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Predicting the performance of cost-effective rollover protective structure designs ☆,☆☆

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ABSTRACT

Agricultural tractor overturns kill more than 100 workers each year in the United States. Rollover protective structures (ROPS) can prevent most of these deaths but can be expensive in retrofit applications. Cost-effective ROPS (CROPS) have been designed and built at the National Institute for Occupational Safety and Health but performance must be evaluated. This study: (1) evaluated CROPS performance, (2) developed a simulation model for probabilistic CROPS evaluation, and (3) evaluated exemplar prototype CROPS performance via simulation of testing requirements. The CROPS prototype evaluated in this study was a Ford-3000 CROPS prototype design. Simulations based on ROPS performance standard SAE J2194 (Society of Automotive Engineers) identified scenarios where the Ford-3000 CROPS might fail. No failure scenarios were identified during simulation of ROPS performance testing to Occupational Safety and Health Administration (OSHA) test procedures and performance requirements. Despite passing experimental SAE J2194 testing, computer simulations found scenarios where the Ford-3000 CROPS prototype design might fail. Re-design of the Ford-3000 concept is necessary before field implementation.

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1. Introduction

1.1. Magnitude of the problem

The agriculture/forestry/fishing/hunting (A/F/F/H) industry sector continues to be one of riskiest industries in the United States. In 2003, the A/F/F/H industry sector had the highest rate of fatal occupational injuries of any sector (US Department of Labor, 2003). Many of the deaths within the A/F/F/H sector are specifically tied to agriculture; many agriculture occupational fatalities involve tractors and tractor overturns. Data for agricultural production from 1992–1998 show the largest source of identifiable fatal injury was the tractor (Hard et al., 2002). When these same data are evaluated by injury event, more than one quarter of all agricultural production deaths (1051) were attributed to “overturning vehicle/machine” for the time period 1992–1998. From 1992–2002, an average of 125 fatalities per year were attributed to tractor overturns (Myers et al., 2008).

A highly effective engineering control already exists to prevent almost all fatalities due to tractor overturn, the rollover protective structure (ROPS) and a seatbelt. OSHA has required ROPS on all tractors (with very limited exceptions) manufactured since 1976. In fact it has been cited that ROPS, when properly used with a seatbelt, typically prevent fatal injury in 99% of overturns (Hallman, 2005). ROPS systems have been commercially available for several decades now in the United States, but this intervention has not saturated the tractor fleet. In 2001, ROPS usage in the United States was estimated at 50% (Myers, 2003). Myers indicated that ROPS usage needs to exceed 75% before significant reductions in rollover fatalities will be realized. More recently, ROPS usage in the United States was estimated at 59% for 2006 (NASS, 2008).

1.2. Regulations and consensus standards

A Society of Automotive Engineers (SAE) industry consensus standard, SAE J2194, provides a test for evaluating the performance of ROPS. Through this test the ROPS is exposed to four sequential loads: longitudinal, first vertical crush, transverse, and second vertical crush. Longitudinal refers to loads in line with the long axis of the tractor. Transverse refers to loads in line with the short axis of the tractor (and perpendicular to the longitudinal axis). As will be

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explained in the Methods section, all loads are based upon the reference mass of the tractor. The same ROPS is used for each of the sequential loads, and the occupant clearance zone is observed for intrusion by the ROPS or exposure to a "virtual" ground plane. Exposure to a virtual ground plane is evaluated to ensure that if the tractor rolled in the direction of the load being applied, the ground would not enter the occupant clearance zone.

The OSHA test procedures and performance requirements in 29 CFR 1928.52 are similar to SAE J2194 in many regards (US Department of Labor, Occupational Safety and Health Administration). Both outline longitudinal and transverse tests. However, the OSHA regulations do not have a vertical crush test. In addition, the clearance volume to be protected has different dimensions from SAE J2194 and required energy levels during longitudinal and transverse tests are different as discussed in the Methods section. OSHA regulations define an agricultural tractor, in part, as a "wheel-type vehicle of more than 20 engine horsepower".

1.3. Past research efforts

ROPS performance research has a long history in the United States. This research dates back to at least 1952 when Osborne Maybrier of Kentucky applied for a United States patent on a "safety guard for a tractor operator" (Maybrier, 1952). More recently, Johnson and Ayers (1994) were among the first researchers to systematically consider ROPS designs for multiple "pre-ROPS" tractors. A pre-ROPS tractor is a tractor design typically developed before 1970 when ROPS were options for tractors, and tractor axle housings were not intentionally designed to support potential ROPS loading. Johnson and Ayers investigated a popular pre-ROPS tractor to evaluate the ability of the axle housing to support a ROPS design. They determined through both static and overturn testing that the particular tractor model investigated (name kept confidential in paper) could support a ROPS for loadings necessary to pass ASAE S519 (equivalent to SAE J2194).

In 2005, Harris, Cantis, McKenzie, Etherton, and Ronaghi presented a paper and results at the annual National Institute for Farm Safety (NIFS) meeting describing progress on attempts to design and commercialize cost-effective rollover protective structures (CROPS) (Harris et al., 2005). The aim of the CROPS concept is to increase the percentage of tractors in the United States with ROPS installed by lowering the economic barrier to retrofitting older tractors with ROPS. Harris et al. provided performance data and plans for a prototype CROPS that one ROPS manufacturer estimated could be manufactured and sold for $290 (2005 United States Dollars [USD]). The same manufacturer estimated the highest shipping cost for the 48 contiguous states to be $193 (2005 USD). Typical ROPS costs (including installation) were estimated at $1000. Cost savings were realized in the design through a weld-free construction of common structural elements and fasteners. A CROPS design for a Ford tractor is shown in Fig. 1.

The CROPS concept is one potential solution to the problem of retrofitting the large fleet of existing US tractors without ROPS. Owusu-Edusei and Biddle (2007) estimated that installing CROPS on all tractors which needed them could save 192 lives over a 20-years period. Previous research has shown that CROPS can be developed that pass the testing procedures outlined in consensus standards (Harris et al., 2005). However, each test represents a single evaluation of the CROPS system, and additional evaluation is necessary to ascertain the influence of dimension and strength variation on CROPS performance. This paper describes our evaluation of CROPS performance through development of a CROPS probabilistic simulation model and examination of exemplar CROPS prototype performance via simulation of testing requirements.

Fig. 1. Ford CROPS prototype.

2. Methods

The current study evaluated the reliability of a CROPS design to meet static testing requirements of SAE J2194 and OSHA regulations as found in 29CFR1928.52. The particular CROPS design evaluated was a Ford-3000 prototype. Reliability was assessed through probabilistic design simulation (PDS) methods utilizing finite element analysis (FEA), response surface methods, and Monte Carlo simulations considering variations in material and geometry input parameters for the Ford-3000 prototype. The basic steps in this study were: (1) perform SAE J2194 experimental static test, (2) develop FEA model based upon SAE J2194 experimental static test data, (3) perform screening tests to identify important prototype factors influencing energy absorption in CROPS within expected variations, (4) utilize design of experiments methods (including central composite design, CCD) to identify important factors and estimate response surface, and (5) perform Monte Carlo simulations on response surface to estimate reliability of design.

2.1. Ford-3000 CROPS design

Fig. 2 shows the conceptual drawing of an early Ford-3000 CROPS design prototype. The Ford-3000 tractor line was manufactured from 1965–1975. A standard tractor weighed approximately 3700 lb. [1678 kg] and had 47 engine horsepower [35 kW]. The axle housing configuration was rectangular in cross-section. The primary elements of the CROPS design for the Ford-3000 include the 2″ × 3″ × 1/4″ [51 mm × 76 mm × 6 mm] tubing utilized for the uprights and crossbar and the 3/8″ [10 mm] thick plate used to fabricate attachment plates and gussets. Fasteners include 5/8″ [16 mm] and 3/4″ [19 mm] grade 5 or 8 bolts.

2.2. SAE J2194 experimental tests

NIOSH researchers conducted all SAE J2194 static testing in the NIOSH High Bay Laboratory in Morgantown, West Virginia. Components of the test facility include: test bed, hydraulic power supply, hydraulic actuators, hydraulic control equipment, data acquisition equipment, reaction frame, and overhead bridge crane.

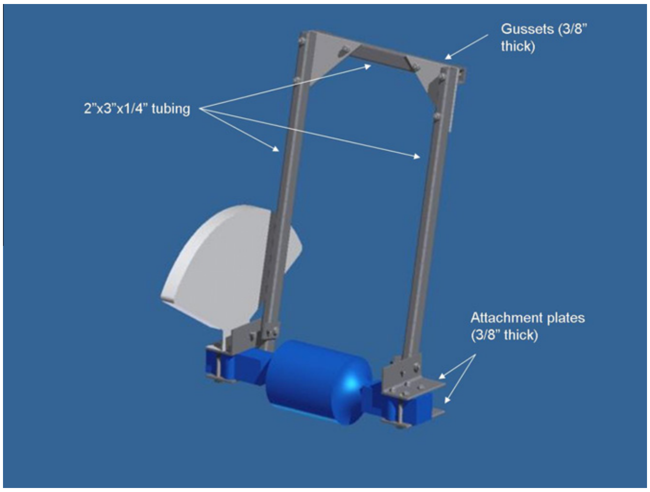

Fig. 2. Ford-3000 CROPS conceptual drawing.

Harris (2008) provides a detailed description of the test facility setup.

2.3. Longitudinal loading

The first static test in the SAE J2194 sequence is a longitudinal load from the rear. Longitudinal loading is defined as loading parallel to the longitudinal median plane of the tractor. The load is to be applied at the uppermost transverse member and at a distance one-sixth of the width of the top of the ROPS inward from the outside corner. Displacement rate is limited to 5 mm/s (0.197 in./s) to be considered static. The test is terminated when there is structural failure, intrusion, exposure, or the energy criterion is met. The energy criterion is compared to the energy absorbed (area under the force vs. deflection curve for the ROPS) during the test. Structural failure is indicated by an inability to support additional loading. Intrusion is movement of the ROPS into the occupant clearance zone, while exposure is movement of the virtual ground plane into the occupant clearance zone. The energy criterion for the longitudinal load in SAE J2194 is 1.4 m_t [Joules], where m_t is the reference mass (in kg). The reference mass selected for testing the Ford-3000 prototype was 1995 kg (~4400 lb.). Discussions with a ROPS manufacturer who worked with NIOSH in development of CROPS led to the selection of 4400 lb. as the reference weight (mass) for SAE J2194 static testing. Using this reference mass value, the energy criterion for longitudinal loading was 1.4 (1995 kg) = 2793 J = 24,710 in.-lb. Fig. 3 shows longitudinal loading of the Ford-3000 CROPS design.

2.4. First vertical crush test

The second test in the SAE J2194 static test sequence is the vertical crush test. For this test the tractor is supported under the axles and a downward load applied with a stiff beam. The resultant crushing force requirement is $20m_t$ [Newtons]. Using the reference mass established previously, the load criterion was 20 (1995 kg) = 39,900 N = 8966 lb. Fig. 4 shows the experimental setup for the vertical crush load.

Fig. 3. SAE J2194 longitudinal loading of Ford-3000 CROPS.

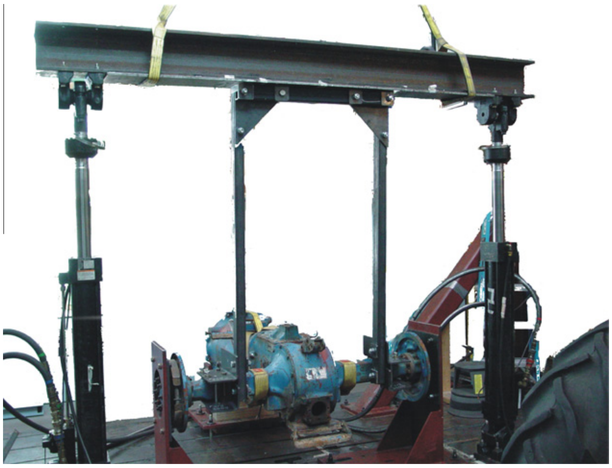

Fig. 4. SAE J2194 vertical crush loading of Ford-3000 CROPS.

Fig. 5. SAE J2194 transverse loading of Ford-3000 CROPS.

2.5. Transverse loading

The third test in the SAE J2194 sequence is a transverse loading. For ROPS which have undergone rear longitudinal loading (50% or more mass on rear wheels), the transverse loading is applied on the opposite side of, and normal to, the longitudinal median plane. Loading for this test was handled under displacement control (~0.5 mm/s [0.020 in./s]) of the hydraulic actuators. The transverse energy requirement is $1.75m_t$ [J]. For the reference mass selected, the transverse energy requirement was 1.75 (1995 kg) = 3491 J = 30,886 in.-lb. Fig. 5 shows the experimental setup for the transverse loading.

As shown in Fig. 5, SAE J2194 allows the upper portion of the clearance zone to tilt during transverse loading.

2.6. Second vertical crush test

A second vertical crush test is required and was performed with the same load criterion (39,900 N, 8966 lb.) as identified previously.

2.7. FEA model development

A commercial FEA software package, ANSYS (version 10.0), was utilized to develop an FEA model for SAE J2194 static testing of the Ford-3000 CROPS. To accurately model the SAE J2194 static test sequence (and later the OSHA regulation test sequence) and to allow future probabilistic design iterations, the FEA model needed to exhibit the following qualities:

- Nonlinear geometry (large deformation/displacements/rotations) and material properties (plastic deformation).
- Parameterized on important input parameters (geometry and material properties).
- Computationally simple to allow multiple runs.
- Ability during longitudinal and transverse loading to calculate absorbed energy under force vs. deflection curve.
- Ability during longitudinal and transverse loading to assess intrusion and exposure criteria.
- Deformed model at end of each static test must be passed onto the next phase of static testing.

To create an efficient, yet accurate, FEA model of the Ford-3000 CROPS, beam elements (BEAM188) were selected in ANSYS. ANSYS labels these elements as 3-D linear finite strain beam elements (ANSYS, Inc., 2005). BEAM188 elements allow standard beam cross sections such as hollow rectangles and L-shaped sections. These elements can also accommodate geometric nonlinearities. Geometric nonlinearities that are addressed within ANSYS include large strain, large rotation, and stress stiffening. Large strain (or finite strain) effects occur when strain exceeds a few percent, and the changing geometry can no longer be considered negligible in strain calculations. Large rotation mathematical formulations are closely related to large strain theory. Stress stiffening refers to the stiffening of a structure due to its stress state. This is applicable to CROPS designs where the bending stiffness may be much less than the axial stiffness.

2.8. Material properties

BEAM188 elements can model nonlinear material behavior throughout the CROPS model. Rate-independent plasticity is used and requires the establishment of a yield criterion, flow rule, and hardening rule to capture the effects of permanent strain throughout the structure. For the Ford-3000 CROPS model, a von Mises stress yield criterion was selected in the FEA modeling software. The stress–strain relationship is considered linear with a slope equal to the modulus of elasticity up to the yield stress. Stress–strain behavior after the yield stress is linear with a slope equal to the tangent modulus.

2.9. Model geometry

The FEA model geometry was created by first establishing keypoints. These keypoints represented critical areas of the CROPS beam such as the beginning or end of a beam. Additional features that had to be modeled included the crossbar, corner gusset plates, and axle housing attachment brackets. BEAM188 elements were utilized to represent the axle housing attachment plates as well as the gussets. In all, the CROPS upright and crossbar beams, attachment brackets, and gusset plates were modeled using 30 beam elements as shown in Fig. 6. The upright to L-shaped plate connection was represented by a special spring and damper element, COMBIN7.

2.10. Model execution

Loading of the model was accomplished in a similar manner to displacement control in experimental testing. That is, the node at

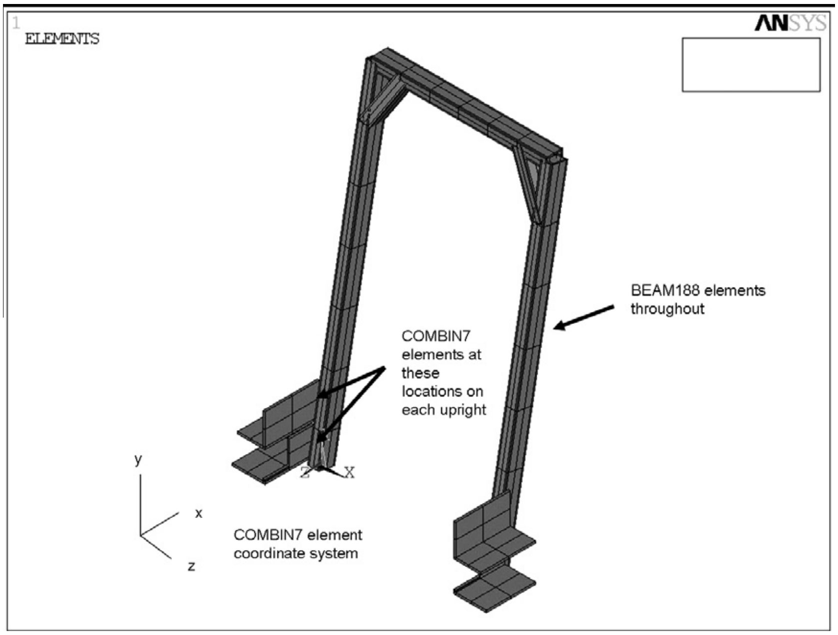

Fig. 6. Ford-3000 CROPS FEA model.

the point of load application was moved by a fixed amount. During model solution, the FEA code solved for the necessary reaction force at this node to cause this displacement. Displacement was incremented ½″ during each FEA solution loop. After each solution loop increment, the reaction force at the node was calculated and absorbed energy (area under force vs. deflection curve as described in SAE J2194) was determined. This energy value was compared against the energy criterion for longitudinal and transverse loading sequences. If the required energy was not yet absorbed, another FEA solution loop was initiated with a ½″ displacement increment. Vertical crush loading was accomplished in a load control manner with the load criterion applied to the required nodes.

2.11. Probabilistic design simulation (PDS)

Preparing the FEA model for probabilistic design simulation (PDS) required two key steps. First, the input variables to be altered and the response variables to be monitored were selected. The following eight variables were chosen initially as input variables (ANSYS variable name in parentheses): beam width (BMWIDTH), beam depth (BMDEPTH), beam thickness (BMTHICK), yield stress (YSTRESS), tangent modulus (TMODULUS), plate thickness (LTHICK), plate yield stress (PYSTRESS), and plate tangent modulus (PTMODULUS). Second, each input variable was assigned a probabilistic distribution based upon expected variation for use in the ANSYS PDS module (Harris, 2008). The distribution for these variables followed the normal Gaussian distribution. Consensus standard limitations and material certification sheets were used to determine the properties listed in Table 1.

Table 1
Truncated Gaussian distribution parameters for FEA code.

	Minimum	Average	Maximum	Std. dev.
ASTM A 500[a]				
BMWIDTH (in.)	1.98	2.0	2.02	0.010
BMDEPTH (in.)	2.975	3.0	3.025	0.0125
BMTHICK (in.)	0.225	0.25	0.275	0.0125
YSTRESS (psi)	46,000	57,250	60,500	2500
TMODULUS (psi)	32,258	35,039	38,489	2609
ASTM A 36[b]				
LTHICK (in.)	0.345	0.375	0.405	0.015
PYSTRESS (psi)	36,000	52,000	58,000	5500
PTMODULUS (psi)	96,491	103,774	157,895	15,351

[a] ASTM (2009).
[b] ASTM (2008).

3. Results

3.1. Comparison of experimental and simulation data

Evaluation of the FEA model was accomplished by comparing simulation results with actual SAE J2194 experimental test results for a Ford-3000 CROPS prototype. Of primary importance was matching of load and displacement data to accurately predict energy absorption within the CROPS structure. Figs. 7–10 show Ford-3000 CROPS experimental data and simulation results.

3.2. Screening tests

With the distributions estimated for each random input variable, the FEA model was executed in the PDS mode. A direct Monte Carlo method was used where each random input variable was randomly assigned a value according to the probabilistic distribution chosen. The model was executed in a mode that called for 30 loops or termination after the mean of the input variables converged to 1% and the standard deviation converged to 2%. The FEA model solution did not converge through all portions of SAE J2194 testing during loop 6 (out of 30). Evaluation of the simulation information for loop 6 suggests that FEA numerical nonconvergence was indicative of CROPS material failure. Table 2 shows the randomly assigned parameters for the loop where failure occurred.

The FEA input code was modified to perform testing as described in OSHA 29 CFR 1928.52. The primary differences between SAE J2194 static testing and OSHA testing are: (1) only longitudinal and transverse loading required by OSHA testing (if appropriate energy is absorbed), (2) increased energy criteria for both longitudinal and transverse OSHA testing, and (3) different means for assessing exposure during OSHA testing (i.e. critical dimensions rather than the SAE J2194 clearance zone).

The OSHA regulations follow much of what was initially included in an earlier ROPS standard, SAE J334. With a reference weight of 4400 lb., the resulting rear load energy requirement is

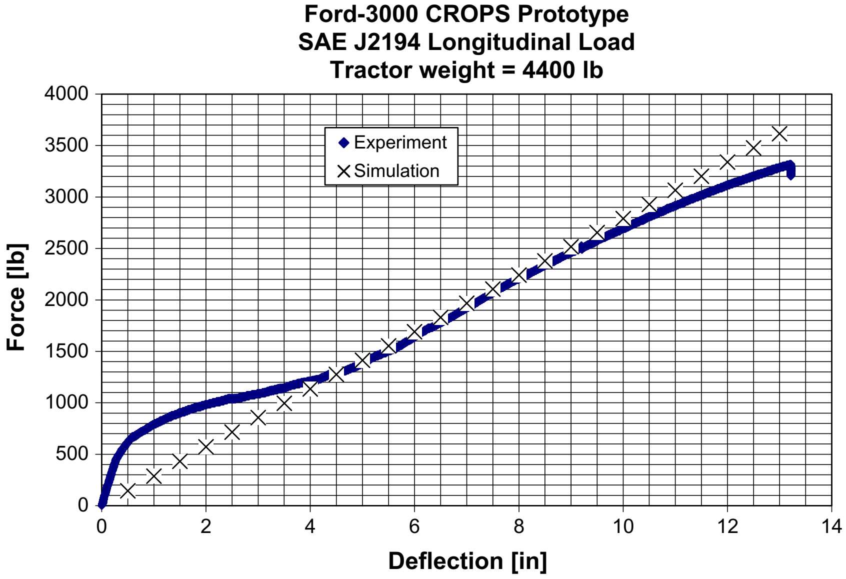

Fig. 7. Force vs. deflection for longitudinal load.

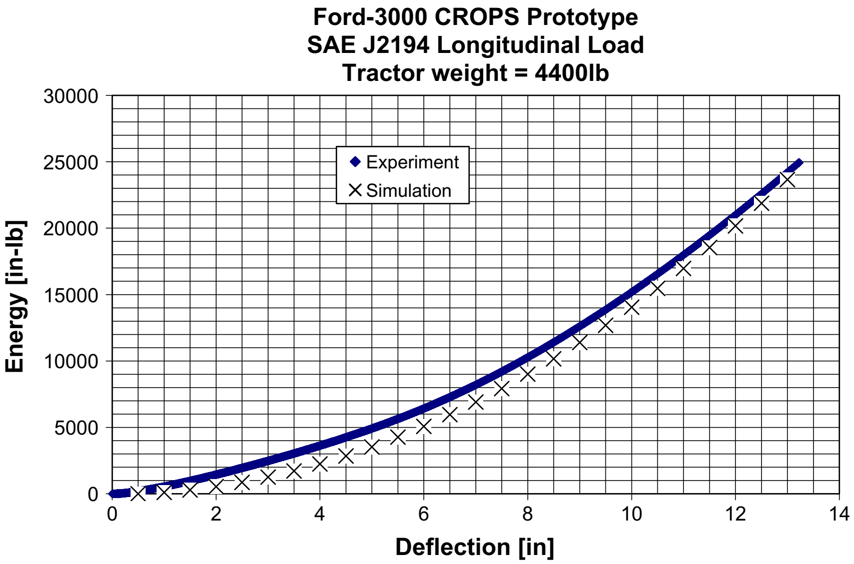

Fig. 8. Energy vs. deflection for longitudinal load.

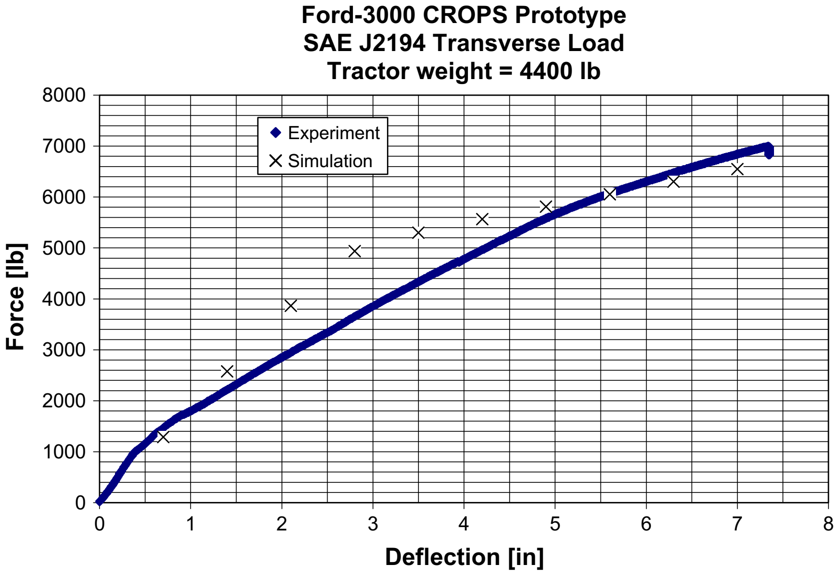

Fig. 9. Force vs. deflection for transverse load.

24,816 in.-lb. The OSHA standard allows the field upset test to be omitted if the rear load energy requirement is raised by 15% to 28,538 in.-lb. The side load energy requirement is 29,796 in.-lb. To avoid the field upset test, this value increases to 34,265 in.-lb.

Exposure and intrusion are evaluated through the use of critical dimensions displayed in Figs. 11 and 12.

Based on these figures, the dimensional requirements of Table 3 must be met.

Fifty initial Monte Carlo loops through the OSHA static test sequence were conducted. All loops successfully solved within the FEA code, and no intrusion/exposure failures were detected. Initial factors of interest in the PDS model were the same as in the SAE testing simulation and are listed in Table 1. Only two of these variables had significant influence at the 2.5% level for transverse load level (RFX) during the OSHA test. These variables were beam thickness (BMTHICK) and beam yield stress (YSTRESS). Sensitivity was calculated in the FEA code and PDS module through use of a nonparametric statistic, Spearman's rank correlation (Dowdy et al., 2004). Each random input variable previously mentioned was evaluated for correlation with the output variable quantifying transverse load level (RFX).

Similarly, the Spearman rank sensitivity was calculated for other important response variables during OSHA transverse loading. *DT* is the FEA response variable which corresponds to *d* in Fig. 11. The sensitivity analysis revealed that the following FEA input variables were significant (2.5% level): BMTHICK, BMWIDTH, and YSTRESS. Response variable *ET* corresponds to *e* in Fig. 12. The sensitivity analysis revealed that the following FEA input variables were significant (2.5% level): YSTRESS and BMTHICK.

3.3. Development and evaluation of response surfaces

Based upon the results of the screening tests, response surfaces were developed to predict output variables for various combinations of the input variables. Development of response surfaces was limited to OSHA testing simulations. As described previously,

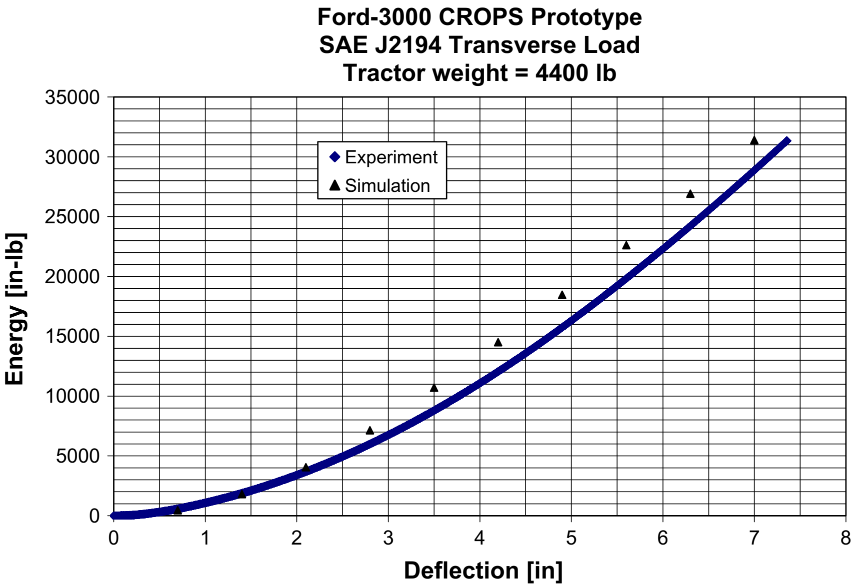

Fig. 10. Energy vs. deflection for transverse load.

Table 2
CROPS parameter values for simulation failure.

Parameter name	Parameter value	Distance from average (sd = standard deviation)
BMWIDTH	1.996″	−0.4sd
BMDEPTH	3.008″	0.64sd
BMTHICK	0.246″	−0.32sd
YSTRESS	59,959 psi	1.08sd
TMODULUS	36,745 psi	0.65sd
LTHICK	0.364″	−0.73sd
PYSTRESS	41,708 psi	−1.87sd
PTMODULUS	99,034 psi	−0.31sd

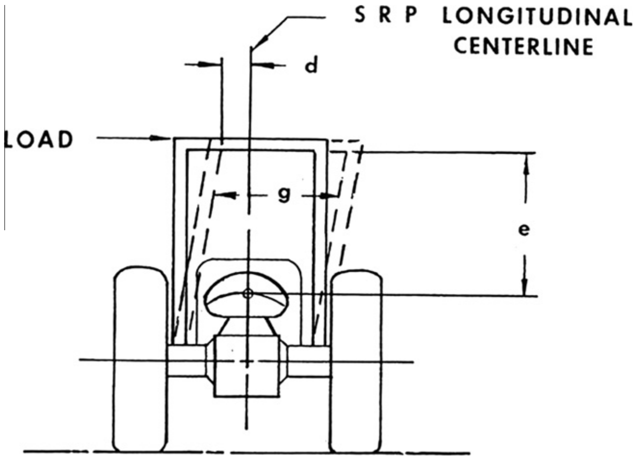

Fig. 11. Critical dimensions for OSHA 1928.52 transverse load.

SAE J2194 static testing simulations identified combinations of input parameters where the Ford-3000 CROPS could not meet the performance criteria of all test phases. This presented a discontinuity in the response of the CROPS structure and prevented the mathematical modeling of a continuous surface.

The transverse (and final) loading phase of OSHA testing was of special interest and was chosen for detailed response surface analysis. The three variables were used that were significantly correlated with dimension *d* (FEA variable DT) during transverse loading. These variables were upright/crossbar beam thickness (BMTHICK), upright/crossbar beam width (BMWIDTH), and upright/crossbar beam yield stress (YSTRESS).

Using these three influential variables only, a central composite design (CCD) was run to evaluate the design space. This CCD design resulted in 15 simulation runs and was a resolution V design. A resolution V design ensured that second order interaction effects were not confounded with each other. A response surface was developed based upon the results of the 15 trials to predict dimension *d* (output variable DT in FEA input file) during transverse loading. The response surface was a quadratic regression which included all linear and cross terms. Based upon a forward-stepwise-regression, the variables and coefficients listed in Table 4 were included in the model:

Scaling for each of the variables was handled by the FEA software as follows:

$\text{BMWIDTH\_scaled} = 8.76610 \times 10^{1} * \text{BMWIDTH} - 1.75322 \times 10^{2}$.
$\text{BMTHICK\_scaled} = 7.01288 \times 10^{1} * \text{BMTHICK} - 1.75322 \times 10^{1}$.
$\text{YSTRESS\_scaled} = 3.46344 \times 10^{-4} * \text{YSTRESS} - 1.92496 \times 10^{1}$.
The entire regression equation is DT = Sum of (Coefficient $*$ Term).
The *r*-squared coefficient of determination for this response surface was 0.793.

A similar procedure was followed for dimension *e* (ET). Although only two statistically significant input variables (YSTRESS and BMTHICK) were identified by the sensitivity analysis, the three variables of highest sensitivity were used (YSTRESS, BMTHICK, and PTMODULUS) to conduct CCD for ET. Table 5 lists the regression coefficients for the variables.

Scaling for each of the variables was handled as follows:

$\text{PTMODULUS\_scaled} = 1.08293 \times 10^{-4} * \text{PTMODULUS} - 1.21406 \times 10^{1}$.
$\text{BMTHICK\_scaled} = 7.01288 \times 10^{1} * \text{BMTHICK} - 1.75322 \times 10^{1}$.
$\text{YSTRESS\_scaled} = 3.46344 \times 10^{-4} * \text{YSTRESS} - 1.92496 \times 10^{1}$.

The *r*-squared coefficient of determination for this response surface was 0.943.

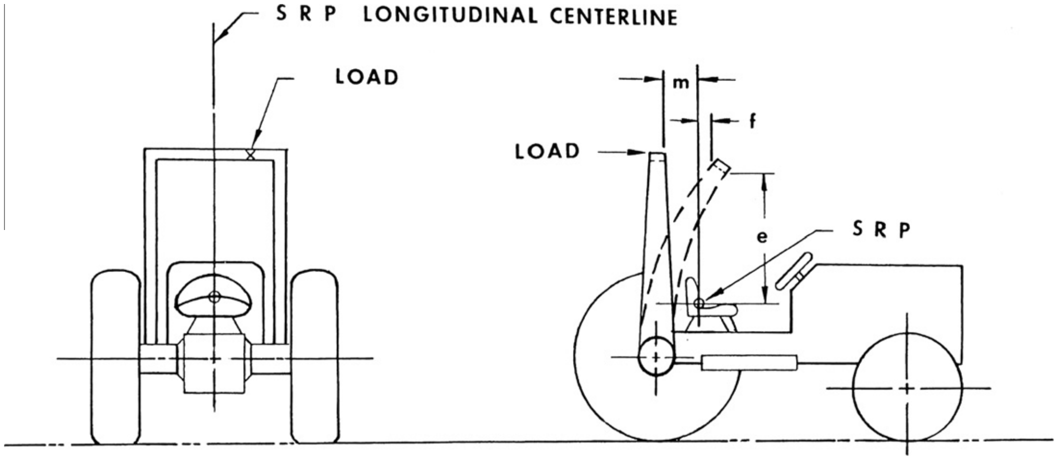

Fig. 12. Critical dimensions for OSHA 1928.52 longitudinal load.

Table 3
OSHA required dimensions.

Dimension	Requirement
d	⩾2″
e	⩾30″
f	⩽4″
g	⩾24″
m	⩽12″

Table 4
Regression coefficients for response surface to predict variable DT.

Term	Coefficient
CONSTANT	7.23333
BMWIDTH_scaled	1.29093×10^{-1}
BMTHICK_scaled	1.34797×10^{-1}
YSTRESS_scaled	1.34797×10^{-1}

Table 5
Regression coefficients for response surface to predict variable ET.

Term	Coefficient
CONSTANT	37.9251
BMTHICK_scaled	2.26535×10^{-2}
YSTRESS_scaled	2.36515×10^{-2}
PTMODULUS_scaled * PTMODULUS_scaled	-1.03057×10^{-2}
BMTHICK_scaled * YSTRESS_scaled	1.83924×10^{-2}

3.4. Monte Carlo simulations and reliability predictions

Monte Carlo simulations (10,000 trials) were performed utilizing the response surface to predict distance d (DT) at the conclusion of the transverse loading of the OSHA test. The histogram in Fig. 13 shows the distribution of this distance variable over the 10,000 Monte Carlo simulations.

Based upon these results, the probability could be calculated that d (DT) would be less than 2″ and the simulated CROPS would fail the transverse portion of the OSHA test. It can be anticipated from Fig. 13 that this probability is quite low, and indeed it was calculated from the distribution within the FEA code as 0%. In fact, 99.7% of simulated DT values were between 6.941″ and 7.637″ according to Fig. 13. Furthermore, when a 95% confidence interval is calculated about the regression estimates for DT values, the lowest DT value computed is 5.48″. This value is derived by using the lowest 99th percentile values for the three regression variables and applying a 95% confidence interval.

4. Discussion

4.1. SAE J2194 static testing

Probabilistic design simulations conducted in this research suggest that the Ford-3000 CROPS prototype design could fail SAE J2194 testing for the reference weight (4400 lb.) and probabilistic distribution of input variables selected in these analyses. Table 2 lists the parameter values utilized in the simulation loop where SAE J2194 requirements could not be met. Comparing this table to the Gaussian distribution parameters, the ASTM A 36 properties were all below average while the ASTM A 500 properties were split between being above average and below average. Table 2 shows the deviation from average for each of the parameters in the particular simulation loop where SAE J2194 test criteria were not satisfied. The last three rows of Table 2 represent ASTM A 36 properties.

These data suggest that additional attention should be given to performance of the ASTM A 36 attachment plates as future CROPS prototypes are developed. As an example, thicker material or additional bracing may be needed in this area.

4.2. OSHA 29 CFR 1928.52 testing

Simulation and failure prediction for OSHA testing concentrated on transverse loading. This was reasonable since no longitudinal failures were detected during the 50 PDS loops described previously. Response surfaces were constructed to predict OSHA dimension d (DT) and e (ET). The response surface to predict DT was a linear combination of parameters BMWIDTH, BMTHICK, and YSTRESS. To predict ET, quadratic terms for PTMODULUS and a cross (or interaction) term for BMTHICK and YSTRESS were included in addition to linear terms for BMTHICK and YSTRESS. This highlights the need to understand the variation in the BMTHICK and YSTRESS input variables. Predicted DT values varied from 6.635″ to 7.851″. This is substantially more than the minimum 2″ requirement. No simulation scenarios were discovered or predicted that would indicate an OSHA static test failure of the Ford-3000 CROPS prototype.

4.3. Research limitations

Simulation limitations of the FEA model must be considered when evaluating the data from this research. As described previously, displacement at the point of load application for both the

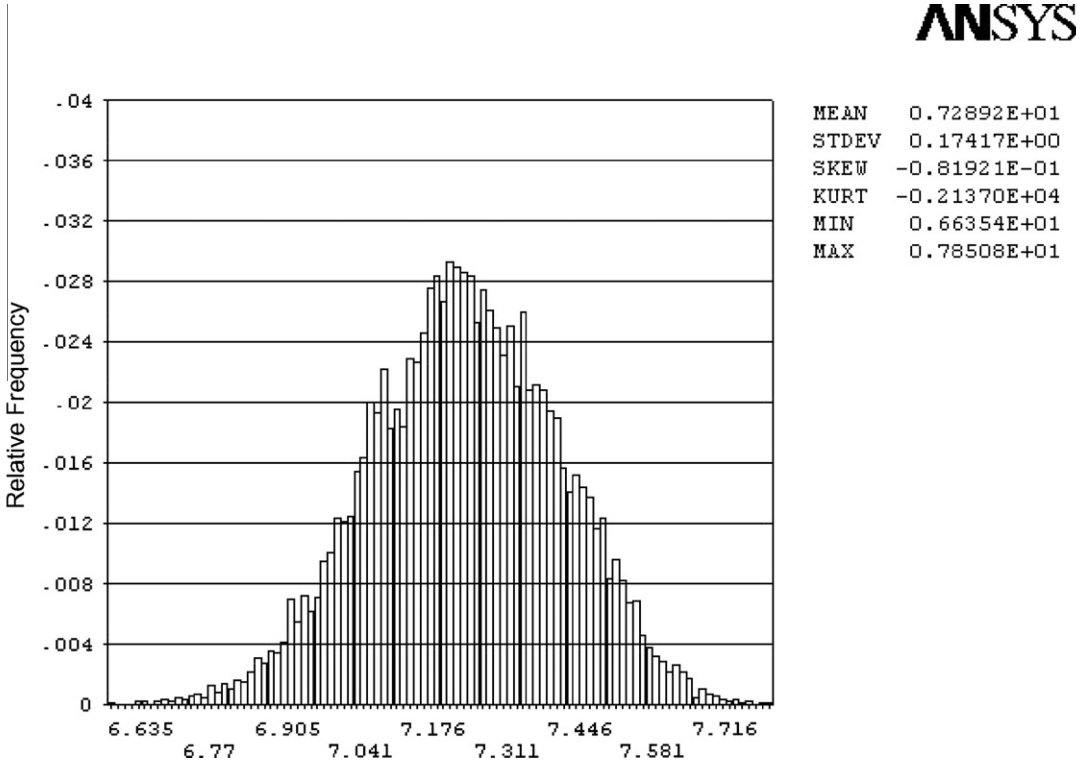

Fig. 13. Histogram for variable DT [units are in.] during 10 000 Monte Carlo Simulations.

transverse and longitudinal tests is applied via 0.5″ increments. This is consistent with measurement requirements for dimensions of the critical zone in OSHA 29 CFR 1928.52. However, this induces some error if the energy criterion is reached during (rather than at the end) of an increment.

Capturing the effect of CROPS prototype machining tolerances (or ''slop'') in the FEA model was difficult. Each bolted connection of the CROPS prototype had a dimensional tolerance (typically 1/16″) added to thru hole diameters to allow easier insertion of bolts during assembly. Many of these bolted connections were at the bottom of the CROPS and thereby affect the movement at the crossbar height of the CROPS more substantially than holes located higher up the CROPS upright. In addition to the displacement differences between experimental and simulation results this may have caused, the stiffness of the overall structure can be affected as bolts may move within the added dimensional tolerance of the hole until the CROPS can ''lock up''. This could explain differences in the initial slope of the force vs. deflection curves for the experimental and simulation results (e.g. see Fig. 7).

In order to complete the nonlinear simulation of the FEA model, material models for CROPS material behavior had to be declared. For the simulations in this research, a bilinear model was used to capture the nonlinear CROPS behavior. This material behavior assumption does not completely match how the material will deform during experimental testing. Sample specimen tensile testing per an ASTM protocol would provide more complete data on material response and would allow a more accurate description of the nonlinear response. However, this type of testing is expensive and time consuming. Bilinear curves can be constructed from material properties supplied by the steel mill. Accuracies of 10% and 5% were recorded for predicting final load levels during longitudinal and transverse SAE J2194 testing. This compares favorably with force measurement accuracy of ±5% in OSHA requirements.

A limitation for the FEA model was that tube holes were not geometrically represented. Representing these through holes in the model would have likely required a different type of element such as a shell or solid and would have also required many more elements. This would have substantially increased the computer solution time for the models by increasing the model degrees of freedom. Stress and displacement prediction accuracy may have been improved by such a model, but the results have shown that the beam models work reasonably well to predict overall deformation of the CROPS. Tube hole assumptions could also have affected the overall stiffness of the axle housing attachment plate-upright joint.

Assumptions regarding the probabilistic distribution of input variables also likely influenced the final results predicted through the response surface method. The probabilistic distribution for two of the three statistically significant variables (BMTHICK and YSTRESS) was fairly well defined. The beam thickness variable (BMTHICK) distribution was largely determined through allowable limits established in the specification standard ASTM A 500. The standard is clear on allowable maximum and minimum values, however, the standard deviation for this distribution was estimated using Tchebysheff's theorem (Scheaffer et al., 2006). Empirically determining the standard deviation would have been preferred if sufficient tubular samples had been available. Beam yield stress (YSTRESS) minimum was clearly defined within the ASTM A 500 standard. However, information about the standard deviation and maximum was determined from steel mill certification sheets for the limited numbers of steel tube utilized in the lab. These data provided reasonable estimates of distribution properties, but additional samples/information would have improved this estimate. Information on beam tangent modulus (TMODULUS) was based upon data provided with the steel mill certification sheets. This was a derived property. Some additional inaccuracy should be expected in this variable compared to BMTHICK and YSTRESS which are measured directly. This distribution estimate would have also benefited from additional sample data. Additional samples are costly in terms of money and time and were not a feasible option for this project.

It is hoped that the model and modeling concepts developed in this research will be useful in predicting the performance of future CROPS designs. The design, development, and test cycle is time consuming and costly; reducing the number of iterations through this cycle should facilitate the process of retrofitting tractors with CROPS and reducing the number of tractor overturn fatalities in the US each year. The model and techniques developed in this research allow evaluation of testing standards for conditions outside of the average. It is important to understand how a design will perform over the expected range of input variable values. Techniques presented in this research can assist the designer to identify those input variables most likely to affect CROPS performance. In addition, the modeling strategy utilized in this study can easily be modified to accommodate CROPS designs for different tractor models. Before new CROPS prototypes would be fabricated, simulations could be conducted to initially assess the probability that the design would pass experimental testing.

5. Conclusions

The primary aim of this research was to evaluate the performance of cost-effective rollover protective structure (CROPS) designs on the SAE J2194 consensus standard and OSHA 29 CFR 1928.52 regulations using probabilistic methods. In addition, the SAE standard and OSHA regulations were compared to evaluate whether one was more conservative than the other.

CROPS performance was assessed using the prototype design for the Ford-3000 tractor. This prototype was tested per SAE J2194 static testing requirements at the NIOSH High Bay Lab facility. These results served as the baseline for final development of the FEA model. When the energy criterion was met, the simulation longitudinal load error was 10%. For the transverse load, the simulation error was 5%. At the longitudinal loading simulation end point, energy absorbed in the simulation differed from experimental energy absorbed by 2%. For transverse loading the difference was 9%. It should be noted that the Ford-3000 prototype CROPS passed all SAE J2194 test requirements.

Probabilistic design simulation requires that random input variables for the FEA model be identified and an estimated distribution be attributed to each variable. Simulation loops were conducted with each input variable assigned a value from the respective probabilistic distribution. During one of the initial thirty simulation loops, the model identified potential failure of the Ford-3000 CROPS prototype during the SAE J2194 static test sequence. Using the same input variable probabilistic distribution, 50 simulation loops were conducted for static test requirements found in OSHA 29 CFR 1928.52. Evaluation of Spearman rank sensitivity showed that three of these variables had significant influence at the 2.5% level for output variable d (DT) during transverse loading. D is a critical dimension defined in OSHA 29 CFR 1928.52 for tracking rollbar transverse movement during transverse loading. The significant variables were beam thickness (BMTHICK), beam width (BMWIDTH), and beam yield stress (YSTRESS).

Using the three identified, influential variables, a response surface was developed to predict d (DT) during OSHA transverse testing. Based upon the mathematical representation of this response surface, 10,000 Monte Carlo calculations were performed. Based upon the distribution of these variables, it was calculated that there was 0% probability of the CROPS design failing critical d requirements of OSHA 29 CFR 1928.52.

One of the aims of this study was to compare SAE J2194 testing to OSHA 29 CFR 1928.52 testing. Initial simulation of the Ford-3000 CROPS prototype using average values for all input parameters indicated that the design would pass SAE J2194 testing. However, when probabilistic distributions were applied to the input parameters, the simulation indicated potential failure during SAE J2194 testing. When similar probabilistic techniques were applied to the Ford-3000 CROPS model under OSHA test requirements, no failures were predicted. The implication from these simulation data is that the SAE static test sequence could be a more conservative design test than the OSHA static test series.

6. Uncited references

Society of Automotive Engineers (2002), US Department of Labor, Occupational Safety and Health Administration (xxxx) and Yeh (1976).

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