundary conditions, and the simulation of rollover situations. In order to ensure that the structure can efficiently absorb and disperse impact forces, FEA assists in identifying high-stress locations and optimizing the distribution of strain energy. By reducing the need for physical prototypes and rigorous testing, this analytical technique not only confirms the ROPS design against strict safety criteria but also improves its efficiency and cost-effectiveness. In final analysis, FEA guarantees that ROPS structures offer the highest level of safety, greatly lowering the possibility of operator injury or death in rollover accidents. An agricultural wheeled tractor's ROPS was analyzed after being simulated using multiple cross sections and standard measurements taken from an existing design. The Finite Element Analysis was used to predict the load withstanding behaviour of ROPS. Geometry, loading and boundary conditions, as well as material qualities, all have an impact on stress, strain, and deformation. When compared to square, hollow circular cross sectioned ROPS, structures with circular cross sections have reduced elastic deformation and minimal stress. However, because circular cross sections are more difficult to manufacture, the best and safest option is a squared cross section. Clearly, there are numerous considerations to consider when selecting the confining material and section geometry. These calculations are intended to show the difference between strength and ductility that exists between FRP and steel confinement, as well as square versus circular cross sections. The optimum combination of properties using stiffness and strength of the ROPS can be obtained by using FE method. Future research should focus on these areas to improve the safety and effectiveness of ROPS, including developing more sophisticated simulation models and conducting long-term field studies.

Funding

This research received no external funding

Author contributions

Sakthivel Murugesan: Conceptualization**,** Ideation, Literature **Elamvazhudi Balasubramaniyan:** Fabrication, Modeling **Kulothungan Subramaniyan:** Editing, Correction

Conflicts of interest

The authors declare no conflicts of interest.

References

1. Ayers, P., Davis, G., Yantis, J., & Kerrigan, S. (2012). Improving ROPS designs for agricultural tractors. International Conference on Safety, Health and Welfare in Agriculture and Agro-Food Systems, 111–117.
2. Fritz, E. A., Case, J. I., & Switalski, W. G. (1992). Small agricultural tractor ROPS – New operator protective zone. SAE Technical Paper Series, 911782.
3. Chennuri, V., Kothagadi, H., & Mohammad, R. (2015). Design and stress analysis of four-post rollover protective structure of agricultural-wheeled tractor. International Journal of Mechanical Engineering and Robotics Research, 4(1).
4. Sardar, S. K., Narkar, K., & Panchagade, D. R. (2014). Optimization of rollover protection structure. International Journal for Scientific Research & Development, 2(4).
5. Kumar, R., Haridass, D., Dhandapani, N., & Dinakar, M. (2018). Non-linear static analysis of off-road vehicle cabin ROPS structure using finite element method. International Journal of Engineering & Technology, 7, 411–414.
6. Hoy, R. M. (2009). Farm tractor rollover protection: Why simply getting rollover protective structures installed on all tractors is not sufficient. Journal of Agricultural Safety and Health, 15(1), 3–4.
7. Kim, K. U., & Rehkugler, G. E. (1987). A review of tractor dynamics and stability. Transactions of the ASAE – American Society of Agricultural Engineers, 30(3), 615–623.
8. Wang, X., Ayers, P., & Womac, A. R. (2009). Static simulation and analyses of mower ROPS behavior in a finite element model. Journal of Agricultural Safety and Health, 15(4), 335–351.
9. Sakthivel, M., & Dhandapani, N. V. (2020). A study of literature review on explicit analysis of rollover protective structure for on-road vehicle by finite element technique. International Journal of Sciences & Research, 9, 387–389.
10. Sonawane, S. R., & Kurkute, V. K. (2015). Experimental and analytical investigation of rollover protection structure for agricultural wheeled tractor. International Journal of Engineering Sciences & Research Technology, 4(10).
11. B. Elamvazhudi, and D. Boodala (2018) Ballistic impact study on fibre reinforced polymer composites using FEA, Mater. Today Proc., pp. 2–9.
12. Elamvazhudi, B., & Gopalakannan, S. (2018). Stress intensity factor calculations for semi-elliptical cracked joints using finite element analysis in 3D. Materials Today: Proceedings, 5, 11808–11818.
13. Selvakumar, P., Mahajan, A., Murasolimaran, R., & Elango, C. (2015). CAE prediction and test correlation for tractor rollover protective structure (ROPS). SAE Technical Paper Series.
14. Anas, S. M., Alam, M., & Umair, M. (2023). Performance of concrete-filled double-skin steel tube with and without core concrete, and concrete-filled steel tubular axially loaded composite columns under close-in blast. International Journal of Protective Structures, 14(3), 299–334.
15. De Domenico, D., Losanno, D., & Vaiana, N. (2023). Experimental tests and numerical modeling of full-scale unbonded fiber-reinforced elastomeric isolators (UFREIs) under bidirectional excitation. Engineering Structures, 274, 115118.
16. Lv, X., Xiao, Z., Fang, J., Li, Q., Lei, F., & Sun, G. (2023). On safety design of vehicle for protection of vulnerable road users: A review. Thin-Walled Structures, 182, 109990.

17. Fan, W., Shen, D., Zhang, Z., Huang, X., & Shao, X. (2020). A novel UHPFRC-based protective structure for bridge columns against vehicle collisions: Experiment, simulation, and optimization. Engineering Structures, 207, 110247.
18. Wang, J. J., Song, Y. C., Wang, W., & Tu, L. F. (2018). Evaluation of composite crashworthy device for pier protection against barge impact. Ocean Engineering, 169, 144–158.
19. Jiga, G., Stamin, Ş., Dinu, G., Dobrescu, T., & Popovici, D. (2015). Comparative studies on the impact behavior of two sandwich structures. Procedia Engineering, 100, 418–427.
20. Georgantzia, E., Gkantou, M., & Kamaris, G. S. (2021). Aluminium alloys as structural material: A review of research. Engineering Structures, 227, 111372.
21. Kim, D. H., & Kim, S. W. (2019). Numerical investigation of impact-induced damage of auxiliary composite fuel tanks on Korean utility helicopter. Composites Part B: Engineering, 165.
22. Kim, M. G., & Kim, S. W. (2021). Impact localization for composite plate using the modified error-outlier algorithm with Pugh's concept selection under various temperatures. Composite Structures, 272, 114226.
23. Gezer, U., Demir, B., Kepir, Y., & Günöz, A. (2023). A numerical study on the low-velocity impact response of hybrid composite materials. Turkish Journal of Engineering, 7(4), 314–321.
24. Saleh, S. M., & Al-Abboodi, İ. (2021). Strength and behavior assessment of axially loaded concrete-filled steel tubular stub columns. Turkish Journal of Engineering, 5(4), 154–164.
25. Harris, J. R., Winn, G. L., Ayers, P. D., & McKenzie, E. A. (2011). Predicting the performance of cost-effective rollover protective structure designs. Safety Science, 49(8–9), 1252–1261.
26. Cesa, T. R., & Oliveira, B. F. (2013). Finite element simulation of a rollover protective structure. International Journal of Structural Integrity, 4(2), 165–190.
27. Kumar, V., Mallesh, G., & Radhakrishna, K. R. (2021). Finite element analysis of a two-post rollover protective structure of an off-highway motor grader. In E. Akinlabi, P. Ramkumar, & M. Selvaraj (Eds.), Trends in Mechanical and Biomedical Design. Lecture Notes in Mechanical Engineering. Springer.
28. Karaca, E. O. ., Tanyıldızı, M. ., & Bozkurt, N. . (2022). Investigation of seismic base isolation systems and their properties. Engineering Applications, 1(1), 63–71.
29. Eser, M. M., & Can, H. (2022). Investigation of the effects of using steel cross and reinforced concrete shears earthquake performance in building. Engineering Applications, 1(2), 157–162.
30. Al-Hagri, M. G., Nakipoglu, A., & Döndüren, M. S. (2023). Effect of arrangement of masonry infill walls, shear walls and steel bracings on the story drift and stiffness irregularity. Advanced Engineering Science, 3, 85–97.