

# Finite Element Modeling of ROPS in Static Testing and Rear Overturns

J. R. Harris, V. H. Mucino, J. R. Etherton, K. A. Snyder, K. H. Means

## Abstract

Even with the technological advances of the last several decades, agricultural production remains one of the most hazardous occupations in the United States. Death due to tractor rollover is a prime contributor to this hazard. Standards for rollover protective structures (ROPS) performance and certification have been developed by groups such as the Society of Automotive Engineers (SAE) and the American Society of Agricultural Engineers (ASAE) to combat these problems. The current ROPS certification standard, SAE J2194, requires either a dynamic or static testing sequence or both. Although some ROPS manufacturers perform both the dynamic and static phases of SAE J2194 testing, it is possible for a ROPS to be certified for field operation using static testing alone. This research compared ROPS deformation response from a simulated SAE J2194 static loading sequence to ROPS deformation response as a result of a simulated rearward tractor rollover. Finite element analysis techniques for plastic deformation were used to simulate both the static and dynamic rear rollover scenarios. Stress results from the rear rollover model were compared to results from simulated static testing per SAE J2194. Maximum stress values from simulated rear rollovers exceeded maximum stress values recorded during simulated static testing for half of the elements comprising the uprights. In the worst case, the static model underpredicts dynamic model results by approximately 7%. In the best case, the static model overpredicts dynamic model results by approximately 32%. These results suggest the need for additional experimental work to characterize ROPS stress levels during staged overturns and during testing according to the SAE standard.

*Keywords.* Rollover, Tractor, ROPS, Finite element.

**A**lthough much has been written concerning the history of ROPS standard development (Jackson, 1985; MacCollum, 1984; Staab, 1971), little information has been uncovered confirming the test parameters of ASAE/SAE ROPS standards. Woodward and Swan (1980) compared the performance of ROPS subjected to the SAE J1040c (SAE, 1979) static test with minimum requirements needed for certification under that standard to obtain an indication of “overdesign” in contemporary ROPS. Their study indicated that as many as 70% of the ROPS designs exceeded the side load requirement by at least

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20%. These results assume that the reference mass in the testing sequence equals the Minimum Possible Machine Mass, the mass of the machine without optional attachments. In contrast, Steinbruegge (1975) rolled tractors equipped with ROPS built to minimally pass contemporary standards into ditches deeper than 45 cm. From the results of this study, Steinbruegge projected that the ASAE/SAE ROPS standard of that time would fail to provide sufficient protection for 81% of the sideways rollovers evaluated in Nebraska. Teaford (1993) provided a fine overview of issues in ROPS design and called for increased use of finite element analysis which capitalizes on recent advances in computer technology.

Finite element techniques for plastic deformation were used in this study to compare stresses in ROPS subjected to a simulated SAE J2194 (SAE Standards, 1997) static testing sequence with ROPS stresses induced by simulated rearward rollovers. The program used was one of the many well-documented, commercially available programs. The stress-strain curve for a mild carbon steel of a type used in marketed ROPS was used to model the material properties. Parametric modeling was used to facilitate investigation of several initial rotational velocities. According to SAE J2194, static testing procedures alone may be used in ROPS certification. However, in an actual rollover, ROPS loadings occur dynamically and may be applied from various orientations. The research described in this article was initiated to gain additional insight into how the structural response of ROPS to dynamic overturns compares with the response to the static test sequence of SAE J2194.

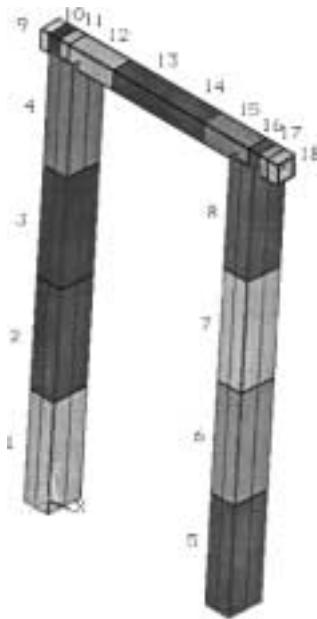
## **Modeling and Simulated Loadings**

Models for both the static test sequence and the overturn (dynamic) simulations were approximately based on a 50 HP tractor with a manufacturer-supplied ROPS. One basic, 3-D, finite element model of the ROPS was used for both static and dynamic simulations. This model consisted of 18 beam elements and 22 nodes (fig. 1a,b) connected to the tractor frame in a cantilever configuration. For this simulation, fasteners between the ROPS and tractor were not modeled since NIOSH testing has shown that very little deformation occurs here. Nodes were initially assigned at the bottom and top of each upright, at each junction of the crossbar with the uprights, and at each end of the crossbar. The remaining nodes were evenly spaced between these end points. For example, nodes 15, 16, and 17 are evenly distributed between nodes 14 and 18. Although only one set of ROPS dimensions was used for this study, the finite element model was developed parametrically to accommodate future studies of a range of tractor and ROPS sizes. Variables that can be altered parametrically can be seen in figure 2 and are listed in table 1 with values used in this simulation.

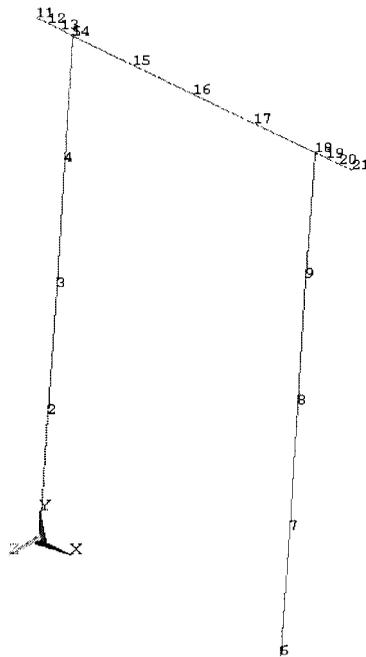
The parametric design permits changes in the ROPS dimensions without varying the number of nodes or elements. It is important to note that this research examined trends for various scenarios for one ROPS finite element model. Some discrepancy should be expected between these simulated results for a "typical" ROPS and experimental results for a particular ROPS.

### **Simulation of SAE J2194 Static Testing**

The static testing portion of SAE J2194 calls for a series of horizontal and vertical loadings where the displacement rate of the ROPS is limited to 5 mm/s. The resulting deformed ROPS must leave a protective zone around the seat and tractor operator. The sequence for the loadings is as follows: rear longitudinal,



**Figure 1(a)**–Finite element ROPS model with element numbers.



**Figure 1(b)**–Finite element ROPS model with node numbers.

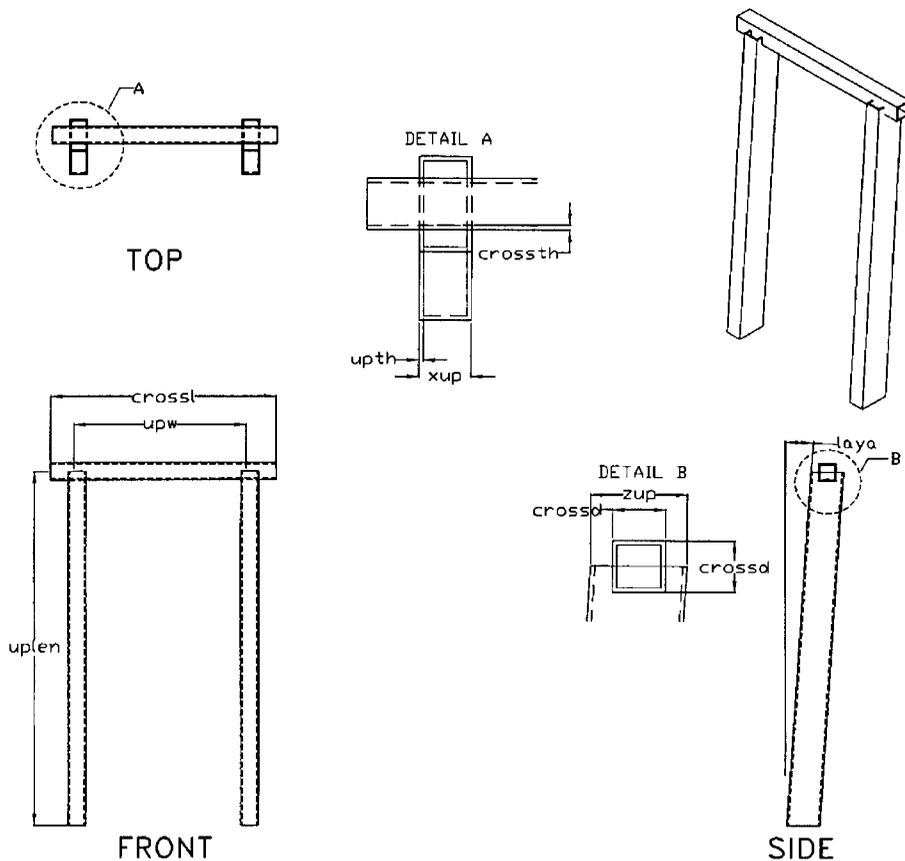


Figure 2–Model parameters.

Table 1. Static model parameter values

Parameter	Value (cm)
X-dimension of uprights (XUP)	7.62
Side dimension of crossbar (CROSSD)	7.62
Thickness of upright beams (UPTH)	0.64
Thickness of crossbar beam (CROSSTH)	0.64
Layback angle of ROPS (LAYA) [°]	9.40
Vertical length of upright (UPLEN)	156.21
Length of crossbar (CROSSL)	97.16
Centerline distance between uprights (UPW)	74.30
Z-dimension of uprights (ZUP)	13.97

vertical crush, transverse, and front longitudinal. Each load, with the exception of the vertical crush, is carried out until the energy absorbed (the area under the force-deflection curve) equals a criterion based upon the tractor's reference mass. The vertical loading test requires the application of a load in proportion to the tractor mass,  $m_t$ . For this study, the reference mass was taken to be the maximum mass,  $m_t$ , reported by the Nebraska Tractor Test (Nebraska Tractor Test 1223 - 1976 - Ford 4600 Diesel, 8-Speed, The Agricultural Experiment Station, Institute of Agriculture

and Natural Resources, University of Nebraska-Lincoln.) for the tractor modeled in this investigation. This mass, 3728 kg, results in the energy criteria found in table 2.

Iteration was used to determine the unique loads that had to be applied to the ROPS model so that the model absorbed the required energy. The iteration was initiated by applying a ramped load with an arbitrarily large end value. The energy absorbed by the model was calculated as the area under the force-displacement curve using the trapezoidal rule. The same test was then repeated using as a final load, the load that produced the requisite energy absorption. This procedure was used for all the tests listed in table 2. The deformed ROPS from each test was used in subsequent testing to achieve cumulative deformation. Figures 3a-d indicate the loading orientations for the ROPS.

Nonlinear material properties and geometry were accounted for in the model. The beam elements representing the ROPS were three-dimensional, thin-walled plastic beam elements with six degrees of freedom. A multilinear kinematic hardening option with a von Mises yield criterion was used.

It should be noted that SAE J2194 also permits a dynamic impact test in which a heavy-weight pendulum swings into the ROPS. The validity of that test would be subject to a different analysis that was not performed for this study. The National Institute for Occupational Safety and Health has a facility for statically testing ROPS and that is why this method was simulated first.

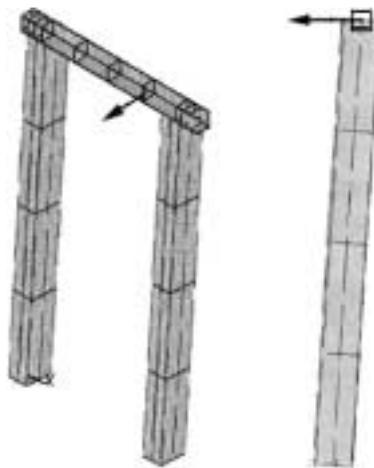
### Simulation of Rear Rollover

The dynamic finite element models used the same ROPS model previously created for static testing and were solved implicitly by the commercial package

**Table 2. Energy criteria for the static tests analyzed**

Test	Energy Requirement*	Energy Criterion (J)
Rear longitudinal	1.4 $m_t$	5219
Transverse	1.75 $m_t$	6524
Front longitudinal	0.35 $m_t$	1305

\* Where  $m_t$  = mass of tractor (kg).



**Figure 3(a)–First longitudinal load.**

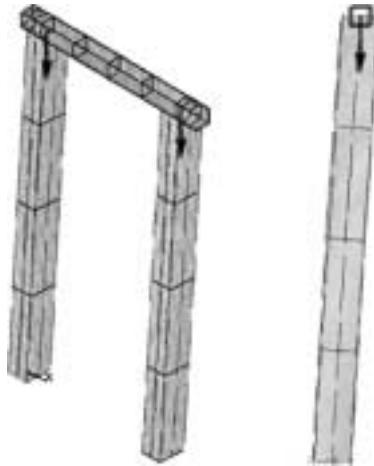


Figure 3(b)–Vertical crush load.

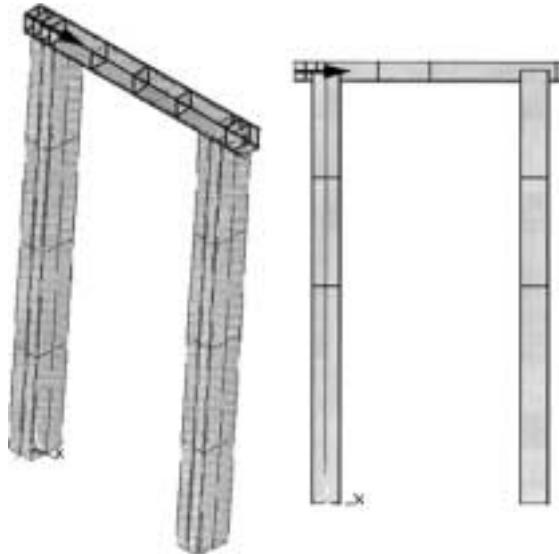


Figure 3(c)–Transverse load.

following Newmark time integration assumptions. A simple tractor frame model was added to approximate inertial effects. It was assumed that the tractor frame does not undergo significant deformation during a rollover, so the primary modeling concern for the frame was to arrive at a reasonable distribution of mass for a proper approximation of rollover dynamics. To achieve this mass distribution, lumped masses were placed at each of the front tires as well as at the center of gravity. The tire masses and center of gravity were known from Nebraska tractor test data for the modeled tractor. The lumped masses were connected to the remainder of the model with rigid beam elements which were given artificially high elastic attributes so that the vast majority of rollover deformation energy was absorbed by the ROPS.

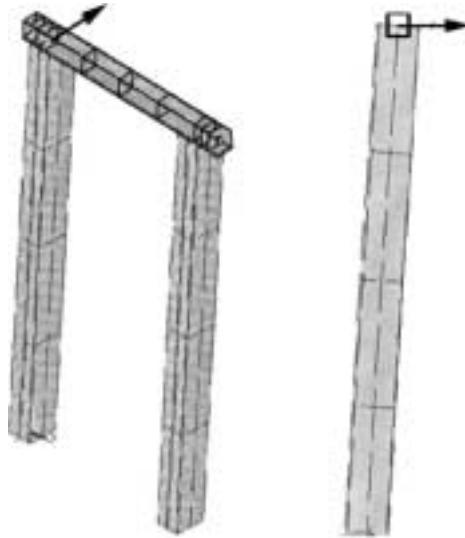
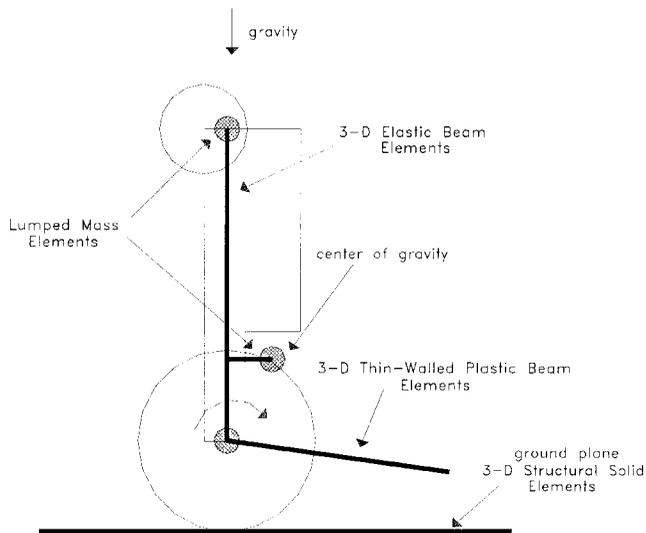


Figure 3(d)–Second longitudinal load.

The ground plane was modeled with solid, elastic eight-noded “brick” elements while three-dimensional contact elements were generated for simulation of the ROPS-ground interface. Approximate interface stiffness properties were obtained through successive approximation. Beginning with estimated stiffness values, several rollover trials were performed until reasonable ground deformation and contact element penetration values were obtained. Penetration into the ground plane was limited to about 0.3 cm to provide a worst-case scenario of an overturn on a relatively unyielding surface. All contact elements utilized a penalty function formulation.

Rear rollovers were simulated for a 60° slope at initial rotational velocities of 1, 2, and 3 radians/s to simulate the field upset test requirements from SAE J2194. If it is assumed that a rear overturn begins when forward progress is stopped, and translational motion is transferred to rotation about the rear axle, 1 rad/s of rotational motion corresponds to 2.61 km/h of forward progress. Likewise, 2 rad/s corresponds to 5.22 km/h and 3 rad/s corresponds to 7.83 km/h. Therefore, under the assumptions made, simulating an initial rotational velocity of 3 rad/s correlates with a forward velocity in excess of the 5 km/h minimum specified by the standard. Slopes were measured with respect to the Z-axis or horizon so that a higher slope refers to a steeper hill. To keep the size of the results file manageable, the tractor was modeled as if it already had climbed the beginning of the ramp. Figures 4 and 5 show the model geometry and initial tractor position. An acceleration field was applied as shown in figure 4 to include gravitational effects. Together with the initial velocity, the acceleration field determined the dynamics of the transient analysis. Effects of engine torque were not included in the model. The tractor frame pivoted about the rear axle as a result of the initial velocity and gravity alone. Both the slope and initial rotational velocity could be entered as parameters by the user. The rear tires were represented by elements that could only act in compression. This representation supported the tractor under its weight, but allowed the tires to leave



**Figure 4–Dynamic overturn simulation model.**



**Figure 5–Finite element model for rear overturn, initial tractor position.**

the ground as the tractor rotated backwards on the ROPS, after the ROPS struck the ground.

## Results

Figures 6a and b compare the stress results for the simulated static and overturn loadings. For the rear rollover simulation, the stress time-history data were analyzed

## Stress Comparison

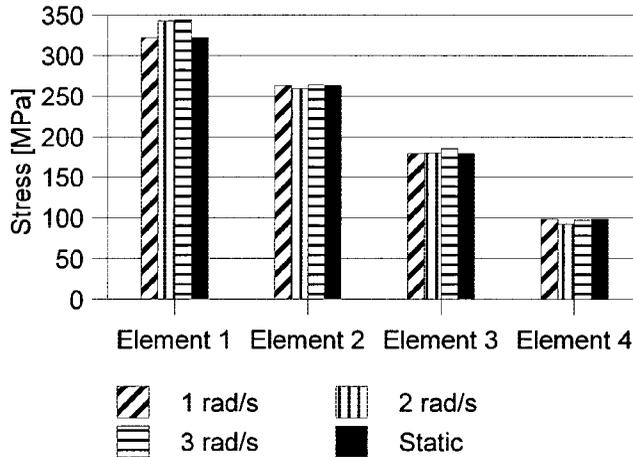


Figure 6(a)–Stress results for elements 1-4.

## Stress Comparison

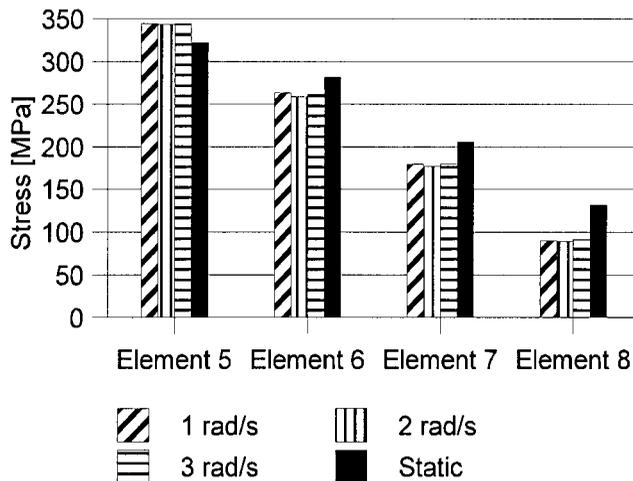


Figure 6(b)–Stress results for elements 5-8.

to determine the maximum axial stress at the nodes for each element. Additionally, the maximum axial stress was determined for each element node during the simulated static SAE J2194 loading sequence. That is, axial stress data were analyzed for each individual element throughout the entire loading sequence, and the maximum value at each beam element end was identified.

For four out of the eight upright elements, the static simulation underpredicts stress experienced by that element in the dynamic simulation. At most the underprediction is approximately 7% of the static simulation value. For the

remaining four elements, the static simulation overpredicts stress experienced by that element in the dynamic simulation. At most the overprediction is approximately 32% of the static simulation value. It is important to note that static underprediction occurs in both elements 1 and 5. These elements have the highest maximum stress level and would likely be used when calculating design stresses.

## Discussion

The goal of this research effort was to gain further insight into ROPS performance under simulated static testing and dynamic rear rollover situations. Finite element analysis techniques that consider plastic deformation were used to simulate static loadings according to certification standard SAE J2194. Rollovers to the rear, using the same ROPS model as that used for the static testing sequence, were simulated in close agreement with field upset requirements of SAE J2194. Pertinent stress data were compiled for nodes and elements. The static and dynamic structural response data were then compared as a means to examine performance requirements set forth in SAE J2194.

Any discussion of simulation results must also mention assumptions made in constructing the models utilized. Most significantly, material properties for the ROPS have been approximated for a typical mild steel. However, since the material properties remain constant for both models, each model is affected equally by material property assumptions and comparisons can still be made. Furthermore, by using the particular beam elements chosen for this analysis, the ROPS uprights are assumed to have constant cross-section throughout. In actuality, many ROPS are manufactured with a tapered cross-section. For the dynamic rear rollover simulations, dynamic effects of the engine and drive train were not included and mass distribution for the tractor frame was approximated by lumped masses placed at the wheels and center of gravity as shown in figure 4. Lumped mass elements were placed at the rear wheels in consideration for future models of other than rear rollovers. For the rear rollover simulation, it was assumed that lumped masses at the axis of rotation, the rear axle, do not contribute significantly to the dynamics of the roll and were set to zero. It was also assumed that the amount of energy absorbed in the tractor frame was negligible compared to the amount absorbed by the ROPS. The fasteners and fastener geometry are a critical component in ROPS performance. However, in NIOSH's field testing experience, deformation of the fasteners was minimal, so was assumed to be negligible for the finite element model.

Contact between the ROPS and the ground in the simulated rear rollovers typically occurred around 1.1 or 1.2 s, as measured from initiation of rearward movement. In comparison, field upset tests inducing rear rollovers performed at Colorado State University (P. D. Ayers, 1993. CSU Field Upset Video, NIOSH Grant No. U07/CCU807121, Hi-Plains Center for Agricultural Health and Safety (HI-CAHS), Department of Agricultural and Chemical Engineering, Colorado State University, Fort Collins) lasted approximately 1.2 s. This approximate value was measured from video of the rollovers which have had time markings in increments of 1/30 s added. Examining times for both cases suggests that the simulated rollover times are reasonable and not out of line with what one could expect for such rollover situations.

From examination of figures 6a and b, the initial rotational velocity appears to have little effect on the resultant stresses. Calculation of the kinetic energy due to the initial velocity showed it to be small in comparison to the potential energy of the tractor at the start of the simulation. The initial velocity could therefore be expected

to have correspondingly little effect on the resultant stresses, supporting the results of figures 6a and b.

Future work might examine whether simulated static testing remains structurally more severe for a different sequence of loads, examine a wider range of rear overturn situations, or include overturns about the longitudinal axis. Simulations of overturns about the longitudinal axis could also be studied for better understanding of variables influencing the occurrence of these particular rollovers. Additional experimental work must be performed: (1) to more accurately characterize the ROPS stress during a rollover; and (2) to assess whether there is a reasonable level of safety built into the current performance standard to account for the range of stresses seen in actual rollovers.

## Conclusions

This research effort began with interest in comparing stresses from the static sequence with those that might be encountered during an actual rollover. The simulations conducted in this study suggest that the static testing sequence does not always overpredict stress in the ROPS for rear rollovers. However, for the localized areas of the ROPS for which the static simulation does overpredict, the overprediction is substantial at approximately 32% of the static stress value for that same area. It must be considered that all work presented in this study examines static testing for a particular loading sequence and selected dynamic rearward overturn situations.

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