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Non-Linear Static Analysis on Roll Over Protective Structure (ROPS) of Asphalt Compactor

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Abstract **:- Roll Over Protective Structure (ROPS) is a passive safety component that protects an operator in case of machine roll. The ROPS has been made mandatory to be installed in the earth moving machines such as compactor, grader, excavator etc., as these machines operate at different inclinations and at different earth irregularities. In this study a ROPS has been proposed for an Asphalt Compactor that is in compliance with ISO 3471 standard. The proposed structure has been designed to meet the packaging constraints of the compactor and to undergo non- elastic deformation without touching the operator at any point when the loads are applied. A Non-linear static analysis has been carried out on the proposed structure using Finite Element Analysis (FEA) tool ANSYS to predict its energy absorption under non-elastic deformation when the loads of lateral, vertical and longitudinal are applied.**

Keywords— Roll Over Protective Structure; Deflection Limiting Volume; Energy absorption; Non elastic deformation; Non-linear analysis.

I. INTRODUCTION

Earth moving machines are also known as off-highway vehicles. They have a wide application in construction, mining, demolition, etc. The different earth moving vehicles include excavators, bull-dozers, backhoe loaders, compactors, trenchers, tower cranes, graders, pavers, dump trucks, etc. In this study, an Asphalt compactor has been considered. Asphalt compactor/ Roller compactors/ rollers are used in the construction of roads by compacting the soil, asphalt and concrete. The Roller compactors operate at various inclinations or uneven terrains like at the edge of a cliff. While operating in such conditions, the machine may lose balance and might roll over which results in injuries or death to the operator. The accidents due to the machine roll over is depicted in the Fig-1a. To prevent this, a Roll Over Protective Structure (ROPS) is installed. ROPS is a passive safety component installed in earth moving machinery to undergo a non-elastic deformation in order to absorb the energy completely in case of a machine roll over. THE ROPS must be tested to check its efficacy by simulating the rolling condition. Various standards are used as a benchmark to test the ROPS. Among them ISO 3471 is a widely used standard. ISO 3471 depicts the structure requirements, loading condition and acceptance criterion of the structure. Since testing is very expensive and time consuming, a finite element analysis (FEA) is preferred. In this study, a two post ROPS for an Asphalt Compactor of 9-tonne capacity has been proposed. The proposed ROPS is checked for its compliance with the ISO 3471 standard by performing a non-linear static analysis.

Fig. 1. Rollover Accident of a Compactor [17]

II. OUTLINE OF ROLL OVER PROTECTIVE STRUCTURE (ROPS)

The ROPS proposed in this study is based on the ISO 3471 and ISO 3164 standards. ISO 3471 specifies the magnitude of loads that has to be applied on the ROPS in lateral, longitudinal and vertical direction. It also specifies the minimum lateral energy to be absorbed by the ROPS under non-elastic conditions. Acceptance criteria for the design is depicted in this standard. ISO 3164 specifies the dimensions of DLV (Deflecting Limiting Volume). A DLV is a space where the operator sits and operates the machine. As per the acceptance criteria in this standard, to ensure the safety of the operator, the deformed of ROPS should not enter the DLV at any instance [2].

Based on these standards, a ROPS is proposed for an Asphalt compactor. The specifications of the compactor are shown in Fig-2. The dimensions of ROPS are limited by the aspects of orthogonal DLV as per the standard and the packaging constraints in the machine. The proposed structure has a tower type vertical column. The cross section of the vertical column has been chosen by using an iterative approach to get the required stiffness. Simple square cross sectioned beams are used throughout the structure. The entire structure is made of ASTM A36 steel and has a thickness of 5 mm. The proposed structure has a total mass of 154.29 kg. The dimensions of the proposed ROPS and the DLV are shown in Fig-3 and Fig-4 respectively.

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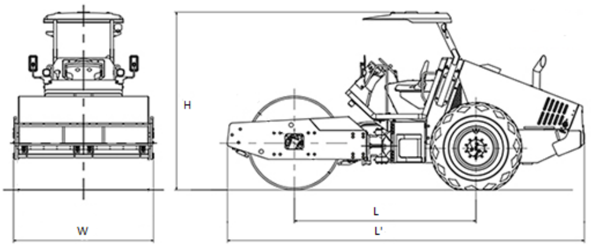

Fig. 2. Specifications of Chosen Asphalt Comactor[15]

The compactor shown in the Fig-2 is just for the depiction of the specifications and does not represent any model or any brand. Also, the ROPS in Fig-2 does not represent the ROPS that has been proposed in this study.

TABLE I. SPECIFICATIONS OF CHOSEN ASPHALT COMPACTOR

Parameters	Values
Overall Length (L')	5710 mm
Overall Width (W)	2300 mm
Height with ROPS/FOPS (H)	3010 mm
Wheel Base (L)	2900 mm
Operating Weight - with ROPS/FOPS	9000

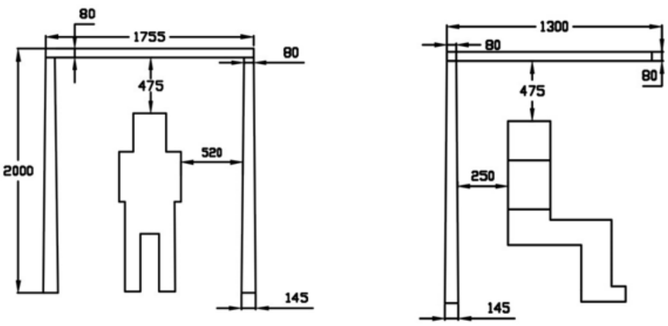

Fig. 3. Dimensions of Proposed ROPS

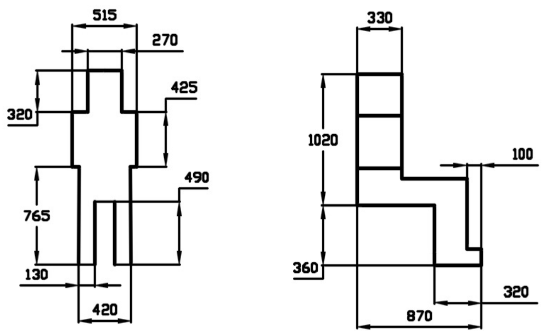

Fig. 4. Dimensions of the Deflection Limiting Volume (DLV) [2]

ASTM A 36 is a low carbon steel with carbon content less than 0.3%. The properties of material are as specified in Table-2 and the Fig-5. shows the stress- strain curve of ASTM A36 [16].

TABLE II. MATERIAL PROPERTY DATA

Properties	Values
Yield Strength	250 MPa
Young's Modulus	200 GPa
Poisson's Ratio	0.3
Bulk Modulus	166.67 GPa
Shear Modulus	76.923 GPa
Tangent Modulus	1.45 GPa
Ultimate Strength	460 MPa

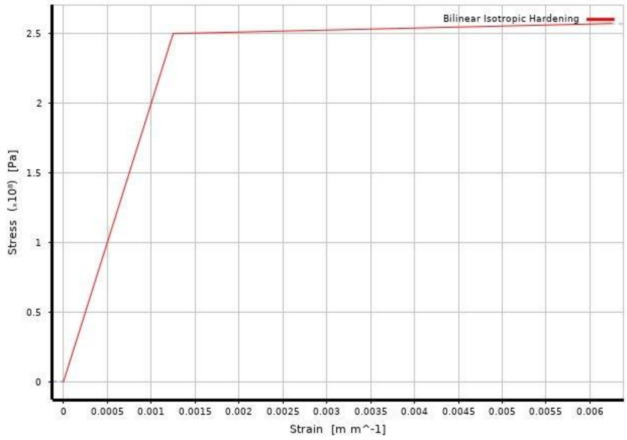

Fig. 5. Stress-Strain Curve of ASTM A36

The structure has been modelled using Catia V5, the model is depicted in the Fig-6.

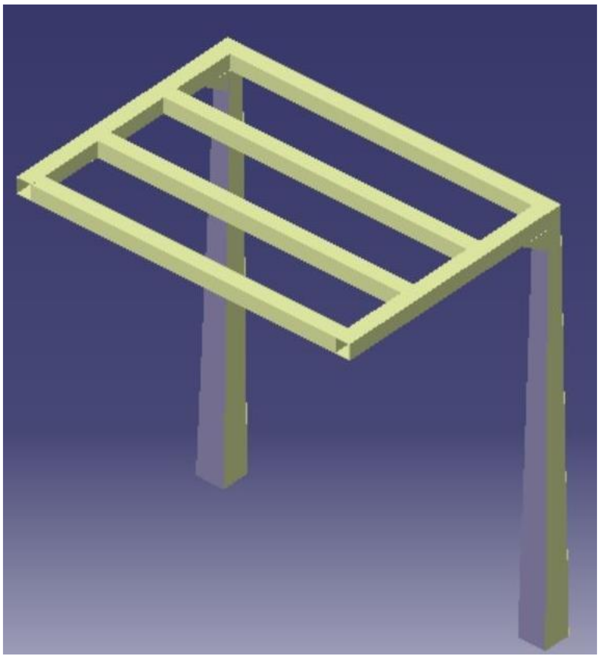

Fig. 6. Catia V5 model of the proposed structure

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The loads acting on the ROPS are calculated as per ISO 3471. These loads are dependent on the machine mass. Table-3 depicts the forces acting along lateral, longitudinal, vertical directions and the energy to be absorbed by the ROPS when lateral load is applied.

As per the ISO 3471, for a compactor of mass(m) 9010 kg,
Lateral load force (N)=5*m
Vertical load force (N)=19.61*m
Longitudinal load force (N)=4*m
Lateral Energy Absorption (J)=9 500* (m/10 000)1.25

TABLE III. LOADS AND ENERGY CALCULATIONS [1]

Parameter	Value
Mass of the machine (kg)	9010
Lateral load force (N)	45050
Vertical load force (N)	176686.1
Longitudinal load force (N)	36040
Lateral load energy (J)	8339.29

III. LOADING AND BOUNDARY CONDITIONS

The proposed structure has been meshed with both hexagonal and tetrahedron mesh of 10 mm size at appropriate locations. There are 105758 elements in the meshed model. The Fig-7 and Fig-8 shows the finite element model of the structure.

Base of the vertical columns of the structure are fixed and the loads of lateral, vertical and longitudinal are applied on the ROPS sequentially as per standards as shown in the Fig-9, Fig-10 and Fig-11.

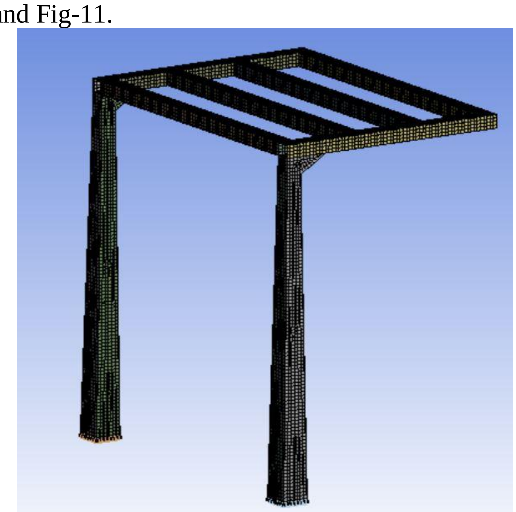

Fig. 7. Finite Element Model of the ROPS

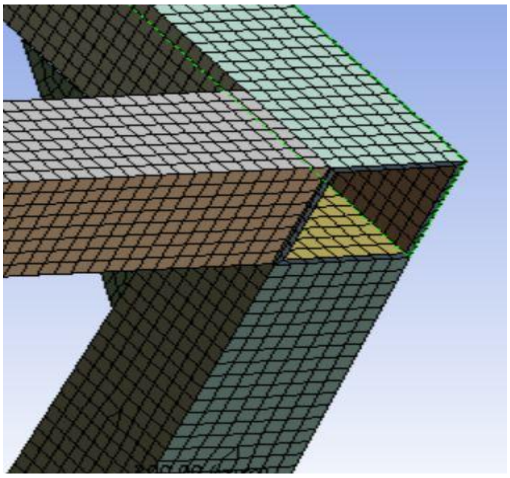

Fig. 8. Finite Element Model of the ROPS

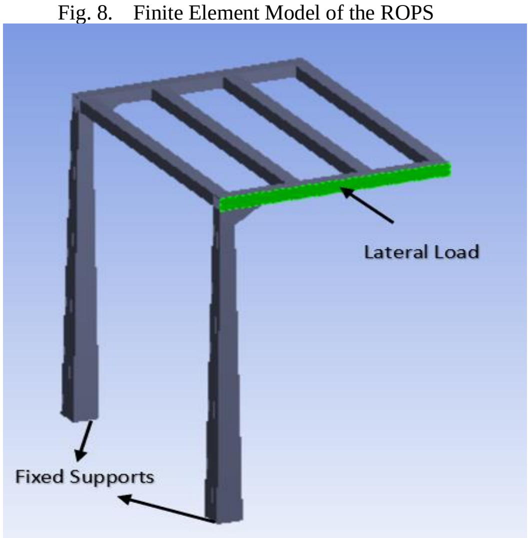

Fig. 9. Boundary Conditions for Lateral Loading

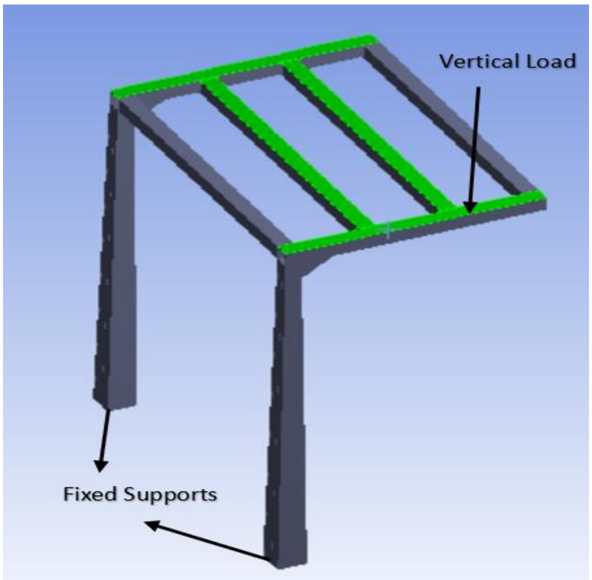

Fig. 10. Boundary Conditions for Vertical Loading

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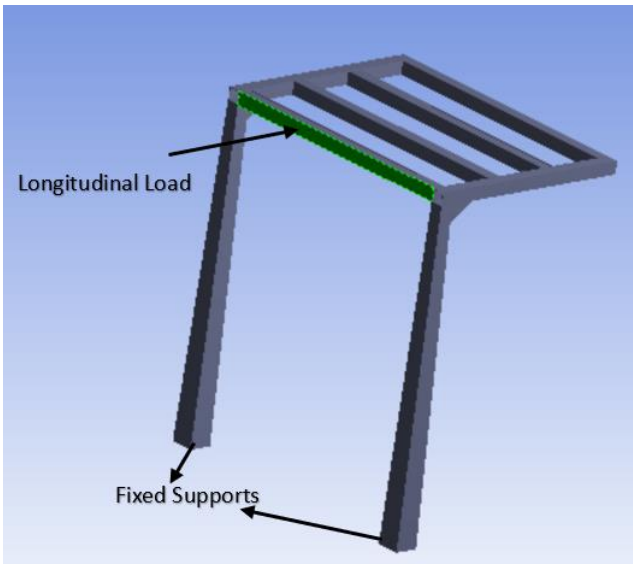

Fig. 11. Boundary Conditions for Longitudinal Loading

IV. Results And Discussions

A Non-linear static analysis is carried out using Finite Element Analysis to predict the energy absorption capacity of the ROPS when it undergoes a non-elastic deformation. Both material and geometric nonlinearities are considered and the loads are applied gradually until the force-energy requirements as specified in ISO 3471 are reached. The studies reveal that the most roll over takes place in the lateral direction, hence it is very important to check the energy absorption capacity of the ROPS for the lateral load. The energy absorption capacity of the structure is found by plotting load vs deformation curve as specified in ISO 3471.

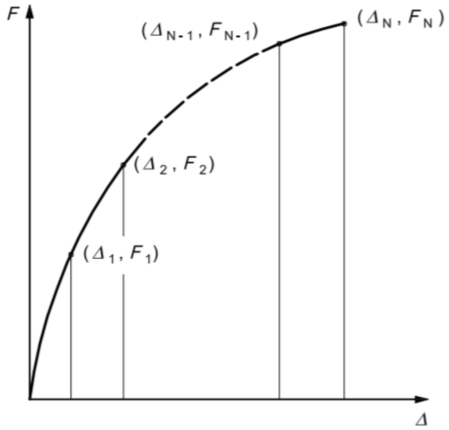

Fig. 12. Load vs Deformation graph as specified in ISO 3471 [1]

The area under the curve shown in the Fig-12 is used to predict the energy absorption, therefore

U=(Δ1*F1)/2+((Δ2-Δ1)*(F1+F2)/2)+.........+((ΔN-ΔN-1)*(FN-1+FN)/2)) ----------------------(1)

where, U is the Energy absorption, Δ is the deformation and F is the load [1]

A. Lateral Loading

The loads are applied gradually until a magnitude of 45050 N is attained. The direction of load is as depicted in Fig-9. The Fig-13 shows the non-elastic deformation of the structure that is predicted using the FEA tool ANSYS for these loads. The maximum deformation of the structure for the applied loads is 316mm.

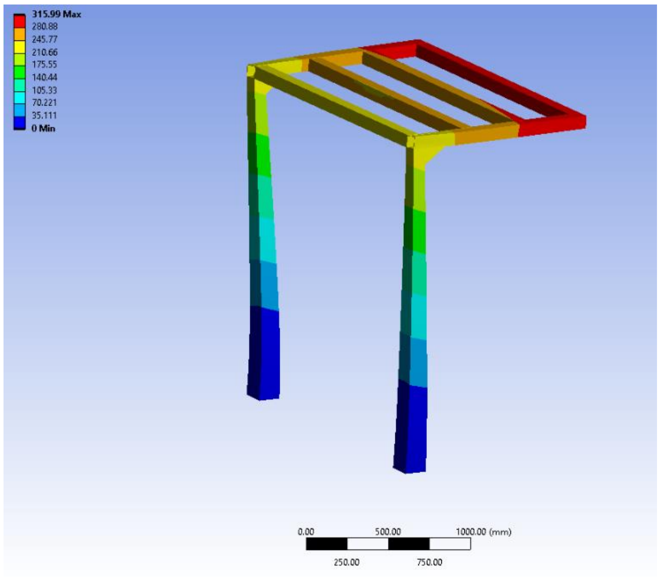

Fig. 13. Deformation due to non-linear Lateral Loading

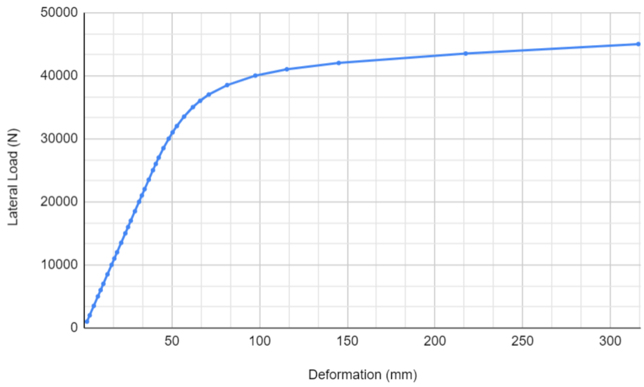

Fig. 14. Load vs Deflection graph for lateral load

As shown in Fig. 14, the curve is linear up to a limit. In this region the lateral load is directly proportional to the structure's deformation. Following the limit, a substantial change in deformation is observed for a small change in load. This section of the graph shows the material non-linearity of the structure.

From equation 1, Energy absorption for the curve shown in Fig-14 is calculated and tabulated in Table-4.

TABLE IV. ENERGY ABSORPTION CALCULATION TABLE FOR LATERAL LOADING

S. No.	Time (Sec)	Lateral Load (N)	Deflection (mm)	Energy Absorption(J)
1	1	0	0	0
2	1.2	1001.1	1.55	0.77
3	1.4	2002.2	3.11	3.11
4	1.7	3503.9	5.44	9.54
5	2	5005.6	7.78	19.48
6	2.2	6006.7	9.34	28.07

7	2.4	7007.8	10.90	48.34
8	2.7	8509.4	13.24	66.50
9	3	10011	15.58	88.20
10	3.2	11012	17.15	104.64
11	3.4	12013	18.71	122.66
12	3.7	13515	21.06	152.64
13	4	15017	23.41	186.18
14	4.2	16018	24.98	210.51
15	4.4	17019	26.55	251.88
16	4.7	18521	28.90	293.73
17	5	20022	31.26	339.17
18	5.2	21023	32.83	371.45
19	5.4	22024	34.41	405.40
20	5.7	23526	36.79	459.53
21	6	25028	39.18	517.63
22	6.2	26029	40.79	558.75
23	6.4	27030	42.45	617.68
24	6.7	28532	45.13	692.30
25	7	30033	48.15	780.53
26	7.2	31034	50.37	848.43
27	7.4	32036	52.81	925.38
28	7.7	33537	56.92	1060.23
29	8	35039	61.94	1232.36
30	8.2	36040	66.08	1379.17
31	8.4	37041	71.02	1496.05
32	8.7	38543	81.48	1891.54
33	9	40044	97.54	2522.60
34	9.2	41046	115.52	3099.45
35	9.4	42047	145.12	4329.22
36	9.7	43548	217.53	7428.19
37	10	45050	315.99	11479.35

As per the ISO 3471, the minimum energy absorption for the lateral load of 45050 N should be 8339.30J. The energy absorbed by the proposed structure is 11479.35 J and the maximum deformation is 315.99 mm. In the proposed structure there is a clearance of about 520 mm in the lateral direction. Therefore, the deformation does not enter the Deflection Limiting Volume (DLV) at any instance. Energy absorption vs time and Energy absorption vs Lateral Load are plotted to understand the behaviour of the ROPS when lateral loads are applied.

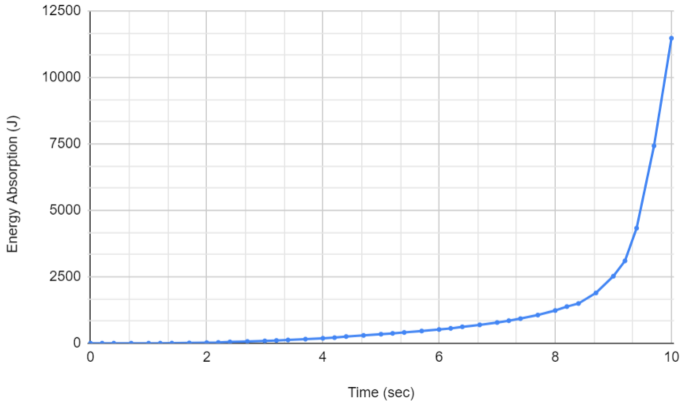

Fig. 15. Energy Absorption vs time for lateral load

In this study, the loads are applied to the structure gradually with respect to time. From the Fig-15, it can be clearly observed that up to 8 seconds the energy absorption is very less. This is because the material in that region behaves linearly. After 8 seconds the energy absorption has increased drastically due to material non-linearity.

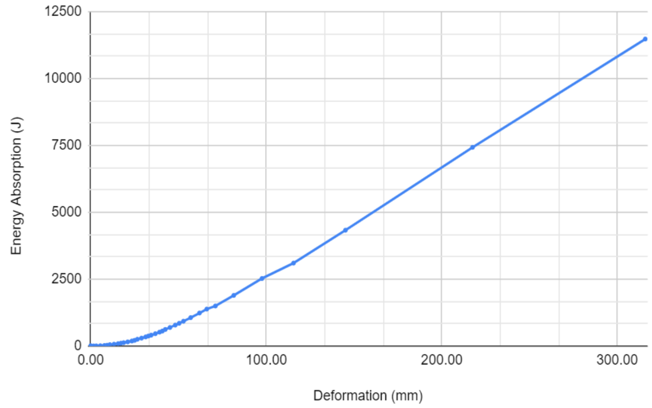

Fig. 16. Energy Absorption vs deformation

The plot in the Fig-16 shows that up to 100mm deformation, the energy absorbed by the structure is quite low. Following that, the energy absorption in the structure steadily increases due to the material's non-linear behaviour.

B. *Vertical Loading*

The loads are applied gradually until a magnitude of 176686.1 N is attained. The direction of load is as depicted in the Fig-10. The Fig-17 shows the non-elastic deformation of the structure. The maximum deformation of the structure for the applied load is 352.56mm.

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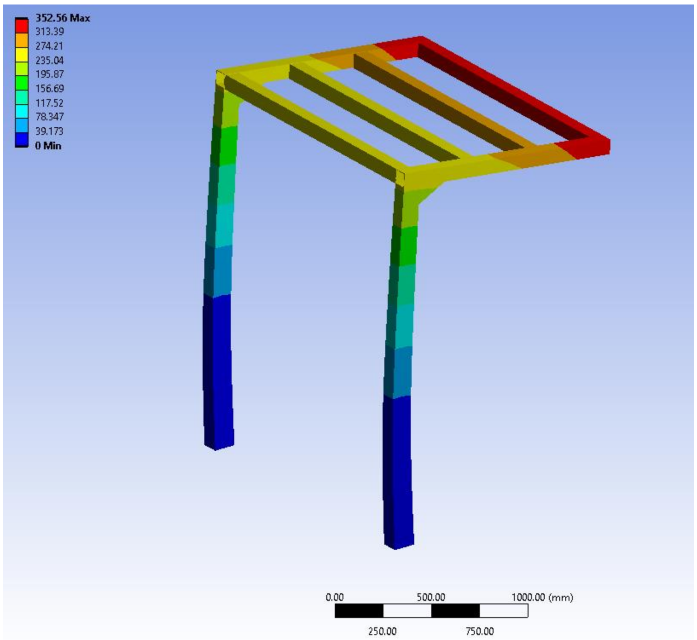

Fig. 17. Deformation due to Non-Linear static Vertical load

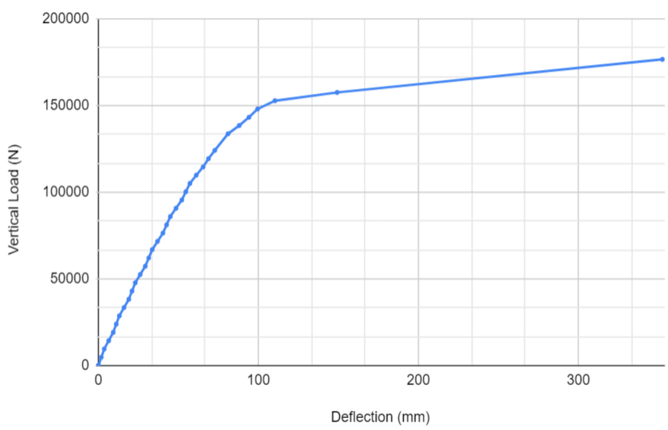

Fig. 18. Load vs Deflection graph for vertical load

The curve shown in Fig-18 is linear up to a limit. In this region the vertical load is directly proportional to the structure's deformation. Following the limit, a substantial change in deformation is observed for a small change in load. This section of the graph shows the material non-linearity of the structure.

From equation 1, Energy absorption for the curve shown in Fig-18 is calculated and tabulated in Table-5.

TABLE V. ENERGY ABSORPTION CALCULATION TABLE FOR VERTICAL LOADING

Sl. No.	Time (Sec)	Vertical Load (N)	Deflection (mm)	Energy Absorption(J)
1	1	0	0	0
2	1.2	4775.3	1.8	4.31
3	1.4	9550.6	3.63	17.40
4	1.7	14326	6.40	50.53
5	2	19101	9.22	97.64
6	2.2	23877	11.14	138.71
7	2.4	28652	13.06	237.76
8	2.7	33427	15.99	328.59
9	3	38202	18.97	435.38
10	3.2	42978	20.98	517.13
11	3.4	47753	23.02	609.45
12	3.7	52528	26.12	765.14
13	4	57304	29.29	938.89
14	4.2	62079	31.43	1066.81
15	4.4	66854	33.60	1263.10
16	4.7	71630	36.92	1492.85
17	5	76405	40.30	1743.32
18	5.2	81180	42.60	1924.23
19	5.4	85955	44.92	2118.61
20	5.7	90731	48.47	2431.79
21	6	95506	52.12	2771.766
22	6.2	100280	54.61	3015.32
23	6.4	105060	57.17	3267.01
24	6.7	109830	61.14	3693.56
25	7	114610	65.46	4177.90
26	7.2	119,380	68.80	4568.55
27	7.4	124160	72.75	5049.54
28	7.7	133710	81	6112.87
29	8	138480	87.99	7064.72
30	8.2	143260	94.11	7926.42
31	8.4	148030	99.48	8146.51
32	8.7	152810	110.33	9777.52
33	9	157,580.00	149.2	15809.95
34	9.2	176,686.10	352.56	65134.40

For the maximum vertical load of 176686.1 N, the energy absorbed by the structure is 65134.40 J and the maximum deformation is 352.56 mm. In the proposed structure there is a clearance of about 475 mm in the vertical direction. Therefore, the deformation does not enter the Deflection Limiting Volume (DLV) at any instance. Energy absorption vs time and Energy absorption vs Vertical Load are plotted to understand the behaviour of the ROPS when vertical loads are applied.

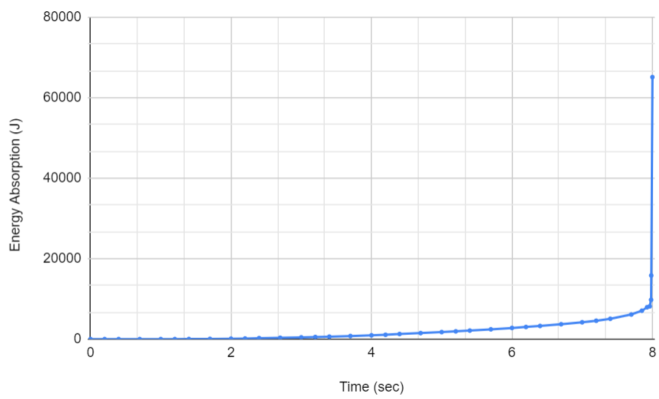

Fig. 19. Energy Absorption vs time for vertical load

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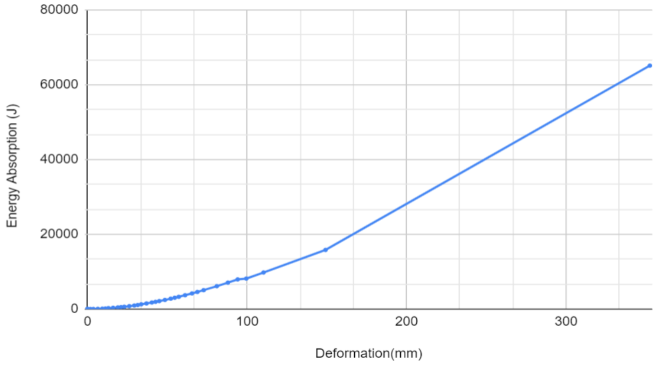

Fig. 20. Energy Absorption vs deformation

The graphs in Fig-19 & Fig-20 depict that the energy absorbed by the structure is significantly low for smaller loads as the material behaves elastically. As the load increases over time, the deformation of the structure rises owing to non-elastic behaviour, which increases energy absorption.

C. Longitudinal Loading

The loads are applied gradually until a magnitude of 36040 N is attained. The direction of load is as depicted in the Fig-11. The Fig-21 shows the non-elastic deformation of the structure. The maximum deformation of the structure for the applied load is 185.33mm.

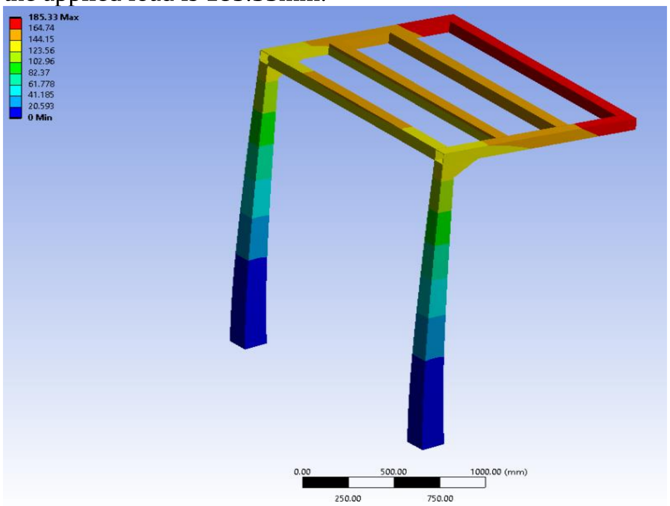

Fig. 21. Deformation due to Non-Linear static Longitudinal load

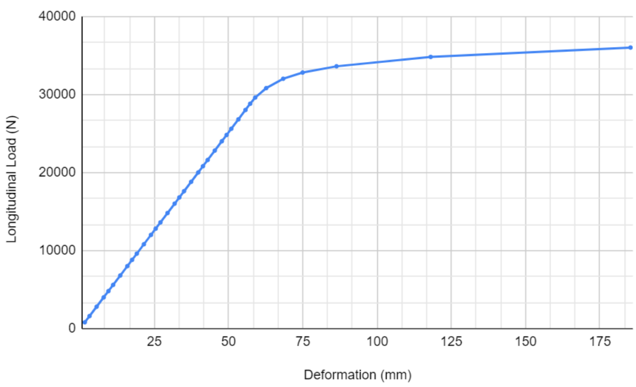

Fig. 22. Load vs Deflection graph for Longitudinal load

The curve shown in Fig-22 is linear up to a limit. In this region the longitudinal load is directly proportional to the structure's deformation. Following the limit, a substantial change in deformation is observed for a subtle change in load. This section of the graph shows the material non-linearity of the structure.

From equation 1, Energy absorption for the curve shown in Fig-22 is calculated and exhibited in Table-6.

TABLE VI. ENERGY ABSORPTION CALCULATION

S. No.	Time (Sec)	Longitudinal Load (N)	Deflection (mm)	Energy Absorption(J)
1	1	0	0.00	0
2	1.2	800.89	1.59	0.63
3	1.4	1601.8	3.18	2.55
4	1.7	2803.1	5.57	7.81
5	2	4004.4	7.96	15.93
6	2.2	4805.3	9.55	22.95
7	2.4	5606.2	11.14	39.52
8	2.7	6807.6	13.53	54.35
9	3	8008.9	15.92	72.03
10	3.2	8809.8	17.51	85.42
11	3.4	9610.7	19.10	100.08
12	3.7	10812	21.49	124.45
13	4	12013	23.87	151.70
14	4.2	12814	25.47	171.46
15	4.4	13615	27.06	205.24
16	4.7	14816	29.44	239.17
17	5	16018	31.83	275.97
18	5.2	16819	33.42	302.08
19	5.4	17620	35.01	329.47
20	5.7	18821	37.40	372.95
21	6	20022	39.78	419.29
22	6.2	20823	41.37	451.78
23	6.4	21624	42.96	498.32
24	6.7	22825	45.35	551.35
25	7	24027	47.74	607.22
26	7.2	24828	49.33	646.06
27	7.4	25628	50.91	686.15
28	7.7	26830	53.30	748.70
29	8	28031	55.68	814.10
30	8.2	28832	57.27	859.30
31	8.4	29633	58.98	923.67
32	8.7	30834	62.66	1035.02
33	9	32036	68.39	1215.02
34	9.2	32836	74.94	1442.91
35	9.4	33637	86.34	1821.91
36	9.7	34839	118.05	2907.43
37	10	36040	185.33	5724.01

For the maximum longitudinal load of 36040 N, the energy absorbed by the structure is 5724 J and the maximum deformation is 185.33 mm. In the structure there is a clearance of about 250 mm in the longitudinal direction. Therefore, the predicted deformation does not enter the Deflection Limiting Volume (DLV) at any instance. Energy absorption vs time and Energy absorption vs Longitudinal Load are plotted to understand the behaviour of the ROPS when Longitudinal loads are applied.

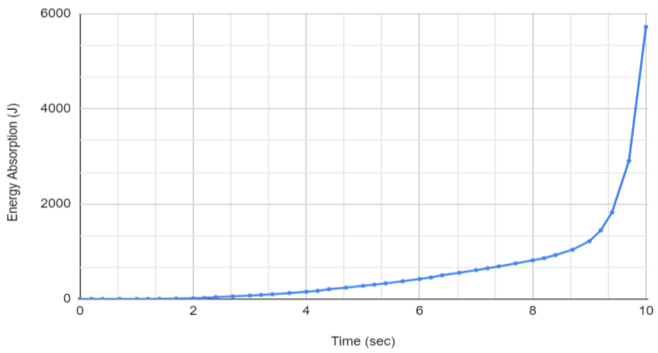

Fig. 23. Energy Absorption vs time for Longitudinal load

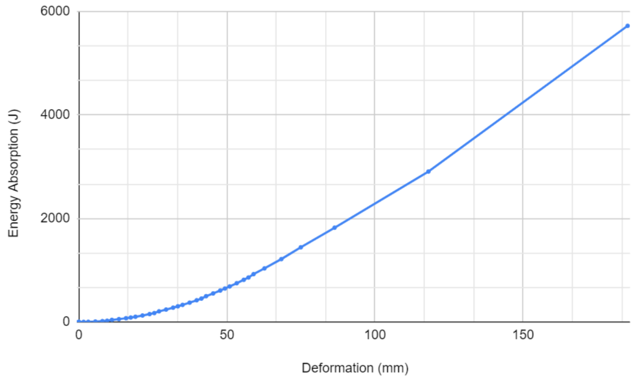

Fig. 24. Energy Absorption vs deformation

The plots in the Fig-23 & Fig-24 show that the energy absorbed is significantly lower for smaller loads because the material behaves elastically. As the load increases over time, the deformation of the structure rises owing to non-elastic behaviour of the material, which increases energy absorption.

TABLE VII. COMPARISON TABLE

Direction of Loading	**Required Minimum Energy Absorption as per standard (J)**	**Energy Absorption by the proposed structure (J)**	**Deformation observed (mm)**	**Actual Clearance (mm)**
Lateral	8339.30	11479.37	315.99	520
Vertical	Not Specified in the standard	65134.40	352.56	475
Longitudinal	Not Specified in the standard	5724.01	185.33	250

From the above table it can be inferred that the deformations due to the lateral, vertical and longitudinal loads do not enter the Deflection Limiting volume and the energy absorption in the lateral case is more than the required minimum energy absorption as specified in ISO 3471. Therefore, it can be concluded that the proposed ROPS is safe.

V. CONCLUSION

A Roll Over Protective structure (ROPS) for an Asphalt compactor of 9-tonne has been proposed in this study. A Non-Linear static analysis has been carried out on the proposed structure and non-elastic deformations, energy absorptions are predicted for lateral, vertical and longitudinal loads using FEA tool ANSYS. As specified in the acceptance criterion of the standard, deformations are not entering the Deflection limiting point at any instance when the loads are applied. Also, the absorbed energy by the structure is more than the required minimum energy. Since the criterions specified in the standards are met, it can be concluded that the proposed ROPS is safe.

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