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Finite Element Analysis and Cost Effective Design for Roll Over Protection Structure (ROPS) of Soil Compactor

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Abstract: -- **Roll over protection structures (ROPS) are intended to protect operators of heavy equipment and are important elements found on different types of machines used in OEMs. Their use is intended to reduce the possibility of operators (who are wearing seat belt) from being crushed if the machine they are operating rolls over. Design of ROPS should cater to force and energy absorption under lateral, longitudinal and vertical loading conditions. The lateral force requirements and the limitations on deflection are intended to assure that ROPS will penetrate the soil and provide a braking action to the roll. Loading requirement of ROPS is also intended to assure that the deflection encountered by the cabin does not enter the deflection limiting volume (DLV) which is defined as orthogonal approximation of a large operator in a normal seated position. The forces applied in the analysis were calculated as per ISO 3471-2008 ROPS and deflection limiting volume was defined as per SAE J397. The new cost effective design calls for repetition of this process again. This paper presents optimization of ROPS using Finite element analysis by considering energy and load conditions of existing structure and to compare the test results with ISO 3471:2008 ROPS.**

Keywords: Roll Over Protective Structure (ROPS); deflection limiting volume (DLV); Modelling; Ansys.

1. INTRODUCTION

Earthmoving machines are particularly prone to loads resulting from accidents such as rollovers or hits by falling objects. Structures which protect the machine operator during roll-overs are mandatory. Machines used both in construction and mining [12], and other machines are subject to the possibility of rollover on a slope or uneven surface. In such vehicles, the most important function of those structures is to protect the operator survival space, defined by the DLV model (Deflection Limiting Volume) [1]. In an accident scenario, the structure of the cabin, apart from protecting the operator should transmit the forces connected with machine rollover and absorb a certain amount of energy. Three strength tests are legally required in the following order: lateral force load (simulation of machine rolling over to the side), vertical force load (crushing of the cabin caused by machine rolling over on its roof), and longitudinal force load (simulation of machine driving or reversing into area with lower height than the height of the machine). In the case of lateral load, apart from transmitting the required force. This is a very difficult problem and in the case of advanced structures it is virtually impossible to solve. The protection structure must be sufficiently stiff to transmit the lateral force

and simultaneously flexible enough to absorb energy [8]. This paper presents the methodology of conducting simulation tests for such units with the application of finite element method and analyzes and discusses the obtained results

2. PROBLEM DEFINITION

Due to the high costs of construction and testing of prototypes, the trend of using Finite Element Modeling has been developing over the decades. The objective here is to develop a Nonlinear Statics Finite Element Analysis of an Optimized Two Post Deployable ROPS in ANSYS; one of the key descriptive words in the previous statement is "optimized". What will be shown is finite element modeling to minimize the tube cross-sections of an already constructed deployable ROPS that was structurally over designed.

There must be some proof of accuracy of the model. In this case, the strategy was to construct a finite element model to match the Energy and Load criteria of already built and experimentally tested ROPS, test results are compared with ISO 3471:2008 ROPS. Then, examine the finite element model and decide the amount to which the particular cross-section(s) can be reduced. It should once again be noted the test results of ROPS Static Load Standard is the judge as to whether the Baseline model of ROPS is acceptable, then the Baseline model is the standard model for judge whether the optimized ROPS is acceptable.

3. ISO Standards for ROPS

This international standard establishes a means of evaluating the load-carrying characteristics of roll-over protective structures (ROPS) under static loading. It applies to the following seated design operator-controlled machines:

- ***Roll-Over Protective Structure (ROPS)*** – System of structural members whose primary purpose is to reduce the possibility of a seat-belted operator being crushed should the machine rollover.

- ***Deflection-Limiting Volume DLV*** - Orthogonal approximation of a large seated male operator wearing normal clothing and a hard hat.

- ***Lateral simulated ground plane (LSGP)*** – For a machine coming to rest on its side, the plane 15° away from the DLV about the horizontal axis within the plane established in the vertical plane passing through the outermost point. The LSGP is established on an unloaded ROPS and moves with the member to which the load is applied while maintaining its 15° angle with respect to the vertical.

The SAE recommended practice covers characterstics and dimensions of critical zone to prevent crashing of operater during Rollover. It is intended to used with SAE reports on minimum performance criteria for Roll over protective structure,the critical zone dimensioned to enclose a large in article clothing

The crtical zone consists of three smaller zones A,B and C shown in figure they contain following

- Zone A: head, upper torso, upper arms
- Zone B: lower torso, lower arms, upper legs
- Zone C: lower legs

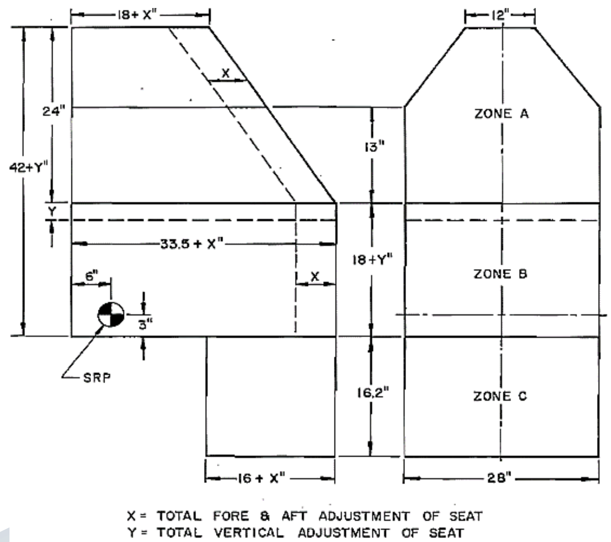

Fig1. DLV model residual space.

4. EXPERIMENTAL TEST

The testing of full scale ROPS of 11tons class compactor has performed the basics for the comprehensive understanding the response behaviour of exbited by the structure. When subjected to loading requirements as per ISO 3471-2008 ROPS standerds with in this chapter a detailed discription of the loading procedure that was used to test the ROPS, that was sutiable for attachment for following vehicle to test the ROPS

Fig.2 Experimental setup of ROPS with DLV

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Table:1 Lateral Load and Energy calculations by ISO- 3741J

Mass (M)	**Lateral load**	**Energy (U)**
10000<M<53780	50000* $(M/10000)^{1.2}$	9500* $(M/10000)^{1.25}$

The lateral load was applied side of the ROPS gradually up to minimum requirements specified by standards examination of resulting load deflection at level of loading indicated that ROPS had not absorbed enough amount of energy to full fill energy criteria of the standard the substantial increase in the lateral deflection and lateral load to the structure to achieve the energy requirement. Loading was substantial increased until area under load deflection is equaled to 13187J. This requirement was achieved at a peak load of 76kN and corresponding lateral deflection of 260mm hence the energy criteria has been satisfied

Table:2 Load and Energy calculations for Experimental model

Deflection (mm)	**Force (N)**	**Energy (J)**
0	0.0	0.0
10	7700.0	38.50
20	15000.0	152.00
30	20000.0	327.00
40	26100.0	557.50
50	30200.0	839.00
60	34200.0	1161.00
70	39000.0	1527.00
80	43200.0	1938.00
90	47300.0	2390.50
100	50600.0	2880.00
110	53600.0	3401.00
120	56400.0	3951.00
130	58000.0	4523.00
140	60000.0	5113.00
150	61400.0	5720.00
160	63400.0	6344.00
170	65100.0	6986.50
180	66600.0	7645.00
190	67500.0	8315.50
200	69400.0	9000.00
210	70000.0	9697.00
220	71600.0	10405.00
230	72500.0	11125.00
240	74000.0	11858.00
250	75000.0	12603.00
260	76000.0	13358.00

5. SIMULATION RESULTS

The Hypermesh is used as Pre-processing software for current ROPS model. The complete meshing is carried out by Shell meshing, the Shell element type SHELL-181 was selected to model the response of ROPS to establish static loading requirement as per Standards

The second element type 1-D BAR element, the 1D element type of BEAM188 was selected which is used at the loading section of the ROPS

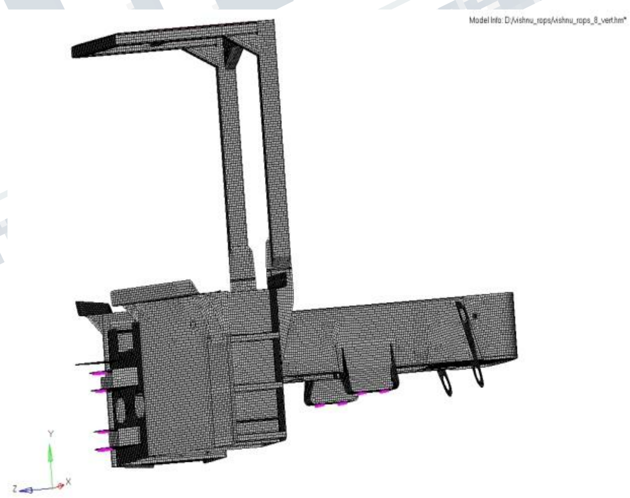

Fig.3 Finite Element model of ROPS

The Beam elements (BEAM188) are created on the ROPS tube as per the ISO standard for load application. The boundary condition was adopted in Hypermesh, The model is imported in to the ANSYS classic, Static Nonlinear analysis is carried out by application of load on the beam element in terms of Displacement 250mm, with 25 sub steps with increment of 10mm, ANSYS solve the solution and corresponding loads are given in MNTR file.

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The corresponding Energy is calculated by using this formula and graph

Table:3 Element quality criteria

Sl.No.	Parameter name	Limiting Value
s	Warpage	<5
2	Aspect ratio	<5
3	Jacobian	>0.6
4	Quad element (interior angle) Minimum Maximum	>450 <1350
5	Tria element (interior angle) Minimum Maximum	>200 <1200
6	Minimum Length of the Element	>2

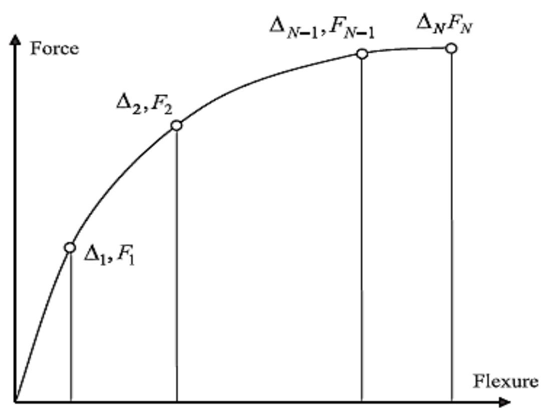

Fig.4 Force flexure curve under load.

$$U = \frac{\Delta_1 F_1}{2} + (\Delta_2 - \Delta_1)\frac{F_1 + F_2}{2} + \cdots (\Delta_N - \Delta_{N-1})\frac{F_{N-1} + F_N}{2}$$

Table:4 Load and Energy calculations for Baseline model

Deflection (mm)	Force (N)	Energy (J)
10	7429	37.145
20	14769	148.135
30	21922	331.59
40	28804	585.22
50	35321	905.845
60	41377	1289.335
70	46666	1729.55
80	50871	2217.235
90	54220	2742.69
100	57045	3299.015
110	59551	3881.995
120	61785	4488.675
130	63757	5116.385
140	65517	5762.755
150	67089	6425.785
160	68491	7103.685
170	69755	7794.915
180	70885	8498.115
190	71901	9212.045
200	72811	9935.605
210	73628	10667.8
220	74366	11407.77
230	75033	12154.765
240	75643	12908.145
250	76203	13667.375

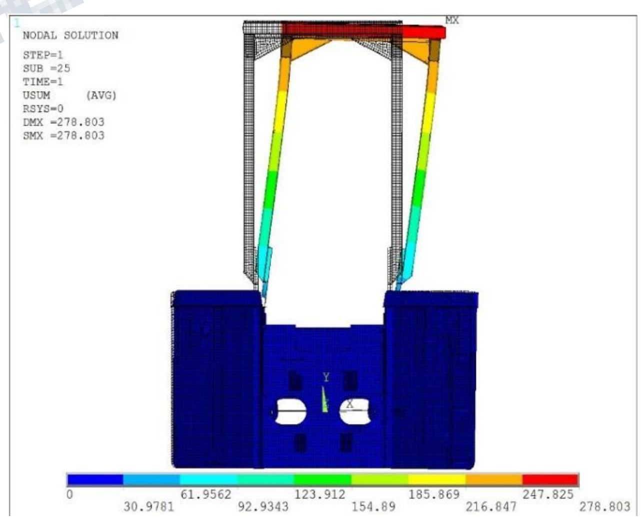

Fig.5 Contour lines of plastic deformations for lateral force front view of base line model

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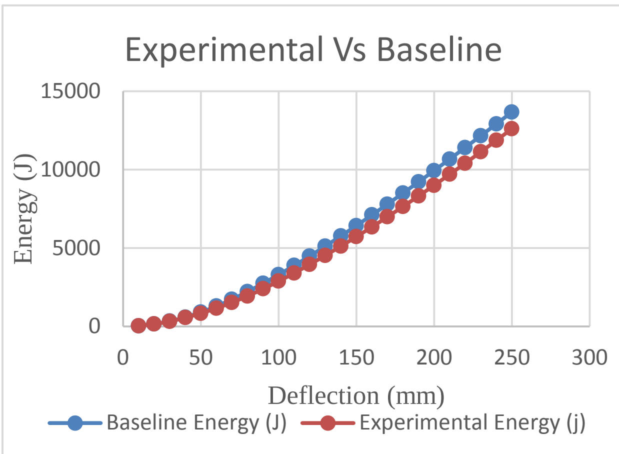

Fig.6 Energy vs. Deflection for baseline model

The results are tabulated in the table, the load and energy conditions are satisfied at 160mm and 250mm respectively, Energy Absorption criteria are used to design the rollover protective structures. It states that the kinetic energy of rollover must be absorbed by the plastic deformation of structure. This energy absorption is achieved by extensive plastic deformation material. So, the rollover structure should not be very stiff as that absorbed will limit the amount of energy the absorbed by the structure.

Changing the ROPS tube structure to C-channel and inserting three 8MM plates in that C-section, dimension of C-channel. In this cost reduction model an 8mm continuous plate is placed and Nonlinear static analysis has been carried out and results are compared with Baseline model for proving the energy and load criteria to prove that design for strength and life requirements.

The following Cost reduction model is matching the results with Baseline model are good, energy criteria is at displacement of 250mm and load criteria at 170mm. it has Max Vonmises stress 380.035MPa and Max plastic Vonmises strain 0.082575mm shown in table, applied load has been unloaded and it has been undergone a plastic deformation of 96.17 mm

Table:5 Load and Energy calculations for Cost-reduction model

Deflection (mm)	Force (N)	Energy (J)
10	8082.6	40.413
20	16065	161.151
30	23742	360.186
40	30843	633.111
50	37115	972.901
60	42504	1370.996
70	47050	1818.766
80	50832	2308.176
90	54001	2832.341
100	56743	3386.061
110	59152	3965.536
120	61275	4567.671
130	63142	5189.756
140	64787	5829.401
150	66251	6484.591
160	67563	7153.661
170	68748	7835.216
180	69822	8528.066
190	70805	9231.201
200	71705	9943.751
210	72532	10664.936
220	73294	11394.066
230	73998	12130.526
240	74654	12873.786
250	75266	13623.386

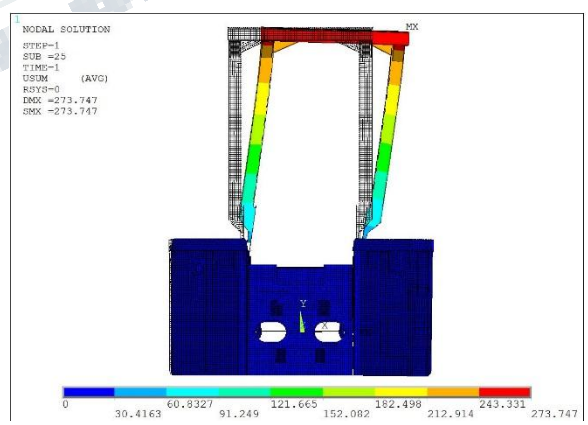

Fig.7. Contour lines of plastic deformations for lateral force front view of cost reduction model

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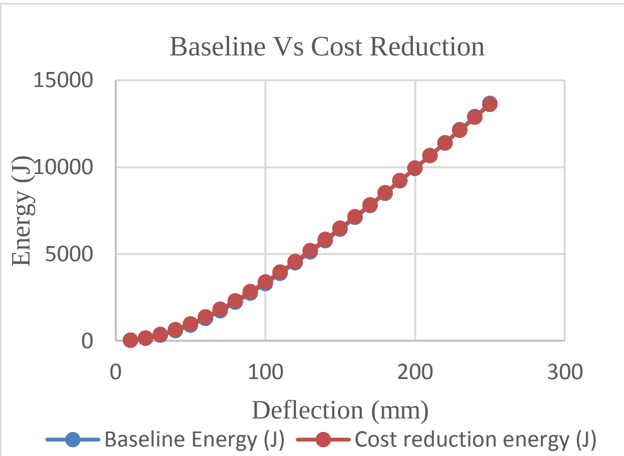

Fig.8 Energy vs. Deflection for baseline model

The above graphs shows the Energy criteria and loading criteria of Cost reduction model is completely converging with the Baseline results, hence this model has been suggested for design recommendations

6. RESULTS AND DISCUSSION

The Finite element analysis gives the ability to depict elastic to plastic behavior in full-scale ROPS testing, which saves cost and time in building and experimentally testing a full-scale ROPS.

Table:6 comparison between Baseline Model Vs Cost-reduction model

	Baseline model	Cost reduction model
Displacement at ISO Force Criteria	160	170
Displacement at ISO Energy Criteria	250	250
Max von Mises stress	411.135Mpa	380.035MPa
Max plastic von Mises strain	0.095491mm	0.082575mm
Permanent Plastic Strain	104.82 mm	96.17 mm

The first research was focused on using finite element analysis to predict the behavior of a commercial two-post ROPS for 11tons class compactor. The second phase of research dealt with the development of a two-post ROPS. Initially, the prototype was then experimentally tested for verification. A two-post deployable ROPS was built, and the loading and energy criteria are tested as per ISO 3471:2008 ROPS to verify deployment criteria were met.

The third phase of research in this document much has been presented about the development of a cost-effective design of two-post ROPS. Solving the Baseline model with non-linear static analysis, the loading has carried out and results are matched with experimentally tested for verification, in cost reduction model we are replacing the imported tube structure to C-channel and placing three 8mm plates.

Finally, the energy and force requirements of the optimized ROPS were correlating with Baseline model, in this cost reduction model energy and force requirements results are converging well with baseline model and, hence shown to meet the static requirements of the ISO 3471:2008 ROPS Standard, which was the judgment for acceptance. The objectives of this paper have been met.

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