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Some Aspects of the Roll-over Protective Structures Evaluation, Using Shock Loading Simulation

The objective of this paper is the highlighting of the main aspects that be considered in numerical simulation of the behavior of roll-over protective structures that are included in mobile machinery cabs, using finite numerical simulation. In first part of the paper are presented, briefly, the legislative framework and the reference documents governing the mechanical protection of the human operator of machinery and equipment construction. Next, are analyzed the roll-over protective structures and the main aspects related to their evaluation by shock loading simulation. In this context, are given the necessary information to correctly model the real problem so that the results to have an imposed accuracy.

***Keywords**: Roll-over protective structures, shock loading, numerical simulation*

1. Preliminary

One of the main causes of accidents involving earthmoving machinery is machine roll-over. In this context, the capacity of the cabin structure to protect the human operator is one of the most important performance requirements that must be taken into account since design stage of the machine.

Roll-over protective structure (ROPS) is a system of structural members whose primary purpose is to reduce the possibility of a seat-belted operator being crushed should the machine roll-over. Structural members include any sub frame, bracket, mounting socket, bolt, pin, suspension or flexible shock absorber used to secure the system to the machine frame, but exclude mounting provisions that are integral with the machine frame.

This system must be designed so that, if the machine rolls over, the human operator is protected by an appropriate deflection limiting volume (DLV).

Because of its importance, this area is governed by a series of regulations and standards. The main reference document is the standard ISO 3471 - *Earth-moving* *machinery – Roll-over protective structures – Laboratory tests and performance requirements*. Based on this standard was developed European Standard EN ISO 3471, respectively the national standard SR EN ISO 3471.

The standard ISO 3471 provides details on the laboratory tests and protocols. This International Standard specifies performance requirements for metallic roll-over protective structures (ROPS) for earth-moving machinery, as well a consistent and reproducible means of evaluating the compliance with these requirements by laboratory testing. The requirements refer to force resistance in the lateral, vertical and longitudinal directions and energy absorption in the lateral direction. There are limitations on deflections on directional loading (lateral, vertical and longitudinal).

The evaluation procedures described in the standard are derived from investigations on ROPS that have performed intended functions in a variety of actual roll-overs, as well as from analytical considerations. In this context, the standard evaluation procedures will not necessarily duplicate structural deformations due to a given actual roll.

The standard describes instrumentation requirements, test facilities and gives formulae to be used.

Test loading procedures are described as well as temperature considerations and material criteria. Performance criteria are set up by the standard's function of specimen size.

It is important to note that the forces applied to ROPS during of the experimental evaluation of the conformity, are static forces. The values of these forces depend on the direction of application, type of car and it's mass.

Other reference documents associated with the domain of protective structures of the earth-moving machinery are:

- ISO 3164: *Earth-moving machinery – Laboratory evaluations of protective structures- Specifications for deflection-limiting volume*;
- ISO 3449: *Earth-moving machinery – Falling-object protective structures – Laboratory tests and performance requirements*;
- ISO 6165: *Earth-moving machinery – Basic types – Identification and terms and definitions*.

2. Simulation types for ROPS behavior using virtual models

In recent years, finite element method has proven to be one of the most powerful tools for exploring the field problems. Thus, finite element method has become a powerful design tool that allows the generation of models of reality affected by a small number of simplifying assumptions.

An important ahead step was in the study of dynamic problems using finite element method.

Numerical simulation of the behavior of mechanical systems using finite element method, known as *mechanical event simulation*, is a good example on this line because, mainly, it's possible to eliminate the rule-of-thumb methods.

In this area, simulation of ROPS behavior under the action of shock loads from roll-over of the machine may be an important application of virtual engineering.

In terms of complexity of the virtual model which is used in simulation, there are two possible approaches:

- Limited simulation: simulation of ROPS behavior under the action of shock loads from roll-over of the machine, using *only the virtual model of protective structure*;
- Extensive simulation: simulation of ROPS behavior under the action of shock loads from the roll-over machine, using *both virtual models of protective structure and of the base machine* (more or less simplified).

In *limited simulation*, in order to determine, by simulation, the distribution and magnitude of stresses and deformations induced in protective structure during shock, it is necessary to know the speed of the structural member which strikes the ground in the first moment of shock and magnitude of the force acting to this structural member for overturned position of the machine. Typically, these physical quantities are results of a preliminary calculation.

A convenient approach to determine the speed of the structural member which strikes the ground in the first moment of shock is to consider energy conservation. Figure 1 shows the calculation scheme to determine the speed above mentioned, in case of lateral roll-over of the machine.

The calculus scheme shown in Figure 1 considers that the lateral roll-over is produced by free rotation around a longitudinal axis A and starts when center of gravity of the machine (G) and the axis A are in the same vertical plane. In the lateral overturned position, the earth-moving machine rests on the ground along the axis B and axis D, containing the topmost edge of the ROPS.

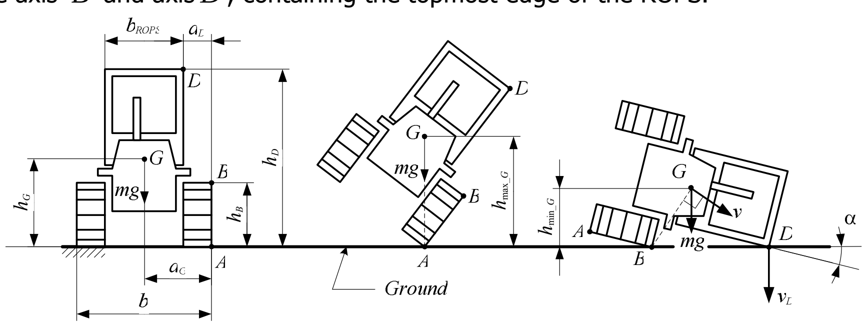

Figure 1. Calculus scheme for speed of ROPS in first moment of the impact

In Figure 1, m means the total mass of the machine and G means center of gravity of the machine. Total mass of the machine include ROPS, all tanks full and all necessary equipment in normal operation in work area, but excludes mass of ballast and parts which can separate from machine in the event of a roll-over.

Based on the law of energy conservation, the energy of system composed by base machine and ROPS, at the beginning of the roll-over, is equal to the energy of system at the time of impact.

Under this condition, with the notations used in Figure 1, we can write

$$mgh_{\max\_G} = mgh_{\min\_G} + m\frac{v^2}{2}, \tag{1}$$

resulting from this that the velocity v is

$$v = \sqrt{2g(h_{\max\_G} - h_{\min\_G})}. \tag{2}$$

At the impact moment, speed of the topmost structural member of ROPS is

$$v_{impact} = v_D = v \cdot \frac{dist_{(B,D)}}{dist_{(B,G)}}, \tag{3}$$

where

$$dist_{(B,D)} = \sqrt{a_D^2 + (h_D - h_B)^2}, \tag{4}$$

$$dist_{(B,G)} = \sqrt{a_G^2 + (h_G - h_B)^2}. \tag{5}$$

To determine the magnitude and direction of the force acting on the topmost structural member of the ROPS for lateral overturned machine can be used the calculation scheme presented in Figure 2.

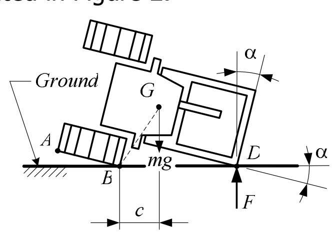

Figure 2. Calculus scheme for magnitude of the force acting on the topmost structural member of the ROPS for lateral overturned machine

With the notations from Figure 2, we obtain

$$F = mg \cdot \frac{c}{dist(B,D)}, \tag{5}$$

where g is gravitational acceleration and c is horizontal projection of the distance between axis B and center of gravity, G.

Distance c is calculated using the following equation:

$$c = \frac{dist^2(B,G) + dist^2(B,D) - dist^2(G,D)}{2 \cdot dist(B,D)}. \tag{6}$$

In equation (6), $dist(G,D)$ is distance between center of gravity of the machine and axis D. This distance, with the notations used in Figure 1, is given by

$$dist_{(G,D)} = \sqrt{(a_G - a_D)^2 + (h_D - h_G)^2} \ . \tag{7}$$

After determining the speed v_{impact} and magnitude of the force, it is possible to performing limited simulation. In this context, it simulates a mechanical event in which a test object with mass

$$m_{test\_object} = F/g \ , \tag{8}$$

having a uniform rectilinear motion with velocity v_{impact}, strikes the protective structure which is positioned corresponding to overturned position (see Figure 3).

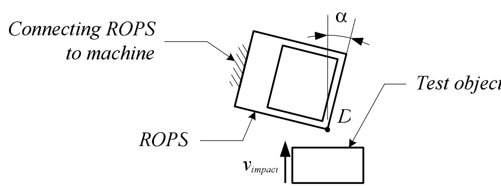

Figure 3. Mechanical event in limited simulation

Extensive simulation can consider the entire process of roll-over of the machine, or a part of this process, prior to the impact (see Figure 4).

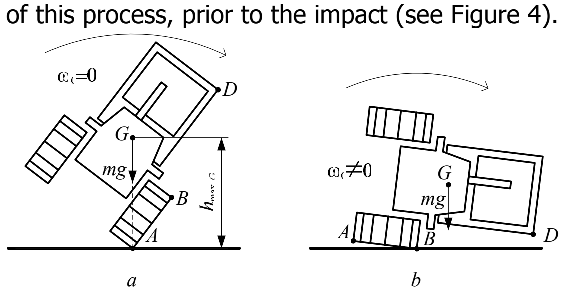

Figure 4. Mechanical event in limited simulation
a - entire roll-over process; b - part of roll-over process, prior to the impact

If the entire process of roll-over is considered in the simulation, are not required any preliminary calculations, because all forces in the system, during the simulated event, are caused by gravitational field and motion.

If in simulation is considered only a part of the roll-over process, it is necessary to assign to model an appropriate initial angular velocity ($\omega \neq 0$), corresponding to the simulation start time.

Obviously, the second way is recommended because it shortens the time required to solve the numerical model and also it is possible to move the focus of the analysis on the phenomena which occur during the shock.

Similar approaches can be used in other cases of roll-over of the machine.

3. Essential aspects related to the preprocessing of the ROPS models for the numerical simulation of their behavior

The obtaining of the results with an acceptable accuracy level in the numerical simulation for the behavior of the ROPS is conditioned to their proper modeling. In this context, the essential modeling aspects are discussed below.

- Geometry of the structure.

In general, a FEA program includes a graphical engine for generating of the structure's geometry which will be analyzed. However, the current trend is to generate the geometry of the structure outside the FEA program, in a specialized CAD program. Then, geometry is imported in FEA program using a standard graphics format.

It is recommended that ROPS geometry to be generated using parameters so any changes dictated by ensuring the imposed conformity to can be made easier.

- Selection of the correct finite element type.

Usually, this selection is made to best represent the geometry and type of analysis required. The finite elements may also contain mid-side nodes for models that are expected to experience bending.

In general, protective structures of the earth-moving machinery are frameworks which are made from rectangular or circular pipes.

Given this, for the mesh associated to the structure is recommended to use bi-dimensional finite elements. Thus is avoiding excessive schematization of the structure, when using one-dimensional finite elements, or excessive great models having needs to expensive resources when using three-dimensional finite elements.

- Choosing the correct material models

This phase has a decisive influence in obtaining results with acceptable accuracy.

The most commonly used material in making of the roll-over protective structures is steel with breaking tenacity.

Should be noted that shock load that occurs in a roll-over event is likely to cause permanent deformations in roll-over protective structure. Therefore, the numerical simulation will have the appropriate settings in terms of considering the large deformations and the solving method. Therefore, in FEA packages, for steel materials, if large displacements are possible and the stresses may exceed the yield stress, according to the type of material, will choose a bilinear model.

- Simulation parameters

It is advisable to specify the appropriate *length of time* which would be observed in simulation of the event. Additionally is specified the *number of steps* to take per second to calculate the displacements and stresses over time.

Also, it is advisable to specify the appropriate load curves that will be used to scale the magnitudes of all of the loads during the analysis and any acceleration field if necessary.

It is necessary, specify the location of all *contact surfaces*, so that when solving model can be correctly detected all areas of impact.

Last, but not finally, very important for an acceptable accuracy of the results is the specification of the *convergence criterion* and the *corresponding tolerance*. Usually, convergence criterion is "displacement only" and corresponding tolerance is "displacement tolerance". The dynamic nature of mechanical event simulation requires that Newton's Second Law be applied throughout the event. Equilibrium iterations are required to enforce observance of this law. Convergence is achieved when the equilibrium residual is below the displacement tolerance value. A displacement tolerance is used because the system of equations solved is in terms of displacements. The small tolerances will lead to accurate results, but to large time analysis. In such situations, one approach that can be helpful is to perform a trial analysis with the convergence tolerance relaxed. This type of trial analysis will likely reaches completion and run faster than an analysis with a tighter convergence tolerance. Thus, it is possible to spot any modeling problems and identify areas of greatest stress concern where the finite element mesh should be refined.

4. Advantages and disadvantages of numerical simulation of the behavior of roll-over protective structures

The numerical simulation of the behavior of rollover protective structures for their compliance evaluation, versus experimental evaluation, presents several advantages, among which the most important are discussed below.

- Numerical simulation eliminates the need of the experimental installations necessary in laboratory testing of these structures. The laboratory testing of rollover protective structures is quite expensive. In this context, according to ISO 3471, is required an anchorage of the representative specimen to a bed plate and an installation for generating the test forces.
- Numerical simulation allows detailed investigation of shock. Thus, numerical simulation can reveal phenomena that occur during of the shock very difficult if not impossible to be experimentally recorded.
- Numerical simulation can take into account an arbitrary number of boundary conditions. In this context, it is possible the study of the behavior of structures in the various assumptions related to their connection with base machine and in various loading conditions which are compatible with the overturning of the machine.
- Software platforms used in numerical simulation allow storage of the large information amounts. For each studied structure can store a large relevant information amount that can be organized in databases, easily accessed later.

The main disadvantages of numerical simulation of the behavior of rollover protective structures are:

- Imperfection of the material models. The main source of error in the finite element method and consequently in the mechanical event simulation is modeling the behavior of the materials. Thus, for results with greater accuracy is required the laboratory study of the behavior of materials used for modeling of the structural members. After this study, in preprocessing phase or the finite element model, material will be defined in accordance with the experimental results.

- Large period of time necessary for solving numerical models associated with the finite element models. This time may be significantly larger than time of the laboratory testing of the representative specimen. This happens especially in case of the extensive simulation and/or when are imposed too restrictive convergence conditions for iterative calculation process.

5. Conclusions

Even with reserve of the disadvantages which are presented in the previous paragraph, numerical simulation of mechanical structures behavior is, today, a very powerful tool for the engineers.

However, obtaining the results which are not only plausible, but true, is conditioned by the deep understanding of the problems, it correct modeling and by setting the appropriate parameters for the simulation.

It is also advisable to validate numerical simulation of the behavior of protective structures, even using their simplified models. Once is validated the modeling procedure, the numerical simulation can be used to evaluate all of the protective structures belonging to the class of the structure that was used for validation.

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