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Finite Element Analyses and Correlation with Physical Tests of a Rollover Protective Structure (ROPS) Performance

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Abstract—*In all agricultural tractors and construction machines, a number of passive safety devices are used to ensure that the operator is free from injury in the event of an accident. In case of overturning of the tractor, the parts which aim to protect the operator by providing a living area where he/she can stay inside without being damaged are called as Rollover Protective Structures (ROPS). The main reason for this is that the usage of tractors and construction equipment has increased considerably. The widespread use of these machines brings with it the possibility of accidents, and with the introduction of international standards, this situation forces the tractor and construction machinery manufacturers to take measures in this regard. Therefore, ROPS design in tractors is becoming an important issue day by day. In this study, the analysis of the designed ROPS equipment by the finite element method is performed and it has been examined whether it conforms to the protective structure standards before the prototype production. When the prototypes produced after virtual verification were tested according to the relevant performance standards, there was an acceptable level of correlation between the analysis and test results. Based on this correlation, it is possible to predict the behavior of a protective structure in tests at the design phase, so it renders possible to reduce the prototype and test costs.*

Keywords— *Agricultural Tractors, Rollover Protective Structure, finite element method.*

I. INTRODUCTION

Protective structures were first developed in Sweden in the 1950s. While their initial adoption in the national standards was in Scandinavia, they were later adopted internationally as OECD codes, EEC / EC regulations, and ISO standards[1]. A research that examining tractor accidents in Turkey between 1990-2001 was presented by M. Golbasi. According to this research; in 746 tractor accidents in the form of rolling, roll-over and rolling stock, It was found that 81.64% of the tractors did not have a standard cabin or safety roof and only 18.36% had such a structure. In addition, the absence of protective structure increased the mortality rate in these accidents approximately 3 times.

Protective structures can be said to be basically two types of use: Cabinet Type and Frame Type. Cabs are generally used in field tractors. The cabs protect the operator from bad outdoor conditions (noise, dust, hot air, etc.), as well as to protect the driver from damage if the tractor rolls. The crush resistance in the event of rolling of the cabins on tractors and construction machines is determined by specific standards regulated by organizations such as OECD and SAE.

Another type of protective structures called frame-types. They are built like 2 or 4 post structure and their duties are to prevent tractor overturn and to protect the operator from damages in the event of overturning tractor. Usually, 2 post ROPS are used and the location of the ROPS can be different regarding the type of the tractor. In field tractors, ROPS equipment is located at the rear side of the tractor. These types of structures are designed as non-foldable. In orchard tractors, the ROPS equipment is located at the front of the tractor and it is designed as foldable. Generally, the operators use this equipment as folded because of height advantage in narrow areas, therefore, this situation creates a danger in the event of a tractor overturn. In this study, frame type ROPS which located on the front of the orchard tractor will be examined regarding protective structure performance. After performing numerical analysis of models, a correlation between numerical models and their physical test results has done. An example of frame type ROPS was shown in figure 1.

Fig. 1. Example of a frame type front ROPS.

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II. ROPS TEST METHODOLOGY

With the increase in mechanization in agriculture, accidents related to agricultural machinery increase in parallel. The increase in accidents related to agricultural machinery forced agricultural machinery manufacturers to take measures in this regard and to add additional safety equipment to the machinery they produce also. The performance of this safety equipment is measured according to a number of criteria set by international standards. These standards are not complicated as well as in automotive, but they become important regarding improving mechanization in agriculture and the studies related to them are increasing day by day.

ROPS testing standards are organized by OECD and the main duty of these standards is to protect to an operator in the case of the tractor rollover. ROPS test procedures are examined as two varieties called Cabs and ROPS Frames but the main principle of procedures is same. At the beginning of the development in ROPS testing standards, tractors or construction machines were testing by rounding from a hilly place. This condition corresponding to real accident case but it is an expensive method and difficulties were encountered many times while testing by this method. Afterward, standard committees developed new methods for ROPS testing. As a first, a dynamic method came into force by OECD. In this method, an impact is applied to the protective structure with the help of a mass hung at the end of the pendulum. The weight of the suspended mass and release angle of the pendulum are depending on the tractor's class and specifications. Then, a static test method was developed and this method is used often rather than dynamic method thanks to the ease of application. In a static method, various different loadings simulating tractor rollover are applied to protective structure sequentially. The energy must be absorbed by ROPS at each loading stage is depending on the tractor's class and specifications also. While the dynamic method is providing a better simulating of the actual rollover condition because of taking the material behavior at high strain rates into consideration, the static test provides a better assessment of strength and weaknesses of the structure. Currently, committees responsible for the standards provide a choice between static and dynamic testing methods. In this study, the ROPS model design will be validated according to the static test method. The related standard is OECD Code 6.

Applied loads and energies must be absorbed by the protective structure are calculated by using tractor reference mass and tractor dimensions. Reference mass is related to unballasted mass and maximum permissible mass. Reference mass is the mass of the tractor including fundamental components such as coolant, oils, fuel etc. But optional accessories such as front and rear tire ballast, mounted implements, mounted equipment or any specialized components. Maximum permissible mass is the maximum mass that technically permissible furthermore given by the tractor manufacturer via vehicle identification plate or operator’s handbook. The ratio of maximum permissible mass to reference mass must be greater than 1,75[3].

The static test procedure and performance requirements are documented in the OECD Code 6 standard. Applied loads specified by the static method are located in standard as imposed displacement and force. Imposed displacements are applied longitudinal, vertical and lateral directions. At each loading, the protective structure has to absorb certain energy level without violating the clearance zone which is calculated regarding tractor measures. Before doing tests, the clearance zone must be calculated for the tractor specifically. This place is kind of safety zone that the operator can stay without damage while tractor overturn. Clearance zone calculation will be discussed later.

A. Loading Sequence

1) Rear Loading

The rear load is applied longitudinally in the forward direction and it must be applied in a vertical plane which parallels to the tractor's median plane. The point of load is selected from the ROPS and it must be the first hitting point to the ground plane in the case of overturning in rearward or forward direction. Generally, this point is selected from the top level of the protective structure. And also it must be located at 1/6 of the width of the ROPS away from the lateral side. An imposed displacement is applied to load application point longitudinally and when the protective structure absorbs the required energy level, the loading is removed. After completing load and remove process, a line is generated between the top level of the ROPS and the top level of the rear hard fixture. This line should not penetrate to the clearance zone. Additionally, during the loading time, any crack may affect functionality should not be seen. The energy value must be absorbed by the protective structure is calculated according to Eq. (1):

$$E_{rear} = 500 + 0.5\boldsymbol{M} \quad (1)$$

Where $\boldsymbol{M}$ is the reference mass of the tractor.

2) First Crush

A crushing process is applied to the uppermost zone of the protective structure. The actuator tool can be considered as an infinite rigid plate. The crushing is applied until reaching to a certain force value that calculated by Eq. (2):

$$F_{v1} = 20\boldsymbol{M} \quad (2)$$

During the loading time, any crack may affect functionality should not be seen.

3) Front Loading

Front load application is similar to the rear loading. The load application point is symmetric with rear load application point according to the tractor middle vertical plane. The loading direction is rearward. The energy value must be absorbed by the protective structure called E_{front} is also calculated by Eq. (1). It is not necessary additional clearance zone violation control.

4) Side Loading

Side load is a most critical loading regarding clearance zone violation. The load application point is selected on the same side of front-loading and it must be the point on the ROPS which hit to the ground plane in the case of sideways overturning. An imposed displacement is applied to load application point in a lateral direction and when the protective structure absorbs the required energy, the loading is removed. After completing load and remove process, a plane is generated by using 3 points that one of them is the load application point. Other points are taken on headlight and fender that hitting to the ground plane. During the side loading time, this plane should not penetrate to the clearance zone. Similar to the other loadings, any crack may affect functionality should not be seen. The energy value must be absorbed by the protective structure is calculated according to Eq. (3):

$$E_{side} = 1.75\mathbf{M}(\mathbf{B_6}+\mathbf{B})/\mathbf{2B} \quad (3)$$

Where;

***B*:** Minimum overall width of the tractor

***B*$_6$:** Maximum outer width of the protective structure

5) Second Crush

A second crushing process is the same application with first crushing. The force value called F_{v2} is calculated by Eq. (2).

Table I is showing loading sequence and energy/force level.

TABLE I. ROPS static loads.

	ROPS Load Case	Load/Energy
1	Rear longitudinal loading in forward direction	$E_{rear} = 500 + 0.5M$ [kJ]
2	First vertical crush	$F_{v1} = 20M$ [N]
3	Front longitudinal loading in backward direction	$E_{front} = 500 + 0.5M$ [kJ]
4	Side load in lateral direction	$E_{side} = 1.75M(B_6+B)/2B$ [kJ]
5	Second vertical crush	$F_{v2} = 20M$ [N]

A schematic presentation for static load cases was shown in figure 2.

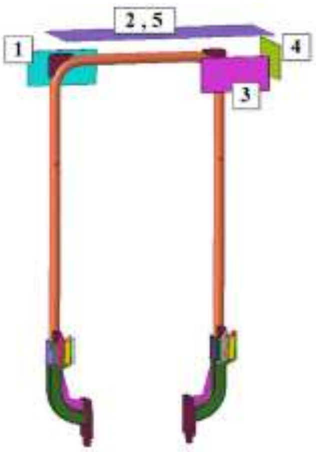

Fig. 2. ROPS loading sequence.

B. Clearance Zone

The basic task of the protective structure is to provide a safe space that the operator can stay without any damage in the case of tractor overturn. Before the loadings related to ROPS testing, the clearance is generated by using tractor seat position and other parts of the tractor. The illustration about clearance zone calculation was shown in figure 3.

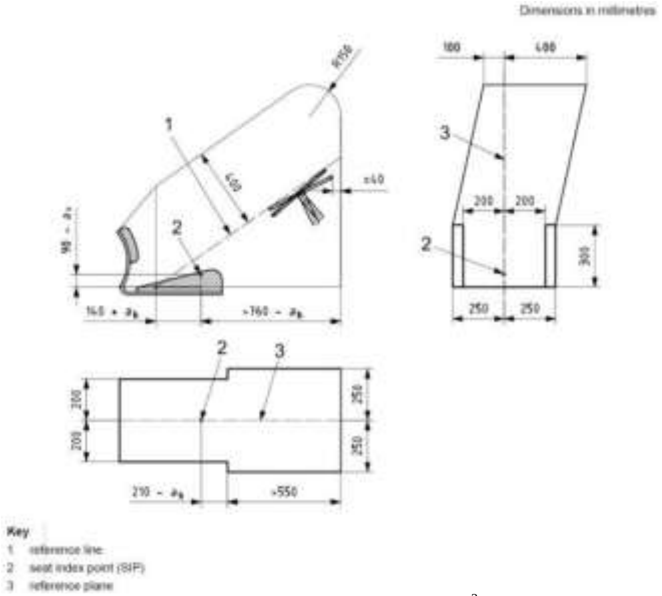

Fig. 3. Clearance zone calculation[3].

III. ROPS DESIGN

In this stage, a brief description of the protective structure that concerned in this study will be given. Type of the construction is a front ROPS bar composed of three main parts. These parts are mounts, front roll bar and rear hard fixture located behind the driver seat. ROPS mounts are made of Fe 360 C material and they provide a connection to tractor body with 10.9 property class bolts. The rear hard fixture is made of Fe 510 D material and it is fixed to the rear axle of the tractor with brackets made of Fe 510 C material. The front roll bar is made of FE 510 D and it can be folded with the help of pins between pillars and roll bar. The finite element model of the protective structure was shown in figure 4.

Fig. 4. Finite element model of the ROPS.

IV. FINITE ELEMENT MODELLING

ALTAIR/HyperWorks simulation software package was used to build the FE Model and to perform the analyses. Profile and plate parts modeled with shell elements. The wedges on the roll bar and mounting brackets modeled as solid. 8-node hexa and 6-node penta elements were used for solid elements and for 4-node quad and 3-node tria elements were used for shell elements.

Simulations were performed by using "Explicit Time Integration Method". At the end of each loading, the deformed model was extracted from post-processor software via state file and the next loading was applied to the deformed model.

As a material model, the isotropic elasto-plastic Johnson-Cook material model was utilized. As an input for this material model; elastic modulus, poisson ratio, density, yield stress, ultimate tensile stress and elongation at tensile were defined. Yield and tensile stresses for utilized materials were shown in Table II.

TABLE II. Material ınformation.

Material	Yield Stress (MPa)	Tensile Stress (MPa)	Elongation at Tensile (%)
Fe 360 C	235	360	25
Fe 510 D	350	510	20

V. ANALYSIS - TEST RESULTS

The analysis was performed by using RADIOSS software. For each loading, the trial load was applied until the energy/force level reached. After getting maximum load point, plastic strains were checked to control crack possibility.

The reference mass for energy/load calculation is 2250 Kg for the tractor in question. For the rear loading as a first load stage, the energy must be absorbed by the protective structure becomes 1625 J by using Eq. (1). In the analysis, 315 mm displacement was obtained to reach the required energy level. There were not seen any critical plastic strain value for a crack generation. In the physical test, 287 mm displacement value was obtained and it was not seen any crack problem. Displacement vs energy curves for analysis and test results was shown in figure 5.

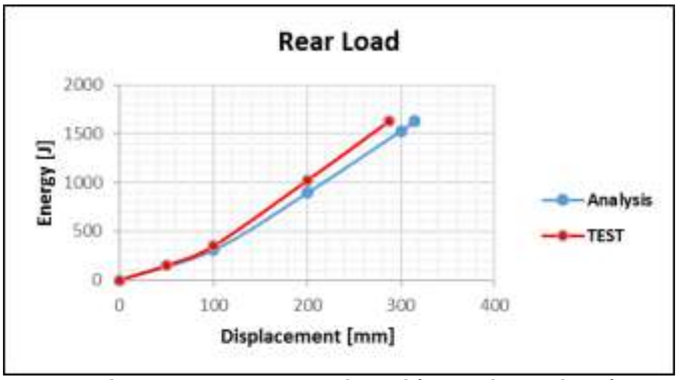

Fig. 5. Displacement – Energy curves obtained from analysis and test for rear loading.

For the front loading, The energy value is same with rear loading as 1625 J. The displacement obtained from simulation is 314 mm. The displacement value in the physical test was obtained 318 mm. Therefore, there is a strong correlation between analysis and test results for front loading. After simulation and physical test, there were not seen any critical deformation can cause crack generation for both. The displacement vs energy graph was shown in figure 6.

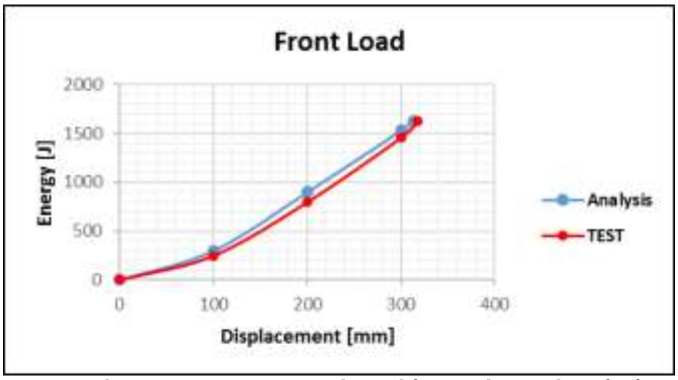

Fig. 6. Displacement – Energy curves obtained from analysis and test for front loading.

The required energy level must be absorbed by the protective structure for side load is calculated as 2893 J. Minimum overall width of the tractor is 1672 mm and maximum outer width of the protective structure is 785 mm. In the analysis, there were seen 222 mm displacement to reach the required energy level. In the physical test, this value obtained as 230 mm. The displacement vs energy graph was shown in figure 7.

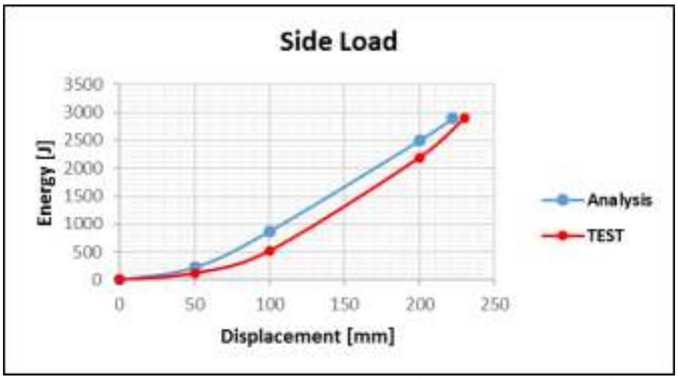

Fig. 7. Displacement – Energy curves obtained from analysis and test for side loading.

Sideloading is the most critical condition regarding clearance zone violation. After analysis, there were not seen any penetration to the clearance zone. In the physical test there were not seen any penetration also. The gap between the clearance zone and ground plane was shown in figure 8.

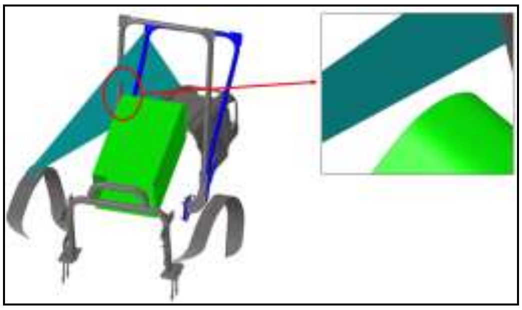

Fig. 8. Gap between clearance zone and ground plane.

At the end of the loadings, there were not seen any critical deformation can cause the visible crack on the structure the plastic strain contour on the structure was shown in figure 9.

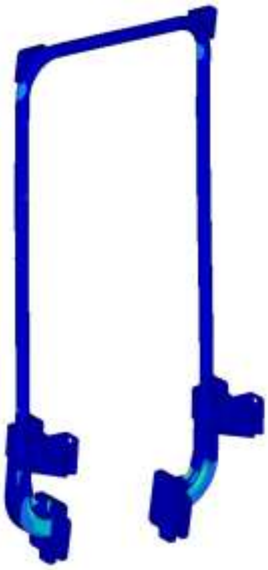

Fig. 9. Displacement – Energy curves obtained from analysis and test for side loading.

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