

Analyzing tractor rollovers using finite element modeling

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Each year, hundreds of people die as a result of agricultural tractor rollovers. The National Institute for Occupational Safety and Health (NIOSH) within the U.S. Department of Health and Human Services is charged with conducting research to ensure the safety of America's workers and to help prevent such deaths.

Engineers from the NIOSH Division of Safety Research (DSR) are studying tractor rollovers and attempting to solve an old

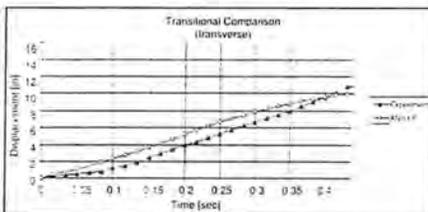


Figure 1.

problem through application of new technologies. NIOSH researchers are using ANSYS® software to simulate tractor rollover dynamics and to study the structural response of the rollover protective structure (ROPS), or rollbar, during a rollover. Such analyses allow researchers to study rollover mechanics via computer and have the potential to reduce the number of field tests required. In addition to studying the structural response of the rollbar, researchers are interested in understanding the conditions precipitating rollover, and want to use this information to design new safety controls or improve older technology.

Development of a rear-rollover model

A rear-rollover model was developed to simulate the effects of a tractor progressing up the grade of a hill, becoming stuck and rolling over by rotating about the rear axle of the tractor. This particular rollover scenario was chosen since it is specified in the current standards for certification of ROPS, ASAE S519¹. The standard cites that a slope of -60 degrees (as measured from the horizon) is needed to induce the rollover, and speeds ranging from 5 to 8 km/hr (3 to 5 mph). To simulate these conditions, the finite element model was rotated 60 degrees

to the Z-axis (see Figure 1) and provided an initial rotational velocity about the rear axle. The rotational velocities were chosen as if all of the forward velocity of the tractor was translated to rotational velocity.

The rear-rollover model consists primarily of two parts: the ROPS and the frame. Eighteen 3D, thin-walled plastic beam elements, BEAM24, were used to model the ROPS. The tractor frame was modeled with rigid 3D elastic beam elements, BEAM4. Elements comprising the frame were utilized to position lump masses representing the front and rear wheels, as well as the center of gravity for the tractor. The distributed centers of gravity were necessary to capture the dynamics of the tractor and thus model the loads on the ROPS. No structural analysis of the frame was intended. Consequently, relatively high stiffness values were supplied for the frame elements. Center of gravity information was obtained from tests performed at the University of Nebraska².

Contact between the ROPS and ground was handled through CONTACT48 contact elements. Rear tires were simulated by a spring-damper control element that acted in compression only. Until contact between the ROPS and ground occurred, the rear axle was only allowed one rotational degree-of-freedom about the X-axis, or transverse tractor axis. After contact occurred, the Y-translational constraint was removed, allowing vertical translation so that the tires could leave the ground. The control element was activated via the element birth option, and the spring-damper combination simulated a tire by permitting only limited motion in the negative Y direction. Free motion was allowed in the positive Y direction. Changes in either the stiffness or damping of this element did not appear to significantly affect the results of the simulations.

The entire tractor model was constructed parametrically to allow easy alteration of key design variables, such as the distance between rear or front tires, thickness of ROPS material, ROPS length and many others. Initial rotational velocity can easily be changed as well. A variety of speeds spanning the recommended range of the standard were simulated.

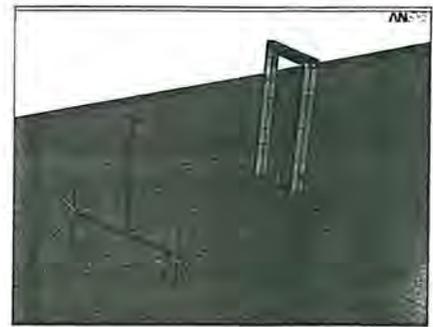


Figure 2.

Development of a side-rollover model

A model was also developed to simulate a rollover occurring about the longitudinal axis of the tractor. To simulate this behavior, the finite element model to simulate this behavior was based upon the earlier model used in the rear-rollover study and can be seen in Figure 2. However, with this model, representation must be added for contact points on the tires and hood assembly that would touch the ground in a side rollover. As with the tractor frame, these contact locations were modeled with "rigid" 3D elastic elements, BEAM4.

The side-rollover behavior simulated was a tractor traveling along the side of a hill perpendicular to the grade and striking something resembling a ramp. To represent this scenario without using additional contact elements to represent a ramp, the tire nodes for the model were given a ramped displacement boundary condition that would raise the tires as if they were climbing a ramp. This ramp representation served to control the speed of the tractor. At the top of the ramp, the constraints on these nodes were released. The tire nodes on the other (non-ramp) side of the tractor were only allowed to rotate about the longitudinal axis to this point in the simulation. As the nodes for the tires on the ramp side of the tractor are released at the top of the ramp, the tractor begins to rotate more quickly about its longitudinal axis. When the center of gravity node passes approximately over the point of rotation, all constraints are deleted from the remaining nodes (non-ramp side of the tractor), allowing for free movement of the tractor. In addition to the contact elements between the ROPS and the ground, contact elements have been added for the tire-ground and hood-ground interface.

As with the rear-rollover model, the side-rollover model was designed parametrically. The tire representation can easily be changed to add additional wheel spokes and thus possible contact points (Figure 2). The

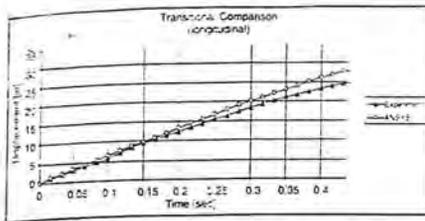


Figure 3a.

slope of the hill across which the tractor is moving can also be altered. Simulations were performed for a wide variety of tractor ramp angles and hill slopes.

Experimental results

Relatively little data exist in the literature to document the rollover behavior of an agricultural tractor, making it difficult to gauge the accuracy of the finite element simulations. To examine the results of the rear-rollover model, video-recorded rollover events from the High Plains Intermountain Center for Agricultural Health and Safety at Colorado State University³ were used. Time indices in increments of 1/30 second were added to the video to determine the speed at which the rollovers occurred. The rollover period measured from videotape for rear rollovers, performed according to ASAE S519, matched well with simulation-predicted rollover periods of approximately 1.2 seconds.

To record data on a side-rollover event, a 1/16 scale-model tractor was used. This tractor was instrumented with reflective markers. It was released from the top of a ramp to gather speed before striking a second ramp, inducing the side rollover. Motion measurement data and the positions of the reflective markers, were collected at 60 Hz for the X, Y, and Z translations. Using a 3D optical motion measurement system. The simulation model was scaled to match the model tractor used in the experiments. Figures 3a through 3c are comparisons of the translation data for this simulation at a mid-point on the tractor hood. Discrepancies between simulation and experiment results can largely be attributed to some forced behavior introduced via the boundary conditions. Most notably, the actual tractor will leave the ramp before the top of the ramp, while the simulated tractor is constrained to the imaginary surface of the ramp until the top. This discrepancy is particularly noticeable for the vertical translation comparison of Figure 3c. The models are under constant refinement to improve accuracy. Yet, for some of the ongoing projects, rollover trends and rates provide sufficient information that otherwise would be much more difficult to obtain.

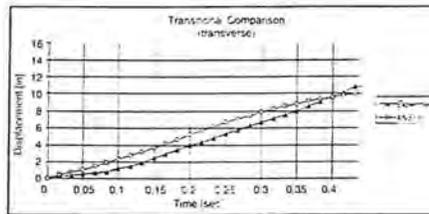


Figure 3b.

Impact of simulation results

Stresses resulting from tractor rear-rollover simulations were compared to stresses resulting from simulations of the static testing requirements in certification standard ASAE S519. The static requirements prescribe a series of four quasi-static loads that must be applied to a ROPS for certification. If the material used in fabrication of the ROPS has had the Charpy V-notch impact test recommended in the standard, then static testing alone is enough to qualify a ROPS for field use without field-upset testing. The stresses from the two simulations were compared to see if the static testing sequence might result in stresses that were similar to those expected from an actual overturn. The rear-overturn simulation resulted in higher stresses than the static overturn simulation for some, but not all cases. These results are not intended to imply that ROPS are not adequately designed. Some ROPS manufacturers perform both static and field-upset testing before certifying a rollbar. A research project has been proposed to collect tractor chassis dynamics and strain measurements from a ROPS during actual overturns, using a remotely controlled tractor. This information could be used to further refine, and perhaps validate, the finite element models so that they might be used to reduce the need for costly field testing.

Researchers at DSR are working with West Virginia University in Morgantown, W.Va., to develop an automatically deploying ROPS, or auto-ROPS. This device would remain in a retracted position during normal operation, so farmers could maneuver tractors in areas of low overhead clearance. If a rollover were detected, the auto-ROPS would deploy to its full height. The side-rollover simulations already discussed are helping to define an algorithm that can be used to identify these rollover events. To date, these models have already been used to refine the sampling time of the deployment-control circuit, so that the auto-ROPS will deploy easily before making ground contact. The side-rollover simulations are most important for this portion of the study, since they occur more quickly than rear rollovers.

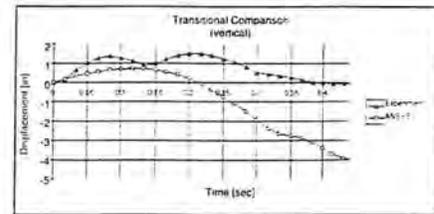


Figure 3c.

Summary

ANSYS is a powerful finite element package that has provided engineers at NIOSH/DSR with the flexibility and feasibility to examine the mechanics and dynamics of agricultural tractor rollovers. Staging actual rollover events can be both time-consuming and costly. While it will still be necessary to perform actual field tests or rollover experiments, finite element simulation models are helping to reduce the number of trials that will be necessary. NIOSH researchers have used the results from simulations of rollovers and static testing to gain insight into current certification standards and refine deployment algorithms for a new auto-ROPS. Perhaps a time is approaching in the not-so-distant future when almost all field upset tests can be accurately and confidently simulated on the desktop.

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Acknowledgments

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*Mention of any company or product does not constitute endorsement by the National Institute for Occupational Safety and Health (NIOSH).

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