Advanced Generation NIOSH Automatically Deployable Rollover Protective Structure (AutoROPS)

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Abstract

Safety is the most important aspects in every society and it is a major issue in the agricultural industry, which continues today as one of the most hazardous industry in the world with comparatively high fatality rates. Hundreds of farmers die each year due to tractor rollovers despite the fact that a highly effective safe guard is available in the form of a rollover protective structure. The use of rollover protective structure on farm tractors has attributed to saving numerous lives and has prevented many human injuries over the years. Many tractors come with the ROPS factory installed; however, many rollover protective structure were apparently removed by the tractor's owners due to the high clearance zone, which may cause the rollover protective structure to hit damage produce located on low hanging tree branches, while working in an orchard and that may cause farmers to lose money. The new NIOSH third generation AutoROPS prototype with low clearance zone was structurally simulated and analyzed using a computer-aided design program ANSYS® to insure the compliance with the Society of Automotive Engineering J-2194 standard requirements. The results proved that the third generations of the AutoROPS did absorb all applied loads in sequence and thus satisfied the J-2194 test requirements.

Keywords:

Tractor, Rollover, AutoROPS, Clearance Zone, SAE J-2194 Standard, ANSYS®.

1. Introduction

Rollover protective structure (ROPS) structures were available for virtually every tractor manufactured but there are numerous tractors without a ROPS still in use. These tractors were either had the protective structures removed or built before Oct. 25, 1976 - the date that all tractors with more than 20 PTO horsepower were required to be equipped with ROPS as shown in Figure 1.

Figures 1. Bulky ROPS mounted on commercial farm tractor

The number of lives lost have continued to occur despite the implementation of ROPS in all new tractors being sold in today's market. The ROPS is designed to work in conjunction with the use of a seat belt. Some of these deaths were due to the removal of the ROPS from the tractor, and/or from the driver not using a seat belt, because without fastening the seat belt, the operator may not remain in the safety crush zone of the ROPS.

The question is why would someone remove the ROPS, which could save his life? One answer would be because the size of the ROPS housing area is too big for some farmers, since farmers want to drive their tractor conveniently below low hanging tree limbs without knocking some crops out of the trees. The need for a more convenient ROPS with low clearance zone in order to fit the farmer's requirements becomes more important than ever. The automatic deployable ROPS (AutoROPS) will perform the same task of a conventional ROPS, but instead of having the post as one solid part as with the ROPS, the AutoROPS will have the post as two telescoping parts, it has one part located inside of the other to meet the farmer's need of low clearance. The deployable part of the AutoROPS will only deploy in the event of tractor rollover to protect the operator from death or severe injury.

2. Review of Literature Review

The National Swedish Testing Institute for Agricultural Machinery in 1954 had done some research on tractor safety. The main goal of the tests was determining the effect of the ROPS during the rollover incidents. These studies focused on an anti-crush protection structure on a farm tractor. The tests conducted were actual rollover tests. The nature of these tests was fairly expensive, inaccurate and non-reproducible due to variations in how the vehicles happen to impact the ground. There were no pre-set standards for the tests. [1]

Harris had built and tested the first generation AutoROPS according to the Society of Automotive Engineering (SAE) J-2194 ROPS Standard [2]. Those deployable AutoROPS were designed and built for use on the Ford New Holland 4600 series Tractor. The tests were aimed to see if the internal mechanisms such as the springs, pistons, and materials could withstand rollover forces. The tests were also used to determine if the rate of deployment was sufficiently fast and finally to confirm that the clearance zone withstand the applied loads and not compressed to insure the operators' safety. The results of those tests came out positive showing that the internal mechanisms and the deployment bars worked and the chosen material did withstand the applied load.

Howard conducted dynamic test on the performance of the mechanisms of the second generation AutoROPS [3]. The study was aimed at the latching mechanisms and rubber parts between the deployable posts to insure that they will handle any impact and release the upper part of the AutoROPS in proper time after a rollover signal was sent to pyrotechnic squibs in an internal piston.

A study by Brewer of West Virginia University, was done on a factory version of the ROPS [4]. The tests were aimed at the posts and the energy absorbed by the structure. The posts were made out of steel and were modeled by Finite Element Analysis (FEM). The study showed that the posts will meet the energy requirement and that the occupant clearance zone remained untouched by the deformed ROPS under the SAE J-2194 standard loads. The results showed the two post structure consistently deployed in less than 0.3 seconds and latched securely.

Gillispie used Finite Element Analysis (FEA) to analyze the sliding-fit joint, the stresses applied on the posts and the post maximum deflection the second generation AutoROPS due to loading [5]. Four directions of static loading were applied to the structure to satisfy SAE J-2194 standard. For the series static loading tests, AutoROPS was found to maintain a protective clearance zone after all loads were applied. The analysis indicated that there was no plastic bending at the sliding-fit joint. The second generation AutoROPS did satisfy SAE J-2194 standard test requirements and no intrusion to the driver's compartment zone. The study also showed the structure was overly stiff and should be redesigned to increase its ability to absorb ground impact energy.

2.1 Research Objective

The objective of this study was designing a new generation of cost effective AutoROPS, which satisfy the SAE J-2194 standard requirements [6] at the same time it need to be smaller in size and weight less than NIOSH first and second generation ROPS while insuring no intrusion to the operator's compartment zone.

3. Method

This study focused on using finite element model (FEM) to model the newly designed third generation AutoROPS base to predict its behavior during static loading. The basis of the displacement-based finite element solution is the principle of virtual displacement (which is also called the principle of virtual work). This principle stated that for any compatible small virtual displacements imposed on the body in its state of equilibrium, the total internal virtual work is equal to the total external virtual work. The use of the principle of virtual displacements, assumes to have the exact solution displacement field of the body [7] [8].

Finite element technique is a numerical procedure; Structural models are divided into smaller parts by meshing using a grid system. If the accuracy criteria are not met, the finite element solution must be repeated with refined solution parameters, such as finer mesh, until sufficient accuracy is reached [9].

SAE sets the design standards and technical requirements for farm machinery to insure design safety. There are two standards sets for two different kinds of tests: static testing and dynamic testing. The major interest in this study is to meet the standard static test requirement. AutoROPS must follow the guideline for the static load testing in order to be approved for commercial use. Energy criterion is considered to be one of the most important requirements to be met during any static load testing on the AutoROPS. Energy absorbed by the AutoROPS during a rollover is related to the mass of the tractor. The reference mass used in this study was 3728.5 kg (8220 lb.) which is the maximum reference mass listed for Ford 4600 series in the Nebraska tractor test.

3.1 Third Generation AutoROPS Apparatus

The new third generation AutoROPS prototype consisted of two telescoping rectangular tubes. The upper tubes were 3.5"X3.5" connected with the horizontal 3.5"X3.5" tube, and two 2"X3" inside posts welded to the base which has a 2 plate connected around the axle four grade 8 bolts, see Figure 2. The rectangular tubes were connected to the base which was mounted on the tractor rear axle base. The tires were removed and the axle bases were fixed.

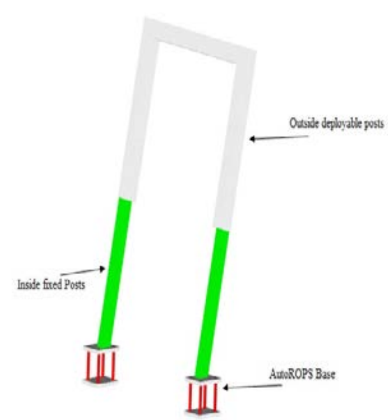

Figure 2. The newly designed third generation AutoROPS prototype

3.2 Procedure

This study was simulating and analyzing a new cost effective AutoROPS base model using finite element analysis (FEM) by using computer-aided design program (ANSYS). AutoROPS must be able to withstand the four series of applied static loading, which were pointed in four different directions and magnitudes. The AutoROPS must fulfill the performance requirement of this SAE J-2192 standard. The AutoROPS base was secured to the Tractor axle so that the member connecting the assembly and the lower plate do not fail or deflect significantly in relation to the protective structure under load. The AutoROPS assembly did not receive any support during loading other than what was due to an initial attachment.

3.2.1 First Longitudinal Loading

The load was applied horizontally and inward from the rear upper outside corner plane of the AutoROPS which would touch the ground first in case of an overturn. The required energy for this impact was calculated by:

$E=1.4\ m_t$ (Joules) (1)

Where: m_t is the mass of the tractor.
E = 46,188 in-lb. (1 Joule = 8.851in-Lb).

3.2.2 Second Longitudinal Loading

The load was applied to the opposite direction and at the other corner from the first longitudinal load as shown in Figure 3. The required energy for this test:

$E = 0.35\ m_t$ (Joules) (2)

Which resulted in E being 11,547 in-lbs.

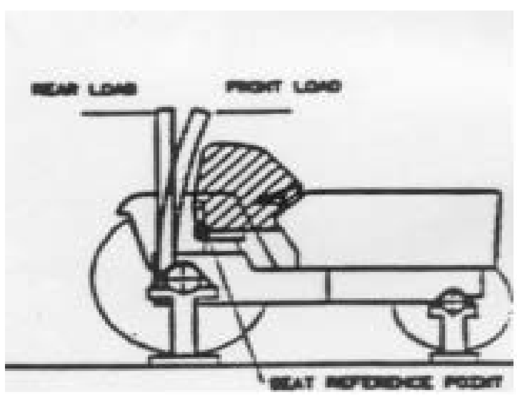

Figure 3. Rear, First longitudinal and second longitudinal loading directions

3.2.3 Side Transverse Loading

The second load on the AutoROPS was applied from a different direction at the point of loading which would touch the ground in case of sideways overturn, see Figure 4. The required energy was calculated as following:

$E = 1.75\ m_t$ (Joules) (3)

For this case E resulted in 57,735 in-lbs.

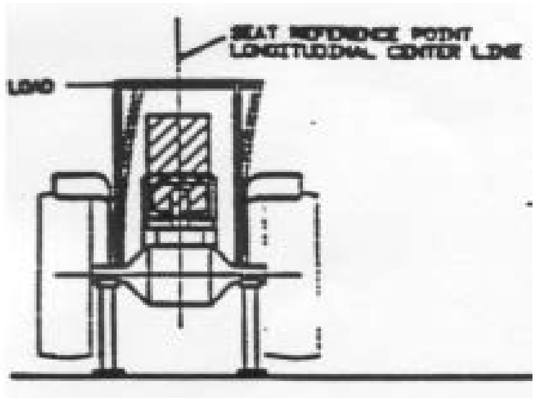

Figure 4. Load applied on AutoROPS from the side direction

3.2.4 Vertical Loadings

The crushing beam was positioned across the rear upper most structural member, see Figure 5. Force of 16,700 lb. was applied over that point which would support the rear of the tractor when completely overturned.

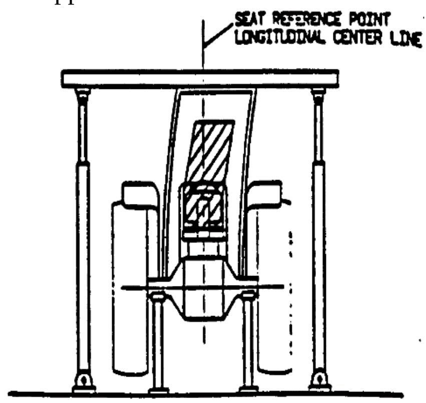

Figure 5. Loads applied on AutoROPS from the vertical direction

The rate of deflection due to static loading should not be any more than 5mm/s based on SAE standard. The determination of the occupant clearance zone was an important process. Success was measured by the ability of the ROPS to absorb the required amount of energy without intrusion in to the clearance zone, see Figure 6. Energy being absorbed by the AutoROPS was calculated using trapezoidal rules of the area under the force vs. deflection curve.

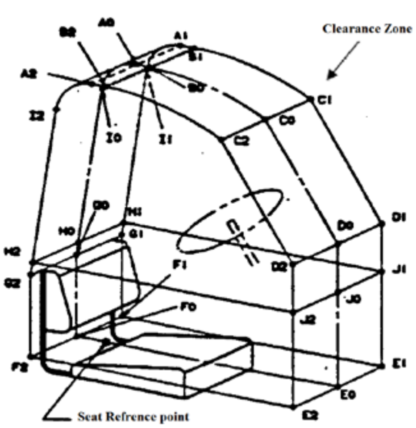

Figure 6. Clearance zone occupancy for tractor's operator

4. Results

This first part of this study focused on testing the stresses on the AutoROPS base. The results showed that the base would easily take the entire load being applied to it. Maximum stress of 38,593 psi was found on bolt number 5, which is below the minimum proof yield stress of 120,000 psi for the grade 8 bolt, the safety factor is 3.1.

4.1 First Longitudinal Test Results

Results from ANSYS program showed that the load on the first longitudinal test was gradually increased until it reaches the maximum required load of 4,630 lb., with the maximum deflection being 11.72 inches. The 3rd generation AutoROPS did withstand the applied load and absorbed a total energy of 46,203 in-lb. without any intrusion into the clearance zone. Stresses were the primary aspects studied in this design. The maximum stress of 64,044 psi was found at the lowest 10 inches the inside fixed post height of the AutoROPS as shown in Figure 7 and 8.

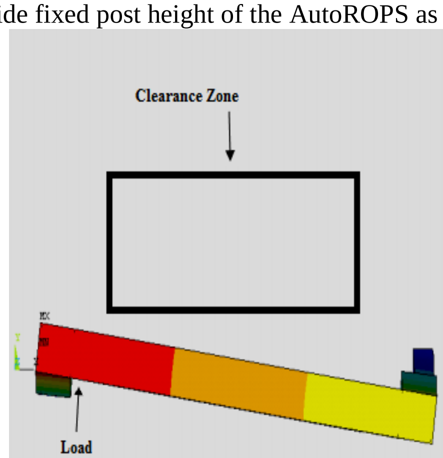

Figure 7. ANSYS Top view result for the loads applied on the first longitudinal test

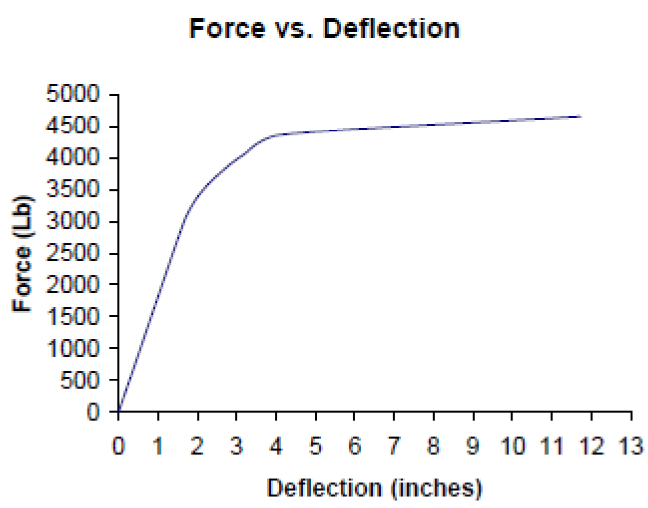

Figure 8. Force vs. Deflection for the first longitudinal test

4.2 Second Longitudinal Test

The maximum force applied on the second longitudinal test was 4,250 lb., thus causing the AutoROPS to deform 4.0 inches. The AutoROPS absorbed 11,581 in-lb. of energy, see Figure 9 and 10

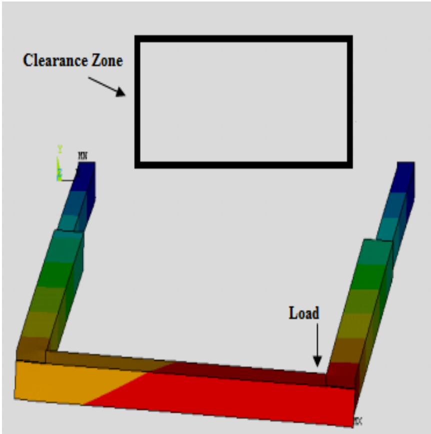

Figure 9. ANSYS top view results of the deflection for the second longitudinal test

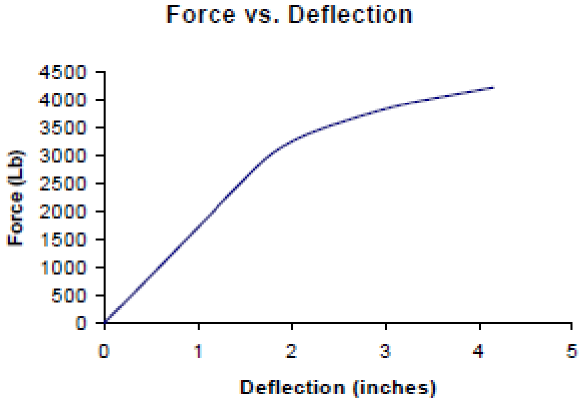

Figure 10. Energy under force deflection curve for the second longitudinal test

4.3 Side Transverse Test

A force of 8,450 lb. was applied on the side of the AutoROPS. And deformed 7.8 inches and absorbed a total energy of 57, 962 in-lb. The deflected AutoROPS did not intrude the clearance zone, see Figure 11 and 12.

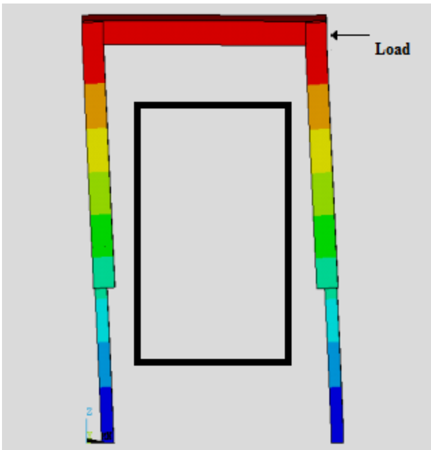

Figure 11. ANSYS result for the rear side view for the side transverse test load

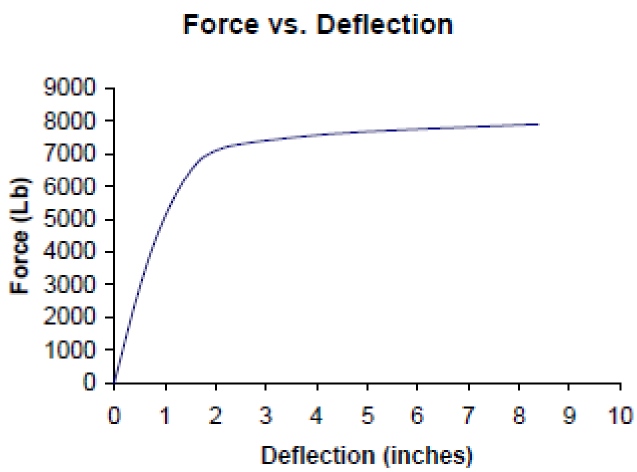

Figure 12. Force deflection curve for the side transverse test

4.4 Vertical Crush Test

The vertical load was applied on the AutoROPS. No latching mechanisms were considered in this study, Therefore: a perfect contact in the overlap area was assumed. The force applied was 16,700 lb. The AutoROPS had relatively no deflection during this test and no intrusion was recorded into the clearance zone.

5. Conclusions and Recommendations

All of the loads were applied in sequence on the AutoROPS. The results met the requirements of SAE J-2194 standards; the AutoROPS absorbed all of the required energies and did not intrude into the clearance zone. Since the fixed inside post for the third generation AutoROPS had smaller tube size, the ability of that posts to withstand the sequence of loading was questionable, but the results came positive, the post did withstand the applied loads. This study also focused on using finite element analysis to analyze the stresses on the base. The results were positive and determined that the base did take the entire load being applied to it. Maximum stresses found on bolts were way below the minimum proof yield stress for the grade 8 bolt. The base did show a good factor of safety during loading sequences. The redesigned version of the third generation AutoROPS has 10 inches of overlapping room between the posts, which met the design criteria and gave enough room for the spring to fit. This design also allows the deployable post to retract all the way down to the base of AutoROPS and to have a height of 39 inches only. First and foremost, this study showed that the deployable AutoROPS is a novel idea to protect tractor operator in the case of a tractor rollover and to meet his need of having a low clearance zone while operating in the farm. Although the third generation AutoROPS has proven effective in this research, it is necessary to continue research on future improvements of the AutoROPS. The possibility of saving even more lives makes the continued research worth looking at.

6. Recommendation for Future Work

The need for better analytical study in designing the AutoROPS becomes very important because the test standards were basically a pass or fail criteria. Since the third generation AutoROPS was a new design, there are other criteria that need to be studied. An example would be how the latching mechanisms would perform during loading and how it can be fitted in the overlapping area between the two posts. Another important subject that needs to be looked at is the deployment time required for the outside deployable posts to be deployed and still meet the necessary standards. Also, aspects of the spring criteria such as size, diameter and the release strength needed to be determined. Last but not least, the material properties like the strength and weight, and the cost of building the prototype need to be researched further.

Acknowledgments

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References

1. Staab, J.E. "Development of ROPS Criteria for construction and Industrial Vehicles". *SAE Transactions*, PP. 2399 - 2411, 1971.
2. Harris, James R. "Finite Element Modeling of Rollover Protective Structures for Analysis of Standard SAES 519", M.S. Thesis, West Virginia University, Dept. Of Mechanical and Aerospace Engineering, 1995.
3. Howard, Steven H. "*A Study of Impact Using 80-dermometer Rubber*". M.S. Thesis, West Virginia University, Dept. of Mechanical and Aerospace Engineering, 1998.
4. Brewer, Clay D. "Solid Modeling generation and Nonlinear Finite Element Analysis Of Two Post Roll-Over Protective Structure (ROPS) in Accordance with SAE J2194 Static Loading Standard", MS Thesis, West Virginia University, Dept. Of Mechanical and Aerospace Engineering, 1996.
5. Gillispie, A. "Optimization of Rollover Protective Structure (ROPS) Using Nonlinear Finite Element Analysis", M.S. Thesis, West Virginia University, Dept. Of Mechanical and Aerospace Engineering, 2000.
6. SAE Standards J-2194 "Roll-Over Protective Structures (ROPS) for Wheeled Agricultural Tractor", 1997.
7. Bathe, Klaus-Jurgen, "*Finite Element Procedures*", Prentice-Hall, Inc. New Jersey, 1996.
8. Adams, V., and Askenazi, A. "Building better Products with Finite Element Analysis" 1st edition, Onward Press, Santa Fe, NM, 1999.
9. Kreyszing, Erwin, "*Advanced Engineering Mathematics*", seventh edition, Wiley, New York, 1993.

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