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DEVELOPING A FINITE ELEMENT (FE) MODEL TO PREDICT THE ROLL-OVER PROTECTIVE STRUCTURE (ROPS) BEHAVIOR UNDER SAE J2194 STANDARD TEST

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Abstract. This research focuses on applying FE technique to predict ROPS stress-strain curves under the simulated standardized tests. The Society of Automotive Engineers (SAE) J2194 ROPS Standard test was selected for this study. According to SAE J2194 standard, the ROPS should pass consequences of four static tests, consists of longitudinal rear loading, first vertical, longitudinal side loading, and the second vertical loading test. The ROPS must absorb a predefined level of energy under longitudinal loads and tolerate a specific force under crushing loads, before the ROPS collapses or the driver's clearance zone is infringed by the ROPS or the ground surface. The tests were simulated by Abaqus for two posts ROPS with corner brackets which were designed with Computer-based ROPS Design Program (CRDP) which is developed to simplify ROPS design and utilize the bolted corner bracket technique. A nonlinear finite element model is developed for predicting the ROPS performance under simulated standard test. The Von Mises yield stress criteria were used for testing ROPS deformation. The predicted stress-strain curves were used to calculate the absorbed energy under lateral and longitudinal loads. The final model should include four steps, model development, model verification, model calibration, and model validation. The model should be calibrated and validated by comparing the model results with experimental test results. The absorbed energy for a designed ROPS for the Long 460 tractor is equal to 2845 J and 3556 J under longitudinal and transverse load, respectively. The Allis Chalmers 5040 absorbed energy is equal to 2579 J and 3224 J for longitudinal and transverse load, respectively. The permanent deflection under 40640 N vertical load was 23.9 mm for Long 460, and under 36840 N vertical load was 7 mm for Allis Chalmers 5040.

Keywords. *ROPS, Model, Finite element method, Standard, corner bracket.*

Introduction

Agriculture is one of the most dangerous industries in the US (Bureau of Labor Statistics, 2014). Tractor accidents are the major cause of death in agriculture, producing about one half of the fatal accidents (Springfeldt, 1996). Tractor overturn is the most common cause of death in tractor accidents. Roughly one third of the fatal tractor accidents are rollover accidents(Murphy and Yoder, 1998). The most effective way to prevent overturn deaths during an overturn accident is use of a rollover protective structure (ROPS) in combination with a seat belt. A ROPS is a structure which absorbs a portion of the impact energy generated by the tractor weight in the rollover accident. The ROPS decreases the possibility of severe human injuries by providing a clearance zone to protect the operator among the ROPS envelope. Several standard test methods have been develop to examine the ROPS performance before applying in the field.

The experimental standardized tests are expensive, laborious, time consuming, and destructive. The static test is less demanding than the dynamic or field upset test but it is still costly and time consuming. Fabbri and Ward (2002) reported that about one third of ROPS standard tests failed at the Bologna standard test station in Italy. The test failure postpones ROPS production project and increases the project expenses. Using the experimental test alone does not provide efficient ROPS design and performance testing. Therefore researchers have used a combination of experimental test and mathematical model to improve and test ROPS performance (Chen et al., 2012; Karliński et al., 2013). The ROPS experimental tests have not been replaced with mathematical models yet. Modeling has been introduced as a method that can simulate ROPS performance in rollover accidents, speeds up the design process and reduces the ROPS production expenses. Modeling increases the understanding of ROPS behavior under the standardized test and can be used as a tool to decrease the possibility of test failure before the experimental test. Therefore researchers have used combination of experimental test and mathematical model to improve and test ROPS performance.

Several authors developed analytical models for predicting the behavior of ROPS in simulated standardized tests (Yeh et al., 1976; Swan, 1988; Kim and Reid, 2001; Thambiratnam et al., 2009; Clark, 2006). Several authors used finite element (FE) techniques to simulate the ROPS deflection under load (Harris et al., 2000; Fabbri and Ward, 2002; Thambiratnam et al., 2009; Alfaro et al., 2010; Karlinsiki et al., 2013).

Several authors used commercial FE software packages to predict ROPS performance under standard test such as, ANSYS (Alfaro et al., 2010) and Abaqus (Clark, 2006; Thambiratnam et al., 2009). Fabbri and Ward (2002) developed a FE-based program to predict ROPS behavior for most common ROPS under Organization for the Economic Co-operation and Development (OECD, 2008) and Economic European Community (EEC, 1987) standardized tests and compared the results with experimental test results. The developed model was accurate for predicting force-deflection to within 30% percent of the actual test values of a two post ROPS with stiff fixing points to the tractor. In the case of weak fixing points the model results were within 50% of the actual test values. The accuracy of the program was directly related to the accuracy of the geometry creation, the description of the material properties and the boundary conditions.

Alfaro et al. (2010) used FE technique to simulate standardized static test based on OECD code 4 and SAE J2194 and predict ROPS force deflection curve. Three models of four post ROPS and a cab were selected for this study. The model results have close agreement with the experimental test results. They estimate the maximum allowable tractor mass based on the ROPS force deflection curves under the simulated standardized test.

STANDARD SAE J2194

Several standards have been developed for testing ROPS performance requirements. SAE J2194 (1997) is an official procedure which was developed for testing ROPS performance of wheeled agricultural tractors. Based on SAE J2194 the static test is applicable for tractors heavier than 800 kg. The static test usually consists of sequences of four static tests including, longitudinal, first vertical, transverse load test, second vertical loading test, and in some special cases over load test. The static test performance requirements would be met if the structural members absorb a predefined level of energy in longitudinal and transverse tests and tolerate a specific force in vertical test without violating intrusion and exposure criteria. The ROPS should not infringe the clearance zone (intrusion criteria) and ROPS should not leave clearance zone unprotected from the ground plane (exposure criteria).

LONGITUDINAL LOADING TEST

The longitudinal load should be applied horizontally and parallel to the longitudinal tractor median plane with rate less than 5 mm/s. The load is applied to the uppermost transverse structural member of the ROPS which is most likely to strike the ground first in an overturn accident (Fig. 1). The first longitudinal test must be inserted from rear of the ROPS until the ROPS absorbed energy (E) is equal to:

$$E= 1.4\ M \qquad (1)$$

Where E is absorbed energy (J) and M is tractor reference mass in (kg). The absorbed energy is the area under force- deflection curve. Tractor reference mass is determined as “A mass, not less than the tractor mass, selected for calculation of the force and energy inputs to be used during test.” Commonly, unladen mass of tractor is selected as the reference mass. Unladen mass of tractor is equal to the total mass of vehicle with the ROPS fitted, full liquid tanks (fuel, lubricant, and coolant), and a 75 kg driver (Rondelli and Guzzomi, 2010)

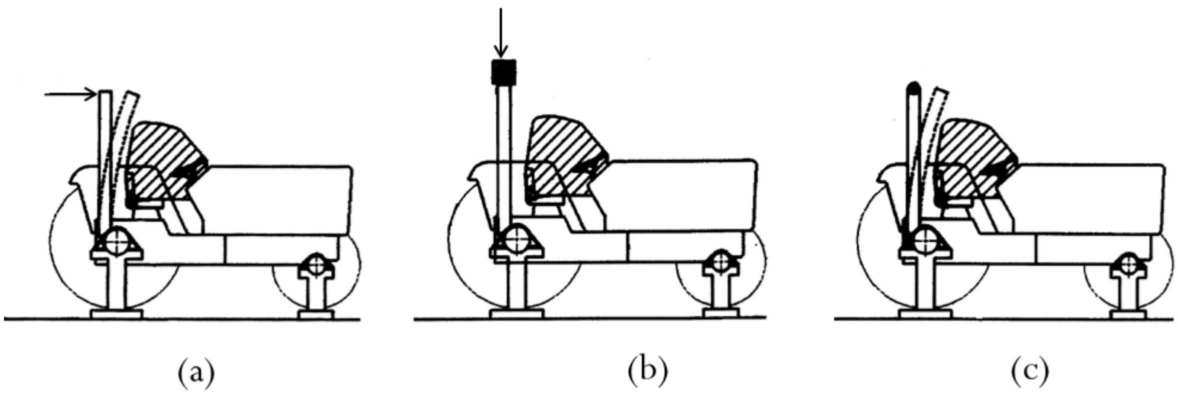

Figure 1. Static tests. (a) Longitudinal load (b) first and second vertical load test (c) Transverse loading test (SAE J2194).

FIRST AND SECOND VERTICAL LOADING TEST

The first vertical load is inserted vertically to the uppermost structural member which is called cross bar (Fig. 1). The inserted load (F) is equal to:

$$F=20\ M \qquad (2)$$

Where F is applied force(N). Exerting load should be stopped at least 5 seconds after cessation of any visually detectable movement. The second vertical test for two post ROPS is exactly the same as the first vertical test (Fig. 1).

TRANSVERSE LOADING

The transverse load which is also called side load must be inserted horizontally at 90 degrees to the longitudinal median plane of the tractor. The side load should be applied to the structural member uppermost on the side (Fig. 1). The test stops when the absorbed energy is equal to:

$$E= 1.75\ M \qquad (3)$$

The ROPS Allowable Deflection (RAD) is defined as the maximum allowable deflection of the ROPS without violating the intrusion or exposure criteria. The ROPS Performance Deflection (RPD) is defined as the ROPS deflection during the four static tests. The RPD is the ROPS deflection to the point that the ROPS absorb the predefined levels of energy in horizontal tests and the ROPS deflection under the vertical tests. During all of the tests the RPD must be smaller or equal to RAD.

COMPUTER-BASED ROPS DESIGN PROGRAM (CRDP)

Tractor rollovers are fatal accidents in US and there are large amount of tractors which should be equipped with standardized ROPS. Prediction shows that only 75% of the tractors in US will be equipped with ROPS by 2024, if no action is taken (Hoy, 2009). A Computer-based ROPS Design Program (CRDP) was developed to quickly generate ROPS designs based on 46 tractor dimensions and the tractor weight (Ayers, 2015). The program output is the ROPS drawings which can be used to construct the ROPS (Fig. 2). The drawing includes the posts, crossbeam, base plate, corner brackets, and strappings. The corner brackets are similar to NOISH

Cost-effective ROPS (CROPS) (Keane and McKenzie, 2013). The strapping is used to support the attachment point of the posts to the base plates. The constructed ROPS need to be tested based on standardized experimental tests (Ayers, 2015).

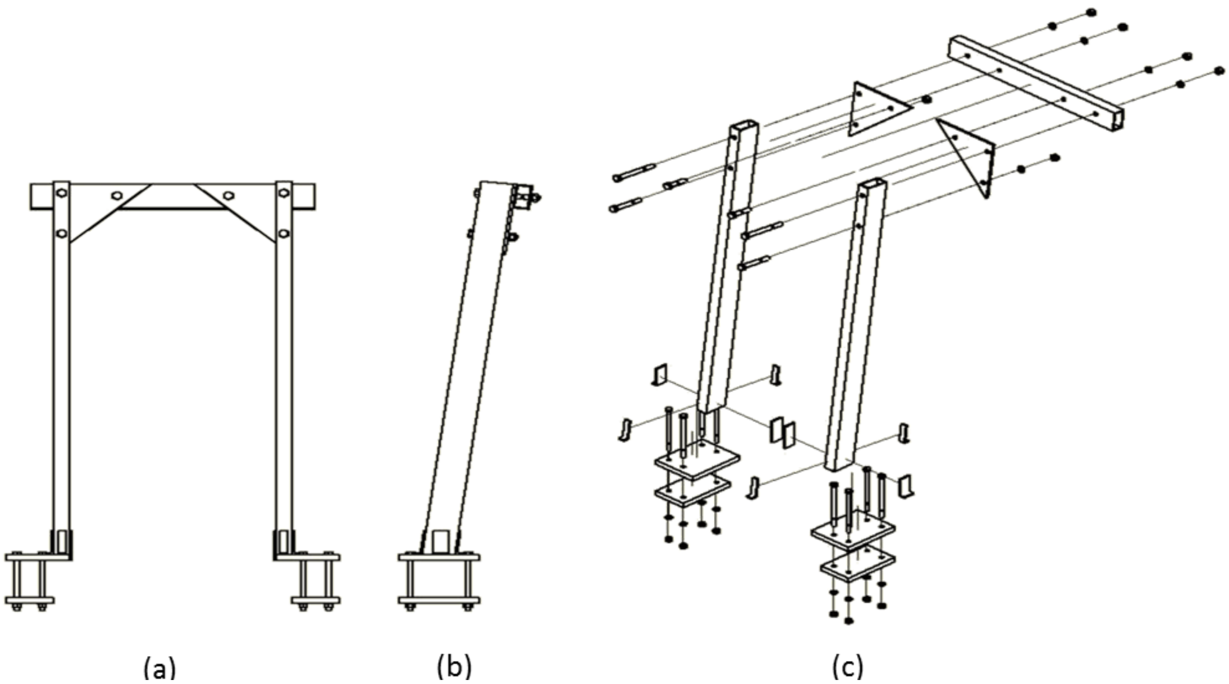

Figure 2. Drawing of the designed ROPS by means of CRDP (a) Front view. (b) Side view. (c) Exploded view (Ayers, 2015).

The final FE model should include four steps, developing model, model verification, model calibration, and model validation. The model should be calibrated and validated by comparing the model results with experimental test results. In the next previous section the experimental test procedure and results are presented.

Although computer models are able to predict the force-deflection curve of ROPS but the experiment test cannot be replaced with computer models. The modeling approach is needed to increase the possibility that the designed ROPS is likely to pass the standard prior to the experimental test. There is no nonlinear FE model available to predict the behavior of rear mount two post ROPS with base plate strappings and bolted corner brackets.

The overall objective of this study is to develop a FE model to predict the agricultural tractors ROPS performance under static SAE J2194 standard. ROPS are designed based on computer based ROPS design (CBRD) program. Specific objectives are to:

1) Simulate the SAE J2194 standard static tests for ROPS,

2) Predicting the force-deflection curves of the ROPS under simulated standard tests, and

3) Compare the ROPS Performance Deflection (RPD) for the simulated and experimental tests.

Material and methods

EXPERIMENTAL TEST

Two ROPS were designed using CRDP for Long 460 and Allis Chalmers 5040 tractors. These two models of tractor were selected since they were identified as the common ROPS request for New York Center for Agricultural Medicine and Health ROPS retrofit program, and a current ROPS design is not commercially available (Ayers, 2015). The output of CRDP is drawing of the ROPS which includes all of the ROPS dimensions and the ROPS price. The summary of the ROPS materials and dimensions are presented in table 1. The final drawing is presented in figure 2.

Table 1. Output of CRDP, Summery of material and dimensions for Long 460 all dimension in inches. (Ayers, 2015).

Part	Quantity	Dimension	Dimension	Dimension	Dimension
Posts Tubing	2	Thickness (0.1875)	Width (2)	Depth (3)	Length (69.8)
Crossbeam Tubing	1	Thickness (0.1875)	Width (3)	Depth (2)	Length (38.8)
Top Base plate	2	Thickness (0.75)	Length (8.875)	Width (6.28125)	
Bottom Base plate	2	Thickness (0.75)	Length (8.875)	Width (5.8125)	
Corner Braces	1	Thickness (0.375)	Length (12)	Width (12)	
Base plate Strapping	2	Thickness (0.25)	Length (20)	Width (1)	
Base plate Bolt s	14	Diameter (0.5)	Grade (8)	Length (10)	

The ROPS were sent to the FEMCO Inc. in McPherson, KS for experimental test. Sequences of three experimental tests were conducted on the ROPS, longitudinal, first vertical, and side loading test. The forces were inserted by means of hydraulic jacks and the deflection was measured by means of a potentiometer. The longitudinal load test for ROPS model Long 460 is shown in figure 3.

Figure 3. Longitudinal load test (FEMCO).

DEVELOPING THE FE MODEL

Solving the engineering problems such as predicting the nonlinear behavior of ROPS by FE software packages includes six steps, creation the geometry of the ROPS, defining material properties, grid generation, determining the boundary condition, solving, and post processing. Abaqus (2011) is one of the most powerful commercial software packages for nonlinear analysis (Yu and Li, 2012).

Results

The results of longitudinal load test for Long 460 is presented in figure 4. The area under force displacement graph equals to the absorbed energy. The area under force deflection curve is equal to the absorbed energy which is equal to 2844.8 J for Long 460. The absorbed energy based on Equation 1 for 2032 kg tractor is equal to 2844.8 J. The RDP is equal to 22.9cm and does not infringe the clearance zone or leave the clearance zone unprotected.

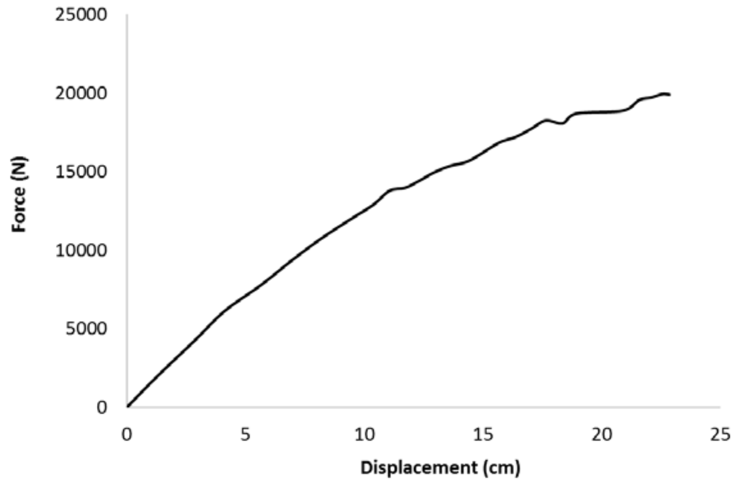

Figure 4. Force displacement longitudinal load graph for Long 460.

Results of longitudinal load, vertical load, and the side load are presented in table 2. In all of these test the ROPS does not infringes the clearance zone or leave the clearance zone unprotected. The FE model should be able to predict the RDP accurately to assure the model can be used to determine if designed ROPS passes the performance criteria in SAE J2194.

Table 2. Applied force as a function of tractor reference mass based on SAE J2194 standard.

	Long 460	Allis Chalmers 5040
Tractor reference mass (kg)	2032	1842
Longitudinal load absorbed energy (J)	2844.8	2578.8
RDP (cm)	22.86	17.55
Permanent deflection(cm)	9.6	7.0
Vertical load (N)	41085	36840
RDP (cm)	5.42	5.8
Permanent deflection (cm)	2.4	0.66
Side load test absorbed energy (J)	3556	3224
RDP (cm)	22.3	16.7
Permanent deflection (cm)	10.8	8.7

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