Dynamic and static ROPS tests on modern tractors

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Abstract

A Roll-Over Protective Structure (ROPS) is a highly effective engineering safety control that can avoid or reduce the severity of injuries in the event of tractor overturns. Strength ROPS procedures were introduced in Europe in the 1950s. These tests require a level of energy based on the tractor reference mass and consider the driver's clearance zone protection. The Code 6 of the Organisation for Economic Co-operation and Development (OECD) is a consensus performance standard established for agricultural front ROPS fitted on narrow-track tractors. These tractors ROPS requires more attention because the clearance zone is reduced to preserve the normal operation in orchard and vineyard. Code 6 foresees dynamic and static procedures for the ROPS tests. Dynamic procedure is based on a 2000 kg mass oscillating and impacting the ROPS, instead static procedure takes into account a slow rate of load application until the energy level is satisfied. In the current study, according to the OECD Code 6, laboratory dynamic and static tests were carried out on a foldable ROPS fitted on a modern tractor. The work was focused on the evaluation of the ROPS behaviour when stressed dynamically and statically. Dynamic test was carried out on the tractor complete of wheels and attached to the ground, so that the ROPS and the tyres absorbed most of the impact energy. Otherwise, static test was carried out on the ROPS fitted on the tractor chassis without the contribution of tyres; the tractor axels were fixed on the ground and the whole energy was absorbed by the ROPS. Tests results indicate that the deflection obtained with the dynamic testing procedure is higher than that of the static one. The results seem to suggest that the dynamic testing procedure is more conservative than the static one. It could be advisable to extend the comparison between dynamic and static procedures to other types of modern ROPS so as to verify if differences continue to be observed.

Keywords: ROPS, tractor, rollover, clearance zone

Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
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</thead>
<tbody>
<tr>
<td>$M$</td>
<td>reference mass</td>
<td>(1478 kg in the tested tractor)</td>
</tr>
<tr>
<td>$B$</td>
<td>minimum overall width of the tractor</td>
<td>(1.375 m in the tested tractor)</td>
</tr>
<tr>
<td>$B_6$</td>
<td>width of protective structure between the right and left points of impact</td>
<td>(1.095 m in the tested tractor)</td>
</tr>
<tr>
<td>$m$</td>
<td>weight of the pendulum block</td>
<td>(2000 kg)</td>
</tr>
<tr>
<td>$g$</td>
<td>gravitational acceleration</td>
<td>(9.81 m s$^{-2}$)</td>
</tr>
<tr>
<td>$F$</td>
<td>OECD Code 6 crushing forces</td>
<td>(N)</td>
</tr>
<tr>
<td>$H$</td>
<td>height of fall of the pendulum block</td>
<td>(mm)</td>
</tr>
<tr>
<td>$E$</td>
<td>OECD Code 6 energy input</td>
<td>(J)</td>
</tr>
<tr>
<td>$v$</td>
<td>velocity of the pendulum block</td>
<td>(m s$^{-1}$)</td>
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</table>
1 Introduction

The tractor is the machine mostly used in agriculture and, due to its wide diffusion, is a major cause of injury for the operator (Harris et al., 2010). The overturning, and specifically the lateral rollover, is the most serious and frequent accident that may occur in field. A solution to this problem, which has been adopted worldwide, has been to provide a passive protection during the rollover by fitting Roll-Over Protective Structures (ROPS). Tractors are normally used in field operation in farms and the variable conditions (such as slopes, slippery surfaces, drainage ditches, etc.) introduce the risk of instability, potentially leading to tractor rollover. Roll-Over Protective Structure (safety cab or frame), is the structure on a tractor the essential purpose of which is to avoid or limit risks to the driver resulting from rollover of the tractor during normal use. The ROPS is characterized by the provision of space for a “clearance zone” large enough to protect the driver when seated either inside the envelope of the structure or within a space bounded by a series of straight lines from the outer edges of the structure to any part of the tractor that might come into contact with flat ground and that is capable of supporting the tractor in that position if the tractor overturns (OECD Codes, 2014). Historically, before the widespread introduction of ROPS, tractor rollover caused the death of many tractor drivers each year; the risk of severe injury or fatality was very high (Chisholm, 1972; Moberg, 1964). Fortunately ROPS have long been recognised as an effective means to greatly reducing the likelihood of operator injury during overturning accident involving agricultural tractors (Springfeldt, 1996). However, the fixing of the ROPS on the tractor has changed considerably over the years (Rondelli et al., 2012). Having introduced as a mandatory requirement on agricultural tractors in Sweden in the late 1950s the ROPS fitting (Moberg, 1973), a similar ROPS approach followed in many countries during the subsequent decade. Development of relevant laboratory test criteria proceeded in parallel to ensure the adequacy of ROPS design for their intended purpose. The OECD test codes have been at the forefront of ROPS performance test criteria development for agricultural tractors, initially with the Code 3 (Dynamic test, OECD Code 3) from the 1960s and subsequently the Code 4 (Static test, OECD Code 4), introduced in the late 1970s. Codes 6 and 7 were developed for the narrow-track tractors (OECD Codes 6 and 7) in the early 1990s. All ROPS test criteria are based on a series of empirical formulae mainly referred to the tractor reference mass, to calculate the minimum level of strain energy. The ROPS must absorb under loading without the structure fails or infringes driver’s “clearance zone”. The dynamic procedure (Figure 1a) was developed by combining research results, testing activity and evaluation of real rollover accidents. As tractor power and mass increased during the late 1960s and early 1970s, it became evident that the dynamic test procedure had limitations, particularly concerning the testing difficulties for ROPS fitted on heavier vehicles (Moberg, 1973). Researchers in Germany, France, the UK, and the European Commission (EC) recognized certain limitation of this method (Schwanghart, 1978; Söhne & Schwanghart, 1978). In the mid 1970 static ROPS test criteria were adopted by the European Union (EU) and the OECD (Figure 1b).

Figure 1: Tractor arrangement for dynamic test (a.) and static test (b.).
The Schwanghart’s results (1978) were taken into account for drafting the new static code; he stated that on average during the dynamic tests, only 50% of the total energy supplied by the pendulum block was absorbed by the ROPS in the form of strain energy. Over the last 40 years ROPSs have made a major contribution to agricultural vehicle safety, even if it is worldwide accepted that it is impossible to protect the operator in all rollover instances. Consequently the ROPS test criteria have to ensure that the tested ROPS will provide “the highest reasonable probability of driver protection” in the event of rollover in “normal operations”. The focus of the paper was to compare the behaviour of a ROPS fitted on a modern tractor when subjected to static and dynamic strength tests.

2 Materials and methods

ROPS dynamic and static tests were carried out at the OECD Test Station of Bologna, Department of Agricultural Food and Sciences, University of Bologna. Three ROPSs were subjected to dynamic tests using the pendulum block and three ROPSs were subjected to static tests with a hydraulic cylinder loading almost “statically” the structure. Tests were performed using the “Standard Loading Systems” available at the Test Station. Load cells and linear displacement transducers were fitted to measure the loading force and ROPS deflection.

2.1 ROPS testing procedures

The ROPS procedures considered are referred to front mounted ROPS on narrow-track wheeled agricultural tractors (OECD Code 6, 2014). During the ROPS tests no parts may intrude into the driver’s clearance zone. A reduced clearance zone is provided for this ROPS type (Figure 2).

In case of narrow track tractors fitted with front Roll-bar ROPS the strength procedures, are completed by two preliminary tests. The protective structure may only be subjected to the strength tests if both the Lateral Stability Test and the Non-Continuous Rolling Test have been satisfactorily completed.

The sequence of strength tests for OECD Code 6 (Table 1) is as follows:

1. Impact (Dynamic test) or loading (Static test) at the rear of the structure;
2. Crushing at the rear of the structure (Dynamic or Static test);
3. Impact (Dynamic test) or loading (Static test) at the front of the structure;
4. Impact (Dynamic test) or loading (Static test) at the side of the structure;
5. Crushing at the front of the structure (Dynamic or Static test).
Table 1: Sequence of codified tests.

<table>
<thead>
<tr>
<th>Sequence of strength tests</th>
<th>Dynamic procedure</th>
<th>Static procedure</th>
</tr>
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</table>
| Impact (Dynamic test) or loading (Static test) at the rear of the structure | \( H = 25 + 0.07M \) if \( M < 2000\) kg  
\( H = 125 + 0.02M \) if \( M > 2000\) kg | \( E = 500 + 0.5M \) |
| Crushing at the rear of the structure | \( F = 20M \) |                |
| Impact (Dynamic test) or loading (Static test) at the front of the structure | \( H = 25 + 0.07M \) if \( M < 2000\) kg  
\( H = 125 + 0.02M \) if \( M > 2000\) kg | \( E = 500 + 0.5M \) |
| Impact (Dynamic test) or loading (Static test) at the side of the structure | \( H = (25 + 0.2M) \left( \frac{B_6 + B}{2B} \right) \) if \( M < 2000\) kg  
\( H = (125 + 0.15M) \left( \frac{B_6 + B}{2B} \right) \) if \( M > 2000\) kg | \( E = 1.75M \left( \frac{B_6 + B}{2B} \right) \) |
| Crushing at the front of the structure | \( F = 20M \) |                |

The tractor Reference Mass \((M\) (kg)) is the mass, selected by the manufacturer, used in formulae to determine the strength tests. With respect to the dynamic test, \(M\) defines the fall height of the pendulum block \((H\) (mm)); instead in the static test, it defines the energy that an hydraulic cylinder has to inputs to the structure \((E\) (J)) In both cases, \(M\) defines the value of crushing force \((F\) (N)) also. The load static procedure is satisfied when the required energy \((E)\) is absorbed by the ROPS; rather, the impact dynamic procedure is satisfied when the pendulum mass is pulled back so that the height of its center of gravity corresponds to the required height \((H)\) and is dropped to impact the ROPS. The Reference Mass must not be less than the unballasted tractor mass and must be sufficient to ensure the Mass Ratio does not exceed 1.75, i.e. tractor Maximum Permissible Mass / tractor Reference Mass < 1.75.

2.2 Control, measurement and data acquisition instruments.

The ROPS was fitted with sensors in order to acquire test data. ROPSs of same type were placed on the tractor and were subjected to the procedure of static loads and dynamic impacts. The control, measurement and data acquisition system is shown in Figure 3.

![Figure 3: Control, measurement and data acquisition system.](image)

Dynamic load cells and linear displacement transducers were used to acquire signals of force and deflection. The output signals from the sensors (Volt) were acquired by Voltage input modules fitted on the Data acquisition system (DAQ - National Instruments). A Com-
computer connected allowed to process data with dedicated software (LabView). The force signal was amplified before the DAQ by means of a charge amplifier (Kistler). In addition to this instrumentation, an high speed camera recorded the tests to better understand the dynamic phases.

## 3 Results and discussions

Strength tests were carried out. The evaluation was based on the energy required in the OECD Code 6 (Table 2). The tractor instrumented and subjected to strength tests at the side of the ROPS structure is shown in Figure 4.

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<th>Static procedure</th>
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<tr>
<td>Impact (Dynamic test) or loading (Static test) at the rear of the structure</td>
<td>( H = 128 \text{ mm} ) ( E = m g H = 2511 \text{ J} )</td>
<td>( E = 1239 \text{ J} )</td>
</tr>
<tr>
<td>Crushing at the rear of the structure</td>
<td>( F = 29560 \text{ N} )</td>
<td></td>
</tr>
<tr>
<td>Impact (Dynamic test) or loading (Static test) at the front of the structure</td>
<td>( H = 128 \text{ mm} ) ( E = m g H = 2511 \text{ J} )</td>
<td>( E = 1239 \text{ J} )</td>
</tr>
<tr>
<td>Impact (Dynamic test) or loading (Static test) at the side of the structure</td>
<td>( H = 288 \text{ mm} ) ( E = m g H = 5651 \text{ J} )</td>
<td>( E = 2323 \text{ J} )</td>
</tr>
<tr>
<td>Crushing at the front of the structure</td>
<td>( F = 29560 \text{ N} )</td>
<td></td>
</tr>
</tbody>
</table>

Table 2: Comparison between dynamic and static procedures.

![Figure 4: Lateral test provided for the OECD Code 6: a. Dynamic procedure, b. Static procedure.](image)

### 3.1 Dynamic test

The dynamic approach was an impact loading: a pendulum block impacted against the ROPS from the drop heights (\( H \)). The height of the pendulum block with respect to the point of impact on the ROPS allowed to evaluate the initial potential energy \( (m g H) \) (Table 2). The swing of the block causes a transformation of potential energy into kinetic energy. Consequently, knowing the velocity \( (v) \) at the impact point, the kinetic energy available \( \left( \frac{1}{2} m v^2 \right) \) was calculated. The pendulum block, after the impact, decreased progressively the velocity.
due to the contact with the ROPS, transferring energy and causing the deflection of the ROPS. To analyse the data the impact event was divided into three phases (Figure 5).

Phase 1: Pendulum block before the free fall ($v = 0$)
Phase 2: Pendulum block at the impact time ($v \neq 0$)
Phase 3: Impact end, corresponding to the maximum deflection of the ROPS ($v = 0$)

![Figure 5: Dynamic impact phases.](image)

![Figure 6: Force and deflection vs. time in the dynamic procedure.](image)

The strain energy in Phase 3, obtained on the basis of force and deflection acquired during the dynamic tests (Figure 6), was different compared to the energy values associated to the previous two phases. Friction and air resistance were factors that greatly affected the energy transferred between phases 1 and 2. Tyres deformation affected the energy transferred be-
between phases 2 and 3. It was possible to evaluate the energy lost in Phase 3 by measuring with the high speed camera the velocity of the pendulum block at the impact time on the ROPS.

### 3.2 Static test

The ROPS was subjected to a very slow increasing load applied by means of a hydraulic cylinder (Figure 7). The rate of load application (0.004 m/s) was so low that it could be considered static. In Figure 8 is shown the behaviour of the ROPS during the side load test: a first elastic deflection till 72 mm then the slope of the curve changes due to the change of behaviour from elastic to plastic. At 228 mm the load was released and there was a springback.

![Figure 7: Force and deflection of the ROPS subjected to the static load.](image)

### 4 Conclusions

The energy corresponding to the pendulum block height in the procedure dynamic is higher with respect to the energy required in the static procedure but the two procedures are considered approximately equivalent in terms of safety because it is known that in the dynamic tests only a portion of energy is absorbed by the ROPS. However the results showed that the official testing procedures were not comparable in terms of total ROPS deflections. In the dynamic tests more than 50% of the total energy supplied by the pendulum block was absorbed by the ROPS in form of strain energy. It could be advisable to extend the comparison between dynamic and static procedures to other types of modern ROPS so as to verify if differences continue to be observed.

### 5 Acknowledgements

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### 6 References


