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Four Computer Programs to Design and Calculate Safety Structures for Old Agricultural Tractors Lacking ROPS

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Abstract: The majority of fatal accidents involve a roll-over of a tractor without a protective structure (ROPS). In the EU there are still a high number of tractors without an adequate structure to protect the driver from a roll-over and the situation is worse in the USA and in developing countries. European directives establish that tractors have to be homologated by CODE 4, CODE 6 or CODE 7 according to their characteristics. A ROPS attachable to the rear axle of different tractor models (T-1 category) has been designed and a model for the calculation of the ROPS to pass the homologation test established in CODE 4 has been developed. The model calculates the maximum forces during the tests and the maximum moments in the critical sections of the ROPS beams and the attachment moments; and is able to determine the needed steel section of the structure tube, the minimum height of the beams to make rigid the lower part of the structure, and the number, quality and shank diameter of the attachment screws of the ROPS Owing to the complexity of the calculations a computer program 'ESTREMA' was developed. Using this program a ROPS for the MF-178 tractor was designed and tested at the Spanish Authorized Station for testing ROPS, and passed homologation test (OECD CODE 4). In the same way, a calculation model for narrow tractors, equipped with rear safety arcs, and a computer program, named "TASTEREMA" were developed to calculate these arcs. For the narrow tractors equipped with front safety arcs, two computer programs were developed, the first one, named "VUELCO", to check whether the structure prevent continuous roll-over of the tractor in the overturn and the second one, named "DASTEREMA" to calculate the needed section for the structure beams. These four computer programs are available in www.unavarra.es.
Key words: overturn, homologation, test, safety

INTRODUCTION and LITERATURE REVIEW

The accidents that imply a roll over are often fatal for the worker that operates the tractor. Accidents caused by roll over represents one third of all deadly accidents in the agricultural sector, and 90% of them refer to lateral roll over, and only 10% of them to roll backwards. Research studies have shown that tractor rollovers are the leading cause of work related death in U.S. production agriculture, where only about 70% of sold tractors were equipped with roll-over protective structures, named ROPS (Freeman, 1999). The majority of the deadly accidents are referred to tractors without a protective structure and not to tractors with it (Arana et al., 2002). A ROPS in combination with a seatbelt can prevent nearly all tractor overturn related fatalities and serious injures (MMWR, 1993).

Myers and Pana-Cryan (2000) compared three strategies to prevent injuries incurred as a result of tractor overturns. These strategies were "do nothing", "install ROPS on tractor that lack a ROPS", and "replace tractor", concluding that the preferred strategy in terms of cost-effectiveness is to "install ROPS" on tractors lacking them for which ROPS are available.

ROPS, acronym of roll-over protective structure, are sturdy frames attached to tractors or built into tractor cabs, to limit the risk for the driver in case of a turnover. These consist of fixed or partially tiltable structures, with defined clearance zones around the driver's seat, thereby offering the driver protection in the event of a turnover (both lateral and longitudinal) (Febo and Pessina, 1989; Ayers et al., 1994). These protective structures are usually built with tubular elements, with a square or circular section, and fixed to the tractor by means of bolts.

On March 1974 European Economic Community Directive (EEC) 74/150/EEC is approved: The objective of this EEC directive is to approach the legislations of the member countries for the homologation of wheeled agricultural and forestry tractors with protective structures. On June 1977 Directive 77/536/EEC established the dynamic tests for the homologation of tractors with protective structures. On June 1979 Directive 79/622/EEC established the static tests for the homologation of tractors with protective structures.

However there is a high number of tractors without the adequate structure to protect the driver from an overturn or roll over (Arana et al., 2002). Given the age of these tractors, they are more prone for having accidents, have general wear and tear, they are lighter and less stable, and oftentimes they are used with newer implements that are too big for the tractor. Some of these tractors have conventional cabs, which although protect the driver from weather inclemency, and improve his/her comfort level, cannot be considered as a protection against roll over. Sometimes it can even become a real trap that could worsen the consequences of an accident if it happens. This very tragic situation forces to design a protective structure compatible, economical and easy to build. This structure should be been able to adapt in any tractor trade mark or model built without a commercial roll over protective structure, officially approved

Tractors having at least two axles for pneumatic tyred wheels or having tracks instead of wheels and with an unballasted tractor mass not less than 800 kg have to be homologated by using CODE 4, narrow tractors equipped with a front safety arc have to be homologated by using CODE 6 and those equipped with a rear safety arc using CODE 7

Authorised testing stations according to OECD codes, which are technically equivalent to selected European Economic Community Directives, test the ROPS. According to the CODES, the ROPS must be tested by a sequence of four static tests and must reach a predefined level of deformation work. Moreover during the loading, no parts should impinge upon the driver's clearance zone.

Methodology and specifications of the static test are determined by the CODES. The main specifications are the location of the seat reference point, the location, shape and definition of the clearance zone, the apparatus used on the four static tests, the test conditions and the sequence of the test. This sequence of test is make up by a longitudinal loading test, the first crushing test, a loading from the side test and the second cruising test

The clearance zone is the zone occupied by the driver during the roll-over, when he permanence in his seat hardly got to the steering wheel. The CODES also determines the energy that the protective structure has to absorb without impinging upon the driver's clearance zone during any part of the longitudinal loading test and the loading from the side test. Also determines the mass that the structure has to resist during five seconds without impinging upon the driver's clearance zone on both cruising tests.

The objectives of this work were to design protective structures in order to absorb the calculated energy required in CODES 4, 6 and 7 tests and to get that the zone of clearance has not been impinged upon during these tests, to develop calculation programs for roll over protective structures for tractors to overcome the homologation test sequence, described in the cited CODES and to validate these calculation programs.

MATERIAL and METHOD

To design the protective structure for wide tractors the following criteria were considered:

The only resistant point common to all tractors, the rear axle tube, determines the structure design for the roll over protective structure. In the initial roll over protective structure design, the structure is attached to the rear axle tube, it is open in a 'V' shape, and makes a parallelogram that wraps around the driver's safety zone (Ponce de Leon et al., 2005). The protective structure has to absorb the energy, fixed on CODE 4 without imfringing upon the driver's clearance zone during any part of the longitudinal loading test and the loading from the side test. The protective structure has to resist during 5 seconds, without impinging upon the driver's clearance zone, the charge fixed on CODE 4, on both cruising tests defined by CODE 4. Oversize is as prejudicial as undersize, because it can increase the forces and strains in the joints between elements (Arana et al., 2004). Figure 1 shows the structure and the safety zone.

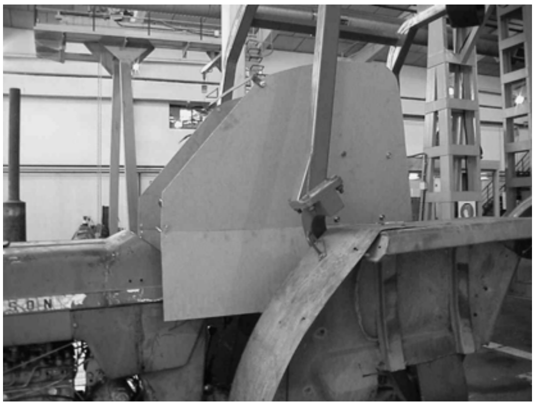

Figure 1. Designed ROPS including safety zone

3D protective structure design, constructing planes and finite elements simulation of strains and deformations were obtained using CADAM Catia V.5R7 program. A protective tubular structure attachable to the rear axis of any tractor was designed, built in steel of 420 MPa of a particular resistance (A-42b). The hollow steel section can be square or circular. This structure is attached to the rear axis and to the fender in tractors with fenders. In order to make a more rigid protective structure and to reduce the value of the maximum moments, it is possible to include in the structure a horizontal beam to join the two beams in 'V' at a chosen height.

It is necessary to calculate the minimum steel section of the structure tube to absorb the roll-over energy, fixed by CODE 4, which is a function of the tractor mass, without infringing upon the clearance zone defined by CODE 4. An admissible maximum deformation for each static test was allowed to impede the structure to infringe on the clearance zone. From the value of the admissible maximum deformation and from the experimental force-deformation curve, the maximum force and development of the moments on the referred beam are calculated as statically indeterminate systems. A deformation totally plastic of a flexor section of ideal plasticity was considered. A small reinforcement of the structure on the lower part was also admitted in calculation due to the fender. When calculating screws and flanges, an admissible resistance from 60% of the limit of fluency was employed to enlarge the security. The complexity of the calculus required us to develop a computer program to calculate easily and quickly the designed ROPS.

The designed protective structure was calculated to be mounted on a Massey Ferguson 178, with an umballasted mass of 2,700 kg and a track of 2.23 m.

Following the design, manufacture and mounting of the ROPS on a Massey Ferguson 178, the tractor was moved to the Mechanization Agricultural Station (M.A.S., Madrid) in order to perform the tests needed to homologate ROPS for tractors. The tractor were prepared and tested according to OECD code.

In the same way front and rear safety arcs were designed for narrow tractors and computer programs were developed to calculate the section of the beams and the screws of these arcs in order to overcome the tests defined by CODE 6 and Code 7 OECD codes respectively. In the case of front safety arc a computer program to ensure the tractor do not roll continuously during the overturn was developed.

RESULTS and DISCUSION

A protective structure, set to the rear axis and fender, was designed according to the objectives of the investigation. It consists on a tubular structure attachable to the rear axis of any tractor, built in steel of 420 MPa of a particular resistance (A-42b). The ROPS, is formed by the following elements: two longitudinal arches attached to the rear axe – trumpet – by means of two iron plates joined by anchorage screws, Two transversal beams, a frontal and a rear one, two longitudinal beams, one on the upper part of the structure, joining the transversal beams, two longitudinal beams in the lower part of the structure, at a chosen height, joining the parts of the arches in 'V'. They reach the attachment point on the trumpet, in order to increase rigidity of the protective structure and to reduce the value of the maximum moments. Metallic braces in all angles and joinings of the structure to the fender. The ROPS is welded to a steel plate on the trumpet and is attached to another similar plate below trumpet, by screws. The attachment screws are placed along the vertical grooves of the trumpet, except in the case of trumpets lacking grooves. It is necessary to fix both steel plates to the trumpet to avoid the spinning of the whole of bolt in a back tractor overturn. Relative position between screws and ROPS joining to the rear axe and the distance between screws and this point determine the calculation of the needed section in the screws.

Once the design was established, a method to calculate the roll over protection structure was developed, based on the following criteria: the OECD standard code of static test (CODE 4), the structure design and the tractor measurements and mass. The calculation method allowed calculating the tractor structure to theoretically endure the sequence of tests described in CODE 4.

To develop the calculation method already described, an Excel program was made and named "ESTREMA", the Spanish acronym of safety structure for mechanical agricultural tractor equipment.

The program requests certain data through different simple forms illustrated and wholly explained, including explanatory drawings. Moreover, it specifies the units that should be employed and limits the data entry to a range of logical values. Error messages are shown if inadmissible data are introduced, resulting in easy management and avoiding the execution of the calculation in case of illogical data or gaps in the forms. As the relative position between screws and ROPS attached to the rear axle and the distance between screws and this point determine the calculation of the needed section in the screws, it is necessary to select one of the following options: "screws at both sides of the ROPS union to the rear axle", or "screws at the outer side of the ROPS". The program shows the calculated structure in a form displaying the section (square or circular) of the steel profile needed, the measurements of the structure and the anchorage (steel plates and screws), different views of the structure, braces and joining points and several specifications to build it. This program requires relatively little operator training.

The software calculates the necessary sections of the ROPS' beams. In a first step, it calculates the maximum admissible deflections of the ROPS during each test that ensures that the deformation produced will not be so high that the structure infringes upon the clearance zone. These deflections depend on the location of the SRP and the shape and measurements of the ROPS. In a second step, it calculates the maximum strengths produced during the tests that depend on the maximum admissible deflections, the absorbed energy required by Code 4, and fluency. In a third step, it calculates the maximum moments in the critic sections of the ROPS, during each test, and the necessary section modulus of the steel section of the ROPS' beams Then, the software chooses the steel section with a section modulus immediately higher than the calculated. Finally, it calculates the attachment moments during each test and chooses the necessary quality and section of the screws that attach the ROPS to the tractor. The program select this section and another two profile sections with the next two section modulus values, as second and third options, but only if those section modulus values were not over 150% of the first option W value, and also calculates the number, quality and section of the screws which attach the ROPS to the tractor trumpet.

A ROPS was designed manufactured and installed, according to the indications of 'ESTREMA' program, on a Massey Ferguson 178, and the tractor was moved to the Mechanisation Agricultural Station (M.A.S.) in order to perform the sequence of tests defined by CODE 4. Tests carried out using a hydraulic cylinder that pushes the structure, were the 'static tests'. During the longitudinal loading test a deformation of 18.5 cm was found and the safety zone, placed farther than 50 cm, was not reached. Figure 2 shows the ROPS during this test.

Figure 2. ROPS during rear longitudinal test

In loading from the side test the deformation reached 21.3 cm with an applied energy of 5437 Joules. Although the deformation was greater, it still did not infringe upon the clearance zone. In the two crushing tests the structure was set up just correcting the movement a bit from the previous tests. The applied force at the end of the test, when the required energy absorption was met, was higher than 0.8 Fmax, the maximum force applied during the horizontal tests. Therefore, the designed ROPS complied all acceptance conditions established in CODE 4.

Although the designed and calculated structure was built and successfully tested, the results revealed that it was too big, too tall; the curved parts on top of the structure increased construction costs and made it more difficult to build. Considering those aspects the ROPS was redesigned, better adapting height to the security zone. For the same reason, the calculation program was improved by including the option to calculate the lower part of the structure with a solid mass profile, since the ROPS was curved at the bottom following the curve of the fender. The option of placing a solid mass structure in the bottom had an added advantage: it required less space between the wheel attachment and the fender.

Once the above mentioned aspects were corrected, a new ROPS for the same tractor was designed and calculated by the "ESTREMA" program (figure 3). This structure was manufactured at the "Verges" workshop (Lleida), and was mounted on a Massey Ferguson 178 tractor, between the wheel and the fender, just as indicated by the program.

Figure 3. Improved ROPS before real overturn

A demonstration of a real turnover was performed with the tractor carrying the new ROPS. To induce a roll over, the tractor was placed on a platform that was turned over laterally from a height of 1.2 m and over a highly compacted floor. This roll over was extremely hard and violent. However the security zone was not infringed upon, due to the security structure.

In the same way, a calculation model for narrow tractors, equipped with rear safety arcs, and a computer program, named "TASTEREMA" were developed to design and calculate these arcs to ensure that these arcs are able to overcome the sequence of tests defined by CODE and CODE 7 without failure.

For the narrow tractors equipped with front safety arcs, two computer programs were developed, the first one, named "VUELCO", to check whether the structure prevent continuous roll-over of the tractor in the overturn and the second one, named "DASTEREMA" to calculate the needed section for the structure beams to ensure the structure overcome the homologation test defined by CODE 6.

The four computer programs reported in this article are available for free in www.unavarra.es.

CONCLUSIONS

It is necessary and possible to design protective structures attachable to different trademarks and models of older tractors. Four computer programs has been developed to calculate the necessary steel section of the protective structure and the necessary attachment screws for each tractor to overcome the homologation tests defined by CODES 4, 6 and 7. The programs are able to calculate the minimum section of the ROPS beams and its measurements to ensure the ROPS success in the homologation tests without any failure on the acceptance conditions. The program "ESTREMA" has been validated because, using it, it has been possible to design a ROPS that overcame the homologation tests without any failure on the acceptance conditions and another ROPS that overcame a real overturn successfully.

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