FEM Analysis of ROPS for Agricultural Self-Moving Machines

Molari G., Badodi M., Guarnieri A.
University of Bologna. DEIAGRA, Mechanics Section
Viale Fanin, 50 – Cap 40127 Bologna, ITALY.
Tel 0039 051 2096191, Fax 0039 051 2096178, mail giovanni.molari@unibo.it

Abstract
The high number of accidents due to a rolling over of agricultural machineries increases the interest of researchers and organisations for standardisation in this field. In the Fifties, standards to test rolling over protective structures (ROPS) for tractors were designed and approved, the same was not defined for agricultural self-moving machines. In the present work an analysis of different categories of agricultural self-moving machines is executed with the goal of evaluating the possibility to introduce ROPS solutions used in tractors. Three categories of agricultural self-moving machines were chosen in function of their dimensions, mass, operations performed, and their diffusion on the Italian and European market. On each machine, an evaluation of the capability to adopt a solution to protect the conducers from rolling over, like to tractors, was analysed. The ROPS design was obtained using a dedicated software to evaluate the resistance of the structures installed at the moment to protect conducers only from environmental aspects, and to design structures able to resist the load cycle imposed by the standards. The results have shown a low resistance level of the structures used at the moment on the machines chosen for the tests. The structures able to sustain the loads imposed by the standards are not too different with regards to dimensions, but an increase of the resistance of the materials or an increase of the thickness of the mountings is necessary.

Keywords: safety, standard adjustment, loading test

1. Introduction

Occupational health problems and industrial accidents are a heavy load for workers, employers and in general for the economy. The agricultural sector is one of the professional activities most affected by injuries, even though the updating of the machineries has decreased the number of fatal accidents in recent years [Eurostat, 2010]. In Italy one of the most frequent reasons of risk for the health is the rolling over of tractors and other agricultural machineries [ISPESL 2009; INAIL 2008].
With reference to tractors, firstly Sweden, in 1959, and then all the other European countries, adopted a regulation requiring Rolling Over Protective Structures (ROPS) on all new tractors. Also in 1959, the Organisation for Economic Co-operation and Development (OECD) developed a test procedure to evaluate the strength of the structures and established energy criteria [OECD, 1959]. The introduction of the ROPS in Europe sharply decreased these fatalities [Springfeldt et al., 1998], while in the United States (US), many tractors are still not equipped with a protective structure and are often associated with fatal injuries [Myers et al., 1998; Janicak, 2000].
With reference to other self-moving agricultural machineries, even if the risk of roll over is real, as reported in all the specific standards related to the safety of these

machines such as EN 632 [EN, 1997] for combine harvesters, EN 706 [EN, 2010a] for grape harvesters, EN 13118 [EN, 2010b] for potatoes and EN 13140 [EN, 2010c] for vegetables harvesters, there are no similar specific standards for tractors.
The directive 2006/42/CE [CE, 2006] reports "*Where, in the case of self-propelled machinery with a ride-on driver, operator(s) or other person(s), there is a risk of rolling or tipping over, the machinery must be fitted with an appropriate protective structure, unless this increases the risk. This structure must be such that in the event of rolling or tipping over it affords the ride-on person(s) an adequate deflection-limiting volume. In order to verify that the structure complies with the requirement laid down in the second paragraph, the manufacturer or his authorised representative must, for each type of structure concerned, perform appropriate tests or have such tests performed.*", but the only a general reference like "*appropriate tests*" is reported.
In this paper two different standards, the ISO 3471 [ISO, 2008] used for earth-moving machines and the OECD CODE 4 [OECD, 2010] used for tractors were compared with the goal of evaluating the possibility of studying a standard for different self-moving machines.

2. Materials and Methods

2.1 Normative

The ISO 3471 standard and the OECD CODE 4 were compared with reference to the load sequence, the kind and amount of the loads, and the clearance zone.
Figure 1 reports the load sequence for the two standards. The OECD Code 4 foresees four different loads: one longitudinal, one vertical, one lateral and one vertical, while the ISO 3471 foresees one lateral, one vertical and one longitudinal load.

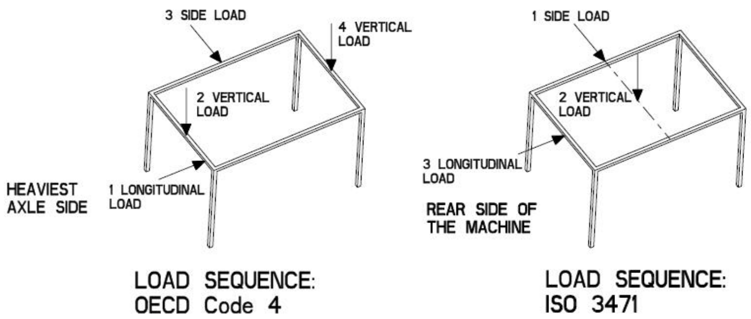

Fig. 1 – Load sequence for the OECD Code 4 and ISO 3471.

The OECD Code 4 standard foresees two vertical loads, one in the front and one in the rear part of the ROPS with respect to the ISO 3471 that foresees only one load in the centre. In the OCDE Code 4 the longitudinal load is lateral while in the ISO 3471 it is central with the consequence of a torsion of the structure in the first one that influences the following loads. The type (with energy target E [J] and with force target F [N]) and the entity of the loads are reported in Table 1.

CODE/STANDARD	OCSE CODE 4	ISO 3471
LONGITUDINAL LOAD		
700<M<4630Kg 4630<M<59500Kg M>59500Kg	E=1.4*M[J]	F=4.8*M[N] F=56000*(M/10000)^1.2[N] F=8*M[N]
VERTICAL LOAD		
700<M<4630Kg 4630<M<59500Kg M>59500Kg	F=20*M[N]	F=19.61*M[N]
SIDE LOAD		
700<M<4630Kg 4630<M<59500Kg M>59500Kg	E=1.75*M[J]	F=6*M [N] E=13000*(M/10000)^1.25[J] F=70000*(M/10000)^1.2 [N] E=13000*(M/10000)^1.25[J] F=10*M [N] E=2.03*M [J]

Table 1 – Type and entity of the loads.

The OECD Code 4 foresees for the longitudinal and lateral load a target on the energy absorbed by the ROPS. In the ISO 3471 the loads are represented by force with the exception of the lateral one that performs an energy target and a force target. Also the comparison between the values of the energy or the force shows a difference between the two standards with higher values for the OECD Code 4 in particular with a mass of the machine lower than 25000 kg.
The safety zones of the two standards are reported in Figure 2. In the ISO 3471 the safety zone was designed taking into account the position of the driver, in the OECD standard the zone refers to the position of the pelvis and the head of the driver.

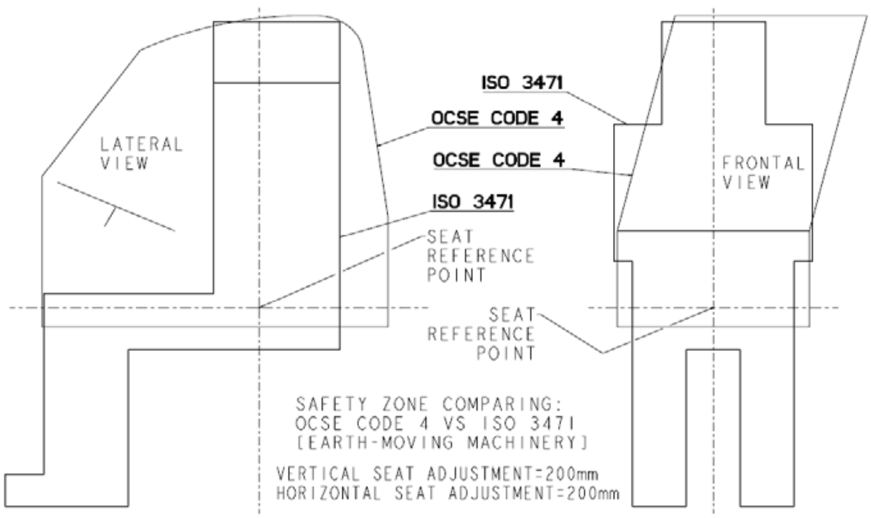

Figure 2 – Safety zone in the two standards.

The two zones are different, in particular the OECD code 4 does not consider the part related to the lower legs, moreover in the lateral view the safety zone defined by the OECD code 4 included the safety zone of the ISO and the zone related to the position of the driving wheel. In the front view the width of the two zones is equivalent but in the OECD Code 4 an inclination in the higher part is considered.
The consideration reported above for the following test takes into account only the OECD Code 4 because the safety level is higher.

2.2 Choice of the machines

For the analysis of different ROPS, four grape harvesters, four combine harvesters, two vegetable harvesters, one olive harvester and one for fruits were chosen. The information regarding the machines are reported in Table 2, in particular the dimensions of the ROPS were analysed.

Machine :	**Mass. [kg]:**	**ROPS type: n° posts**	**Original material of ROPS:**	**Sections dimensions: -Upper elements LxH, S[mm] -Posts LxH, S [mm]**
A: Grape harvester	9700	4	Fe510	Upper el.: 40x40 S=5; 20x40 S=5 Posts: 90x40 S=5; 35x30 S=5
B: Grape harvester	9300	4	Fe510	Upper el.: 40x40 S=5; 20x40 S=5 Posts: 85x40 S=5; 35x30 S=5
C: Grape harvester	9200	4	Fe420C	Upper el.: 50x40 S=5 Posts: 80x50 S=5
D: Grape harvester	3000	4	C40	Circular section diameter 20mm
E: Combine harvester	9800	4	Fe360C	Upper el.: 30x30 S=6 Posts: 60x45 S=6
F: Combine harvester	10200	4	Fe360C	Upper el.: 30x30 S=6 Posts: 60x45 S=6
G: Combine harvester	9600	4	Fe510	Upper el.: 50x40 S=5 Posts: 70x50 S=5
H: Combine harvester	9000	4	Fe420C	Upper el.: 35x45 S=5 Posts: 55x75 S=5
I: Tomatoes harvester	9300	2	Fe42	Upper el.: 35x35 S=5 Posts: 50x50 S=5
J: Fruits harvester	3400	No	-	-
K: Olives harvester	3000	4	C40	Upper el.: 25x35 full sec. Posts: 40x40 full sec.
L: Vegetables harvester	5700	4	Fe42	Upper el.: 30x45 S=5 Posts: 50x50 S=5

Table 2 – Data of the machines analysed.

2.3 FEM Test on the structures

First of all the structures installed on the machines were analysed with the goal of verifying the cabs' safety level and, consequently, the cab that allows to exceed the standard was designed and verified.
The analysis of the cabs was obtained with a dedicated software [Fabbri, 2001] for the analysis with finite elements in a not linear and elasto-plastic field.
The software permits an analysis of the structures submitted to loads fixed by the OECD codes. The structures need to be divided in a finite number of elements connected by junctions. Beam elements were used. In Figure 3 one lay-out of the ROPS is reported.

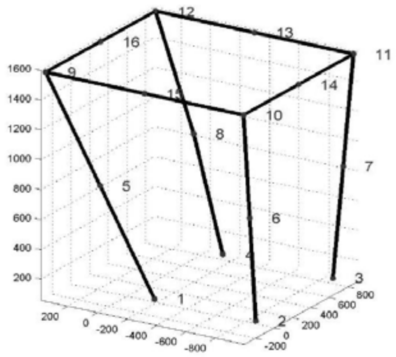

Fig. 3 - Lay-out of a ROPS of a grape harvester and input of the software .
The different loads fixed by the OECD Code 4 are reported in Table 3.

Machine	Longitudinal load [J]	1st crush test [N]	Side load [J]	2nd crush test [F]
A	13580	194000	16975	194000
B	13020	186000	16275	186000
C	12880	184000	16100	184000
D	4200	60000	5250	60000
E	13720	196000	17150	196000
F	14280	204000	17850	204000
G	13440	192000	16800	192000
H	12600	180000	15750	180000
I	13020	186000	16275	186000
J	4670	68000	5950	68000
K	4200	60000	5250	60000
L	7980	114000	9975	114000

Tab. 3 – Loads for the different structures.

3. Results

The results of the tests on the original design of the structures and the dimensions of the ROPS that are necessary to skip the test are reported in Table 4.

Machine	Test result on original design	Necessity of new design	New ROPS type: n° posts	Material	New ROPS section dimension: -Upper elements LxH, S [mm] -Posts LxH, S [mm]
A	Negative	Yes	4	same material	Upper el.: 40x40 full section Posts: 70x70 full section
B	Negative	Yes	4	same material	Upper el.: 40x40 full section Posts: 85x40 full section; 35x30 full section
C	Negative	Yes	4	Fe510	Upper el.: 80x80 full section Posts: 90x90 full section
D	Negative	Yes	4	same material	Upper el.: 40x35 full secton Posts: 40x35 full section
E	Negative	Yes	4	Fe510	Upper el.: 45x45 full section Posts: 70x70 full section
F	Negative	Yes	4	Fe510	Upper el.: 50x50 full section Posts: 75x75 full section
G	Negative	Yes	4	same material	Upper el.: 45x45 full section Posts: 70x70 full section
H	Negative	Yes	4	Fe510	Upper el.: 35x40 full section Posts: 60x70 full section
I	Negative	Yes	4	same material	Upper el.: 95x90 full section Posts: 80x80 full section
J	-	Yes	4	same material	Upper el.: 30x30 full section Posts: 45x35 full section
K	Positive	No	-	-	-
L	Negative	Yes	4	same material	Upper el.: 30x40 full section Posts: 60x60 full section

Tab. 4 – Results.

The results show that only the machine for harvesting olives has a structure that is able to skip the OECD Code 4. In the machine for harvesting fruits there are no structures, and in all the other machines the structure is not able to sustain the load imposed by the standards.
Where it was possible, the original design was maintained and only a modification of the dimensions of the components was modified. In the other cases the structures were modified.

4. Conclusion

In this paper the problem of defining a safety level for drivers of agricultural machineries in case of rolling over was analysed.
The different standards used in other machines like earth-moving machines and tractors were compared. In particular, the OECD Code 4 used for tractors was chosen for the widest safety zone and the higher loads applied to the structures. The code was also applied to different kinds of machines through a FEM software to evaluate the safety level of the structures installed at the moment on the machines and a structure able to overtake the standards was designed.
Only one structure is able to overtake the standards but in the other cases a deep revision of the structure is not necessary, an increasing of the section of the jambs is sufficient.
In conclusion it is possible to design a standard that guarantees conducers of self-moving machinery and adequate safety level. The results of this paper can be considered a first step. More tests are necessary above all to measure the rolling angle in these machines.

References

EN (1997). Standard 632. Macchine agricole, Mietitrebbiatrici e macchine per la raccolta del foraggio Sicurezza, Edition December 1997

EN (2010a) Standard 706. Macchine agricole, Potatrici per vigneto. Sicurezza Edition January 2010

EN (2010b). Standard 13118. Macchine agricole, Macchine per la raccolta delle patate. Sicurezza Edition January 2010

EN (2010c). Standard 13140. Macchine agricole, Macchine per la raccolta delle barbabietole da zucchero e da foraggio. Sicurezza, Edition March 2010

Eurostat (2010), Database health and safety at work

Fabbri A., Ward S. (2001). Validation of a Finite Element Program for the Design of Roll-over Protective Framed Structures (ROPS) for Agricultural Tractors, Biosystems Engineering n. 81 pag. 287-296.

INAIL (2008). Istituto Nazionale per l'Assicurazione Contro gli Infortuni sul Lavoro. Statistics

ISO (2008). Standard 3471 – Earth-Moving Machinery. Roll-Over Protective Structure. Laboratory Tests and Performance Requirements, Fourth Edition 2008-08-15.

Janicak C A (2000). Occupational fatalities to workers age 65 and older involving tractors in the crops production agriculture industry. Journal of Safety Research, 31(3), 143–148.

Myers J T; Snyder K A; Hard D L; Casini V J; Cianfrocco R; Fields J; Morton L (1998). Static and epidemiology of tractor fatalities - a historical perspective. Journal of Agricultural Safety and Health, 4(2), 95–108.

OECD (2010). OECD Standard Code for the Official Testing of Protective Structures, February 2010.

OECD (1959). Standard Codes for the Official Testing of Protective Structure Mounted on Agricultural Tractors. Organisation for Economic Co-operation and Development.

Springfeldt B; Thorson J; Lee B C (1998). Sweden's thirty-year experience with tractor rollovers. Journal of Agricultural Safety and Health, 4(3), 173–180.