ROPS Design for Older Tractors

Final Summary Report

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INTRODUCTION

Tractor overturns are a major cause of agricultural-worker deaths each year. These deaths and serious injuries may have been prevented if the tractors had been equipped with ROPS, and the operator was wearing a seat belt. Many tractors manufactured prior to 1970 did not have ROPS as an option and thus the axle mounts were not designed to structurally support a ROPS during an overturn. If ROPS were available for these pre-ROPS tractors, then rollover protection will be more readily available and lives could be saved. The specific aims of the project were to:

1. Identify two major axles categories of pre-ROPS tractors in order to determine axle designs appropriate for ROPS design and testing.

2. Design, construct and test ROPS for each of the two major axle categories identified. This includes conducting static and field upset ROPS testing in accordance with ASAE S519.

3. Determining torsional axle housing strengths for pre-ROPS tractors (initially vibrational loading tests).

4. The development of guidelines for the design and installation of ROPS for pre-ROPS tractors, focusing on axle housing support.

SIGNIFICANT FINDINGS AND THEIR USEFULNESS (listed by project specific aim)

Identification of Two Major pre-ROPS Axle Categories

A database of tractors in use on U.S. farms (Myers and Snyder, 1995) was used to define the major axle categories for pre-ROPS tractors. The first major axle category includes the axle design for the John Deere A, B, G, 50, 60, 70, 520, 620, 720, 530, 630, and 730 tractors. This axle category consists of about 920,000 tractors sold with approximately 150,000 still in operation. The axle housings, and thus ROPS mounting locations are very similar for these tractor models. Axle drawing for these tractors have been obtained from Deere and Co. Axle housing dimensions and bolt hole locations were identified to assist in the ROPS construction guidelines.

The second major axle category selected covers the Farmall H, M, Super H, Super M, 300, 400, 350, 450, 460 tractors. Again, these model tractors have very similar axle housings and axle housing drawings were constructed. Although ROPS for some of these tractors are listed as being available through Saf-T-Cab, Saf-T-Cab would like a more economical ROPS design (two post). Also, this tractor axle category makes up a large number of tractors in operation (approximately 278,000). Again, axle housing dimensions and bolt hole locations were identified to assist in the ROPS construction guidelines.

(Related Publications - Ayers, 1997; Ayers 1994)

ROPS Design, Construction and Testing for One Tractor in each Major Axle Category

Two-post ROPS have been designed, constructed and tested for the John Deere A and Farmall M tractors. Energy calculations and allowable deflections were used along with the exposure criteria model to design the ROPS dimensions and select the material. The exposure criteria model was modified to assist in the ROPS design for the two tractors. The static lateral, longitudinal and vertical tests were conducted using the ROPS testing apparatus to ensure the requirements stated in ASAE S519 were satisfied.

Both John Deere A and Farmall M tractors were purchased and modified for field upset testing. The modification includes structural support, battery protection, gas tank redesign and installation of a pneumatic power source for starting, braking and clutching. Pneumatic tanks, control valves and cylinders were installed and are radio controlled to provide remote operation of the tractor. The ROPS deflection measuring system was installed. The lateral and longitudinal field upset sites were constructed in accordance with ASAE S519. Field upset testing was conducted for the John Deere A and the Farmall M in 1996 and 1997, respectively. The designed ROPS for both tractors satisfied the ASAE S519 test requirements.

The test results and plans for the John Deere A and Farmall M ROPS were sent to two ROPS manufactures. They are Saf-T-Cab (Fresno, CA) and FEMCO (McPherson, KS). Saf-T-Cab sent a newly designed Farmall M ROPS to Colorado State University. The ROPS was mounted on the remote -controlled Farmall M tractor and field upset tests were conducted. The results of the testing was sent back to Saf-T-Cab, and Saf-T-Cab is selling the ROPS commercially.

(Related Publications - Liu, 1998; Liu and Ayers, 1998; Ayers 1997; Ayers et al., 1995; Ayers et al., 1994; Ayers, 1994; Johnson and Ayers, 1994)

Axle Housing Strength Tests (initially Vibrational Loading Tests)

Initially vibrational loading was a concern when mounting ROPS on pre-ROPS tractors. However, after discussions with Dan Lockie of Saf-T-Cab, Dale Baker and Joe Oliver of Case IH and Murray Madsen of Deere and Company axle strength during the rear upset tests is more of a concern. The shift of emphasis from vibrational loading to axle housing strengths was approved by Dr. John Etherton, NIOSH project advisor.

The concern in the industry is the ultimate strength of the tractor axle housing when subjected to rear (longitudinal) loading. In rear loading, if the axle housing fails, the housing will rotate with respect to the axle and the operator will be crushed. To address this concern, an axle strength test apparatus was constructed. This apparatus consists of a 4 inch diameter, 24 inch stroke hydraulic cylinder attached to a 7 foot length I-beam. A torsional load is placed on the axle housing until failure or the 20,000 lb. limit of the load cell is reached.

The longitudinal torsional strength of 17 pre-ROPS axle housings (8 pre-ROPS model tractors) were tested. The longitudinal strength test were repeated four times for the Ford 8N and

Farmall M pre-ROPS axle housings. Torsional axle housing strength test results of John Deere A, Ford 2N, Farmall H, C, 450 and 460 pre-ROPS axle housings were also obtained.

(Related Publications - Li and Ayers, 1998; Li, 1997; Li and Ayers 1997)

Development of ROPS Design Guidelines Focusing on Axle Housing Support

Guidelines of ROPS design which focus on axle housing support need to consider the design margin between longitudinal yield torque of the axle housing and maximum torque subjected during ASAE Standard S519 longitudinal static test. This design margin is determined to evaluate the appropriateness of the axle housing to support the designed ROPS.

For example, the design margins for the Farmall M ROPS/axle housing combination is described. Static longitudinal tests conducted in accordance with ASAE S519 at Colorado State University revealed an estimated maximum torque on the axle housing as 36,000 Newton-meters. The strength torques of the four Farmall M axle housings were 51,436, 54,857, 46,520 and 49,574 Newton-meters. Their design margin are 1.43, 1.52, 1.29 and 1.38. These design margin calculations are only valid for the ROPS design tested. A change in ROPS design would likely produce a change in the design margin.

Assuming the strength torques of Farmall M axle housings are normally distributed, then the population mean of the design margin is determined by using the Student's t distribution. The probability plot did not show any evidence that the normality assumption is invalid. The design margin of the Farmall M axle housing has a population mean of 1.41 with the standard deviation of 0.10. The 95% confidence interval of the design margin is determined to range from 1.25 to 1.57. The probability of the design margin less than one (the strength torque of the axle housing is equal to the maximum torque applied during ASAE Standard S519 longitudinal static test) is less than 0.35%.

The test results indicate that the Farmall M axle housings tested can successfully support the ROPS design tested. Initial satisfactory results were found for the Ford 8N and John Deere A axle housings, encouraging commercial ROPS design for these tractors. These guidelines can be used to evaluate the appropriateness of axle housing support during ROPS design for pre-ROPS tractors.

A Fortran program was developed to determine if the operator clearance zone is exposed to the ground surface as the ROPS is deflected during the static test. The model results are compared to actual ROPS static tests to evaluate its accuracy. In actual testing the clearance zone was exposed to the ground plane at a horizontal ROPS load point deflection within 24 mm (less than one inch) of the model prediction. This model provides guidelines in ROPS design (particularly sizing and dimensioning) when considering the evaluation of the exposure criteria as defined in ASAE S519.

(Related Publications - Li and Ayers, 1998; Li, 1997; Li and Ayers 1997; Ayers et al., 1994)

DISSERTATION

DEVELOPMENT OF STABILITY INDEX FOR TRACTORS AND ITS APPLICATION IN PROTECTIVE STRUCTURE DEPLOYMENT

Submitted by

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Department of Chemical and Bioresource Engineering

In partial fulfillment of the requirements

For the Degree of Doctor of Philosophy

Colorado State University

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THESIS

STRENGTH ANALYSIS

FOR

PRE-ROPS TRACTOR AXLE HOUSINGS

Submitted by

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for the Degree of Master of Science

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Strength Test for Pre-ROPS Tractor Axle Housings

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Phoenix, Arizona
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Summary:

Tractor rollovers are a major cause of agricultural related deaths each year. A rollover protective structure (ROPS) dramatically reduces fatalities during tractor overturns. However, pre-ROPS (before ROPS were available) tractor axle housings were not designed to support a ROPS. This paper presents the strength test investigating pre-ROPS tractor axle housings. The factor of safety between longitudinal yield torque of the axle housing and the maximum torque subjected during ASAE S519 longitudinal static test is determined. The relationship between twisting angle and torque of the axle housing is established. The results show that the Ford model pre-ROPS axle housing tested can successfully support ROPS. The test was conducted in accordance to ASAE Standard S519.

Keywords:

Rollover Protective Structure (ROPS), Pre-ROPS Tractor, Tractor Safety, Axle Housing, Strength Test.

Introduction:

Tractor rollovers are a major cause of agriculture-worker deaths every year. One out of five agricultural work fatalities is caused by tractor overturns (National Safety Council, 1995). A Rollover Protective Structure (ROPS) is a structural frame designed for protection of the operator in the event of a vehicle overturn. ROPS utilization is shown to have a dramatic impact in reducing fatalities during vehicle overturns (Woodward and Swan, 1980).

All new tractors are manufactured with ROPS, but many tractors produced prior to 1970 did not have ROPS as an option (pre-ROPS tractors) and the axle housings were not designed to support ROPS during an overturn.

Etherton and Myers (1990) estimated that it would take at least 30 years to replace all pre-ROPS tractors. Therefore, fitting pre-ROPS tractors with ROPS is becoming one of the most important safety concerns facing the agricultural industry.

For some pre-ROPS tractors, retrofit ROPS are available (Johnson and Ayers, 1994). However, pre-ROPS tractor axle housings which were not designed to support ROPS may bear much higher loading beyond the normal design range when tractors turn over. It is imperative that ROPS be properly designed and manufactured, and also that the axle housings successfully support ROPS.

ASAE S519 is a standard to define the test procedure and performance criteria for ROPS to minimize the frequency and severity of tractor operator injuries during a wheeled tractor overturn (ASAE, 1992). However the standard focuses mainly on the performance of the ROPS itself, not on the ROPS/axle housing combination; it does not take into account the ultimate strength of the tractor axle housing. Therefore, there is a concern that a ROPS/axle housing combination passing the static test may not be representative of the total range of ROPS/axle housing performance as the quality control of pre-ROPS tractor axle housings is questionable.

The tractor rear rollover is considered more critical than the side rollover in terms of axle housing failures. Failures during a rear rollover are much more dangerous to the tractor operator compared to a side rollover as the axle housing may rotate crushing the operator.

The focus of this study is to present the longitudinal strength test investigating popular pre-ROPS tractor axle housings to determine the safety factor between longitudinal yield torque of the axle housing and the maximum torque subjected during ASAE S519 longitudinal static test. This safety factor indicates how well the pre-ROPS tractor axle housings can successfully support ROPS.

Results and Discussions:

By subtracting the displacement measured in the I-beam deflection test from that in the strength test, the deformation produced by twist of the axle housing was obtained. The twisting angle of the axle housing can be calculated from the dimension of the testing apparatus. Meanwhile, the twisting torque of the axle housing can be calculated in terms of the loading force and the distance between the loading point and the axle housing, which is two meters. For instance, when the loading force is 13,450 Newtons, the twisting torque is 26,900 Newton-meters.

Based on the twisting angle and torque of the axle housing, the relationship between them is established (Figure 3). The curve is initially linear but deviates from linearity as the torque increases. For the axle housing randomly chosen (Figure 4), it is shown that when the twisting torque is less than 23,000 Newton-meters, the relationship between twisting angle and torque is approximately linear with a steep slope. This can be referred to as the elastic deformation stage where little deformation is caused by large torque increases. During the elastic deformation phase, the elastic loading slope is approximately constant and the axle housing obeys Hooke's law. The unloading line would coincide with the loading one, and the whole operation is quite reversible. In this case, 23,000 Newton-meters are called elastic limit torque, the value beyond which the torque is no longer proportional to the angle. When the torque reached 27,000 Newton-meters, the slope of the curve becomes flat where large deformation is obtained with relatively slight torque increases. This can be referred to as the plastic deformation stage, where deformation of the axle housing could not be recovered even after unloading the torque.

The axle housing went from the elastic to plastic stage (or was partly plastic) when the twisting torque was between 23,000 and 27,000 Newton-meters. The cylinder was out of range when the axle housing was twisted to 13 degrees. The beginning of the curve shows some adjustment of the system when the initial load is applied. This part is small and negligible.

The axle housing is expected to work properly in the elastic deformation stage, and the operator is safe as long as the axle housing does not go into the plastic deformation stage. However, although the axle housing is not fractured during the plastic deformation period, the large twist of the axle housing in this phase may cause the ROPS to intrude significantly into the clearance zone, resulting in operator injury.

The twisting torque where the axle housing yields appreciably with little change in torque (or becomes plastic) is defined as the yield torque of the axle housing. Because the techniques of measurement used in practice make it difficult to identify the yield torque precisely, in engineering practice the 0.2% proof torque is used to estimate the yield torque (Gillam, 1969). To find the yield torque, a line is constructed 0.72 degrees to the right and parallel to the elastic loading line. The intersection of this line and the twisting angle-torque curve is the point where the yield torque is defined (Figure 4). This torque is also called 0.2% proof torque, for 0.72 degrees is 0.2% of circularity, 360 degrees. In this case, the yield torque is 26,900 Newton-meters. Since only one side of the axle housing was tested, the yield torque of the entire axle housing can be estimated as

The program result also shows that the probability of the safety factor less than one (The yield torque of axle housing is equal to the maximum torque applied during ASAE S519 longitudinal static test.) is much less than 0.005% (Table 1). Thus, the test results indicate that the Ford axle housing tested can successfully support ROPS.

Conclusions:

Important safety devices should not be limited to new tractors. Older tractors are still frequently found in fields because of their high reliability and quality. The purpose of this study is to help extend ROPS availability to pre-ROPS tractors.

The ASAE standards for ROPS performance tests do not ensure adequate protection of the operator because failure of the axle housing is not addressed.

The longitudinal strength test investigating popular pre-ROPS tractor axle housings were presented. The relationship between twisting angle and torque of the axle housing is established and the safety factor between longitudinal yield torque of the axle housing and the maximum torque subjected during ASAE S519 longitudinal static test is determined. The test results indicate that this model Ford pre-ROPS tractor axle housing can successfully support ROPS.

The axle housing strength should be an important consideration when designing ROPS for pre-ROPS tractors.

Recommendations:

More common pre-ROPS tractor axle housings are involved in further studies. The tests of John Deere and Farmall pre-ROPS tractor axle housings are underway. The safety factors of these pre-ROPS tractor axle housings are being determined.

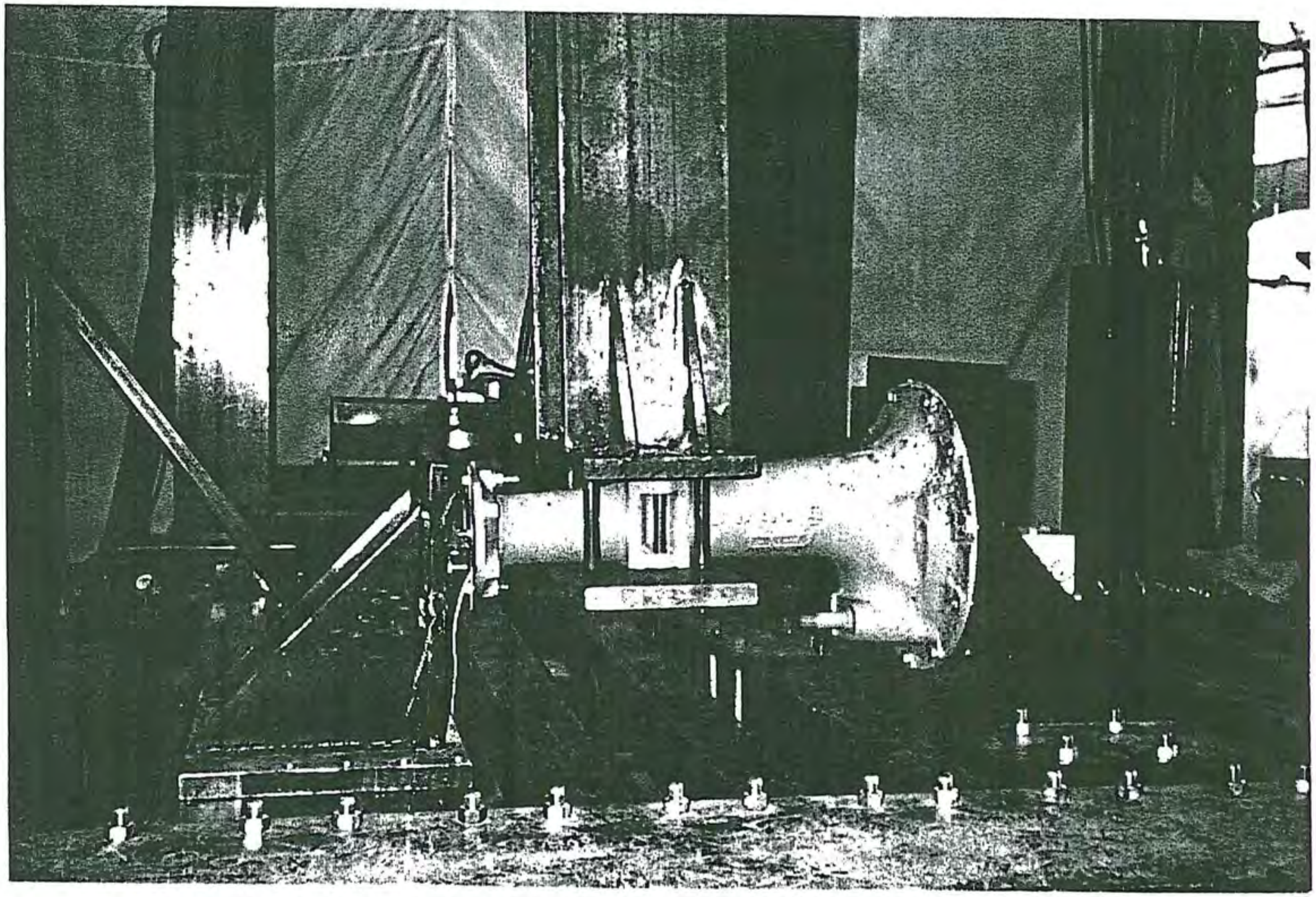

Figure 1 Apparatus for strength tests (side view)

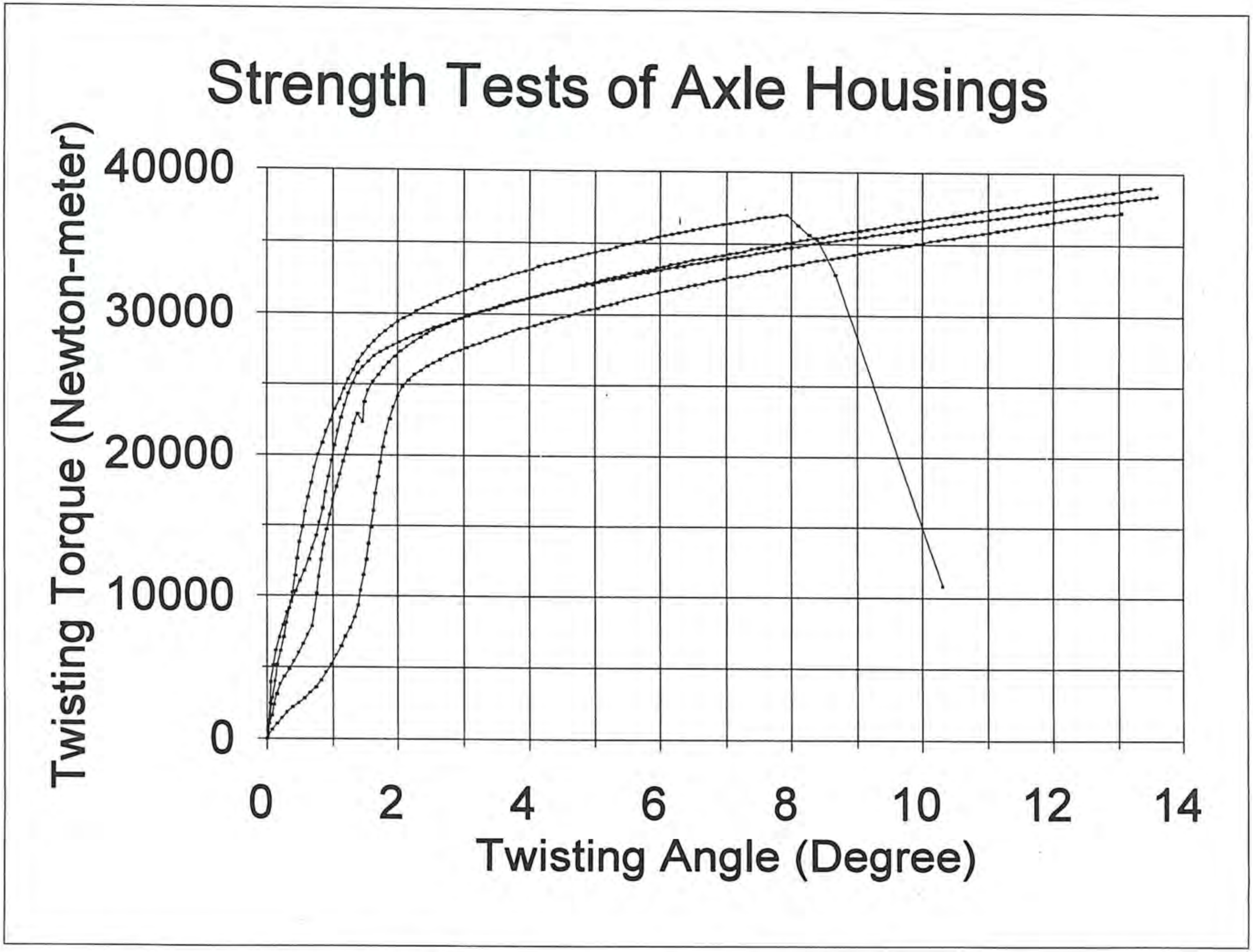

Figure 3 Laboratory tests for four sides of Ford pre-ROPS axle housings

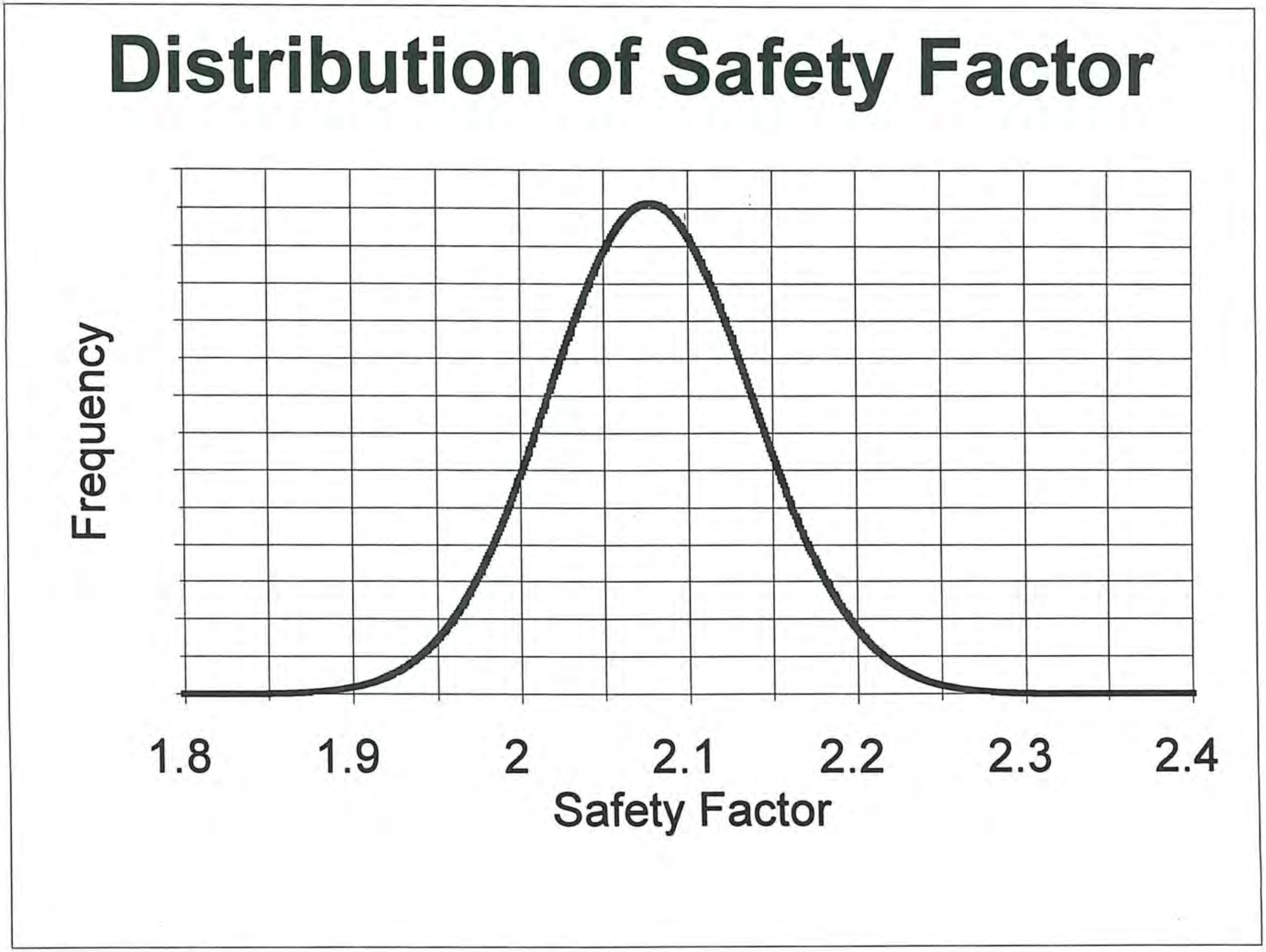

Figure 5 Distribution of safety factor

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ROLLOVER PROTECTIVE STRUCTURE (ROPS) FIELD TESTING FOR PRE-ROPS TRACTORS

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ABSTRACT

Tractor rollovers are a major cause of agricultural-related deaths each year. All new tractors are manufactured with rollover protective structures (ROPS), but many tractors produced prior to 1970 (pre-ROPS tractors) do not have ROPS as an option and were not designed to structurally support a ROPS during an overturn. The dynamic loads imposed on a ROPS/axle combination of a pre-ROPS tractor during a field upset are different from the loads imposed during the static tests. Field upset tests are critical for pre-ROPS tractors to evaluate the structural integrity of the ROPS/axle combination. Both side and rear upset tests were conducted using a remote-controlled tractor. It was determined that ROPS and mounting techniques could be developed to successfully protect an operator of a pre-ROPS tractor in the event of a rollover. Design and testing were subject to ASAE Standard S519. Both designed and retrofit ROPS were used in this study.

INTRODUCTION

Tractor overturns are a major cause of agricultural worker deaths each year. In 1991, nearly 31 percent of U.S. agricultural worker deaths were tractor-related. Of the tractor-related fatalities, 47 percent, or over 200 total, were caused by tractor overturns (National Safety Council, 1992).[1] These deaths and serious injuries might have been prevented if the tractors had been equipped with ROPS, and the operator was wearing a seatbelt.

A roll-over protective structure (ROPS) is a structural frame designed for protection of the operator in the event of a vehicle overturn. ROPS are designed to absorb energy resulting from the impact of the vehicle with the ground surface during an overturn and protect the operator from serious injury. ROPS utilization is shown to have a dramatic impact in reducing fatalities during vehicle overturns (Woodward and Swan, 1980).[2]

Required installation of ROPS has significantly reduced the tractor rollover fatalities in Sweden. In the early 1950s, Sweden began the initial ROPS design work (Bucher, 1966; Sullivan, 1975; Watson, 1967).[3,4,5] The first ROPS were made available for tractors in the 1960s and have since been included in the entire design of many tractors.

An agreement between North American tractor manufacturers resulted in all new tractors manufactured and sold after 1984 being equipped with ROPS. Also, retrofit ROPS are currently available for tractors manufactured with ROPS as an option. Although some tractor manufacturers had ROPS-equipped tractors earlier, many tractors manufactured prior to 1970 did not have ROPS as an option, and consequently, the axle mounts were not designed to structurally support a ROPS during an overturn. Such tractors are referred to as pre-ROPS tractors.

NIOSH (1993) estimates that of the 4.61 million tractors utilized in the United States, 61 percent were manufactured before 1971.[6] Many of these, but not all, are considered pre-ROPS tractors. Colorado farmers were surveyed in 1991, indicating that of 898 tractors listed, 37 percent were more than 20 years old. Of these older tractors, only 11.5 percent were equipped with ROPS. Of all the tractors in the survey without ROPS, only 46 percent had ROPS available from the tractor manufacturer. A 1988 study of West Virginia tractors revealed an average tractor age of 19.3 years (Etherton and Myers, 1990).[7] Only 7.2 percent of the tractors between the ages of 15 and 34 years are equipped with ROPS. By retrofitting farm tractors with ROPS, an estimated 2800 rollover- related fatalities could be prevented in the United States (NIOSH, 1993).[6]

Use of ROPS and seatbelts can have a dramatically positive effect on the possibility of a tractor operator surviving a tractor rollover accident. If ROPS can be successfully attached to the frames of pre-ROPS tractors, the control of this potential hazard can be attained. Fitting pre-ROPS tractors with ROPS is one of the most important safety concerns facing the agricultural industry. Reports of axle casting failures during ROPS testing and actual rollovers indicate the tractor structure and not the ROPS is the area of concern.

In many cases, ROPS are certified as passing either an American Society of Agricultural Engineers (ASAE) or Society of Automotive Engineers (SAE) standard test. The purpose of the standards is to define the test procedure and performance criteria for ROPS to minimize the frequency and severity of operator injury during a wheeled-tractor overturn (ASAE, 1992).[8]

These tests include both static and field upset tests to evaluate the structural integrity of the ROPS/axle combination. The field testing is critical for ROPS mounted on pre-ROPS tractors as the dynamic loads on the mounting components and axle could induce structural failure.

OBJECTIVES

The objectives of this study are to conduct field testing of ROPS to determine if ROPS can be successfully attached to pre-ROPS tractors. Specific objectives are as follows:

1. Develop a remote-controlled tractor to be used for field upset testing.

2. Conduct field upset testing in accordance with ASAE Standard S519 (ASAE, 1992).[8]

3. Evaluate the performance of ROPS and axle combinations under both rear and side upset tests.

FIELD TESTING FOR ROPS AND PRE-ROPS TRACTOR COMBINATION

Field upset tests were conducted to investigate the modified attachment of the ROPS to the tractor axle and the structural integrity of the pre-ROPS tractor axle. The pre-ROPS tractor is operated by remote control to allow a field upset without the operator being in danger of injury. The remote control system allows the nearest researcher (operator) to be over 15 m from the tractor during the rollover.

The remote control system is based on two normally extended pneumatic cylinders (air power). These two cylinders release the clutch and brake when an electric solenoid is activated from the remote-control box, allowing the tractor to move forward. The cylinders are oriented such that if electrical power or air pressure is lost, the clutch and brake are automatically depressed, stopping the tractor. The system also incorporates a fuel shut-off and power shut-off into the control box. A 3.78 l gas tank and sealed battery also were installed on the tractor. The steering is locked in a center position. ASAE Standard S519 testing requires that the tractor operate in a straight line.

A ROPS was designed for the pre-ROPS tractor utilizing finite element analysis, and static tests were conducted in accordance with ASAE S519. Static test results indicate the ROPS absorbs the required energy prior to reaching the failure criteria. A newly constructed ROPS of the same design was then attached directly to the tractor utilizing the fender mounts and four additional bolts with a compression fit on the axle. The plastic and elastic ROPS deflections were measured using a friction collar device specified by ASAE Stand S519.

The rear overturn bank for a rear upset test was constructed of top soil with a front slope of 60 degrees (173 percent grade). The width was 6.1 m, and the height was 2.4 m. The landing area had a cone index greater than 1500 kPa. ASAE Standard S519 was used to design the overturn bank.

The tractor was driven at the test hill at a speed of 5 km/hr using the remote-control system. As the tractor climbed the hill, it rolled over backward under its own power.

With this ROPS/axle combination, the ROPS experienced an elastic deflection of approximately 4 cm. The plastic (permanent) deflection was undetectable and considered negligible. This deflection is acceptable according to ASAE Standard requirements. It also was observed that no part of the normal operator area was intruded by the ROPS or exposed to the ground. The axle experienced no noticeable deformation or fatigue.

The side roll test was run with the same vehicle and ROPS as the rear roll test. The side overturn bank was approximately 1.5 m tall at a slope of 50 degrees. A steel ramp (specified by ASAE S519) was placed at an angle of 12 degrees from the overturn bank. The tractor was run toward the bank at a speed of 16 km/hr (maximum vehicle velocity).

The right side of the tractor climbed the ramp, the left side descended down the overturn bank, and the tractor rolled over on its side. This same ROPS experienced a side elastic deformation of approximately 3 cm and a permanent deflection of approximately 0.5 cm. This deflection also is acceptable according to ASAE Standards, and no part of the operator area was intruded or exposed.

These fields tests suggest that the designed ROPS/axle configuration for the pre-ROPS tractor is adequate to support an actual tractor rollover with regard to ASAE Standards by passing both rear and side upset tests.

A second set of field tests was performed on a retrofit ROPS. This ROPS was designed for a newer, larger tractor than the pre-ROPS tractor but was the only model from the manufacturer that attached without major modifications. The only modification necessary was four new bolts that were required to attach the fenders to the mounting plates of the ROPS. This modification did not alter the strength or mounting of the ROPS. A seatbelt was supplied with the ROPS.

The tractor was driven at the rear roll test hill at a speed of 5 km/hr using the remote-control system. As the tractor climbed the hill, it rolled over under its own power. The retrofit ROPS experienced an elastic deflection of approximately 4 cm. The permanent deflection was undetectable and considered negligible. This deflection is acceptable according to ASAE Standards requirements. It also was observed that no part of the normal operator area was intruded by the ROPS or exposed to the ground.

The new tractor and retrofit ROPS were then tested on the side roll facility. The tractor rolled over, and the elastic deflection was approximately 4.5 cm, and the plastic deflection was approximately 1 cm. No part of the zone was exposed or intruded, and there was no structural damage. These deflections also are acceptable to ASAE Standards. Field testing of a retrofit ROPS suggests that it is feasible to take a manufacturer's ROPS from a newer tractor, typically from the years when ROPS were optional equipment, and fit them to older pre-ROPS tractors.

CONCLUSIONS

Important safety devices should not be limited to new tractors. Most tractor owners find that if a machine is maintained properly, it can be useful for several decades of service. The purpose of this study is to help extend ROPS availability to older pre-ROPS tractors.

A remote-controlled tractor was constructed and utilized for field upset tests in accordance with ASAE S519. Field testing proved that the designed ROPS is acceptable to protect the operator area in the event of a rollover. The clearance zone is neither exposed to the ground nor intruded by the ROPS. It also is shown that retrofit ROPS from other vehicles can be used successfully on pre-ROPS tractors. This investigation shows that, for this particular pre-ROPS tractor, a ROPS can either be designed or retrofit to the vehicle, and field tests can be successfully completed. With proper mounting of the ROPS to the axle, the ROPS can meet the field upset requirements of ASAE S519. No structural failure of the mounting components or tractor axle were observed.

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MODEL TO EVALUATE EXPOSURE CRITERIA DURING ROLL-OVER PROTECTIVE STRUCTURES (ROPS) TESTING

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ABSTRACT. *The recently approved ASAE Standard S519 includes an exposure criteria which must be satisfied by the tested roll-over protective structure (ROPS). The exposure criteria describes a failure condition in which the clearance zone is exposed to the ground plane during a tractor overturn. A Fortran program was developed to determine if the clearance zone is exposed to the ground surface as the ROPS is deflected during the static test. The model results are compared to actual ROPS static tests to evaluate its accuracy. ROPS two-post and one-post static tests were both executed. Results from the two-post test showed the clearance zone was exposed to the ground plane at a horizontal ROPS load point deflection of 316 mm. The one-post test was more conservative and revealed exposure at 313-mm deflection. The model predicted the exposure of the clearance zone at a ROPS deflection of 340 mm. This model can assist ROPS testing when evaluating the exposure criteria.* **Keywords.** *Modeling, Safety, Tractors, ROPS.*

Safety is one of the most important tractor design factors. In 1991, nearly 31% of U.S. agricultural work deaths were tractor related. Of the tractor-related fatalities, 47% or over 200 total were caused by tractor overturns (National Safety Council, 1992). Many of these fatalities could have been prevented if the tractors had been equipped with roll-over protective structures (ROPS) and the operators were wearing seat belts (MMWR, 1993). ROPS utilization has been shown to have dramatic impacts in reducing fatalities during vehicle overturns (Woodward and Swan, 1980). ROPS are designed to protect the operator by absorbing energy resulting from the impact of the tractor with the ground surface during an overturn.

In the early 1950s, Sweden began the initial ROPS design work (Sullivan, 1975). The first ROPS were made available for tractors in the 1960s, and have since been included in the entire design of many tractors. Since 1985, the North American Tractor Manufacturers have made ROPS standard equipment for new agricultural tractors.

In many cases the ROPS are certified as passing either an American Society of Agricultural Engineers (ASAE) or Society of Automotive Engineers (SAE) standard tests. The purpose of the standards are to define the test procedure and performance criteria for ROPS to minimize the frequency and severity of operator injury during a wheeled tractor overturn (ASAE, 1992a). The tests can either be a dynamic (swinging pendulum) or static (slow ROPS deformation) test. There were some doubts that the early ASAE and SAE ROPS dynamic test standards were adequate to protect tractor operators during overturns (Steinbruegge, 1975). The static tests were considered the more viable and accurate means for ROPS testing (Ross and DiMartino, 1982). Recently, the static test appears to be the most popular and it was the primary test considered for this research study.

Earlier versions of the ROPS testing standard, ASAE Standard S383.1 (adopted March 1977 and preceded by ASAE 306.3) and SAE J1194, describe the ROPS failure criteria as intruding on the clearance zone (ASAE, 1992a; SAE, 1992a). As the ROPS is loaded and deforms, it fails when it enters the clearance zone prior to absorbing the appropriate energy requirement. This will be referred to as the "intrusion" criteria. The clearance zone defines the protected region for the operator and is usually based on the 95th percentile man allowing room for controlled movement (Ross and DiMartino, 1982). Additional failure criteria is described as exposing the operator to sharp edges.

For many years, ROPS have been tested to meet the ASAE S383.1 and SAE J1194 standards. In March of 1990 ASAE adopted a new ROPS testing ASAE Standard S519 (ASAE, 1992b). The static ROPS test section conforms to international standard ISO 5700. The SAE Standard J2194, adopted December of 1987, also conforms to ISO 5700 (SAE, 1992b). Many alterations have been added by the ASAE S519 standard including the dimensions of the clearance zone, maximum ROPS deflections, and test requirements and procedures.

The conditions of acceptance for the ROPS in ASAE Standard S519 include: (1) no sharp edges exposed to operator, (2) no parts of the ROPS shall enter the clearance zone, and (3) the clearance zone shall not be outside the protection of the ROPS (ASAE, 1992b). This third failure criteria will be referred to as the "exposure" criteria. It is not explicitly required in the previous ASAE Standard S383.1 (ASAE, 1992a). ASAE Standard S519 (Section 11) explains further that the clearance zone shall be considered to be outside the protection of the structure if any part of it would come in contact with flat ground if the tractor

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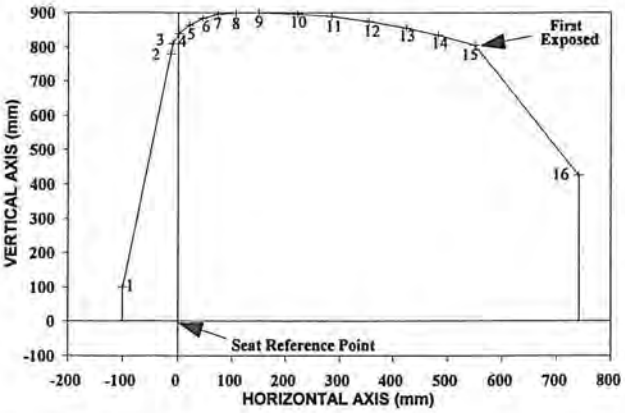

Figure 2–Check points on the clearance zone defined by ASAE S519.

that can support the tractor during a rollover, or (4) the top corner of the front tire. The ROPS point of contact with the ground plane is considered the load point during the ROPS static test. The contact point on the front of the tractor (tire or hood) will depend on the tractor dimensions and the ROPS deformation. Provisions are made in the model to select either the front hood or the front tire as the third contact point.

The model uses three of these points to create an equation of the ground plane. This equation is in the form shown in equation 1.

$$Ax + By + Cz = K \tag{1}$$

where A, B, C, and K are constants and x, y, and z are the cartesian coordinates.

The distance from each check point on the clearance zone to the ground plane is determined. This is accomplished by determining a vector normal to the plane and a vector to the point of interest (the check point). Both vectors start from the same point on the plane, which can be chosen arbitrarily. The distance is the absolute value of the dot product of the two vectors divided by the magnitude of the normal vector.

The ground plane's equation will change every time the ROPS deflects. Each time the equation changes, the distances between points on the clearance zone and the plane will be calculated. In the model, the horizontal deflection of the ROPS is incremented by 5 mm for each loading condition. A new coordinate for the ROPS contact point is calculated assuming the ROPS length is constant and the ROPS is hinged at the mounting point. Thus, for the model, the load point deflection is the same for both the one-post and two-post ROPS (in this appplication the term "one-post ROPS" is used to describe a two-post ROPS without a crossbeam). The validity of this assumption was determined using laboratory results and will be discussed later.

A flow chart of the model algorithm is shown in figure 3. The calculations continue until the distance from

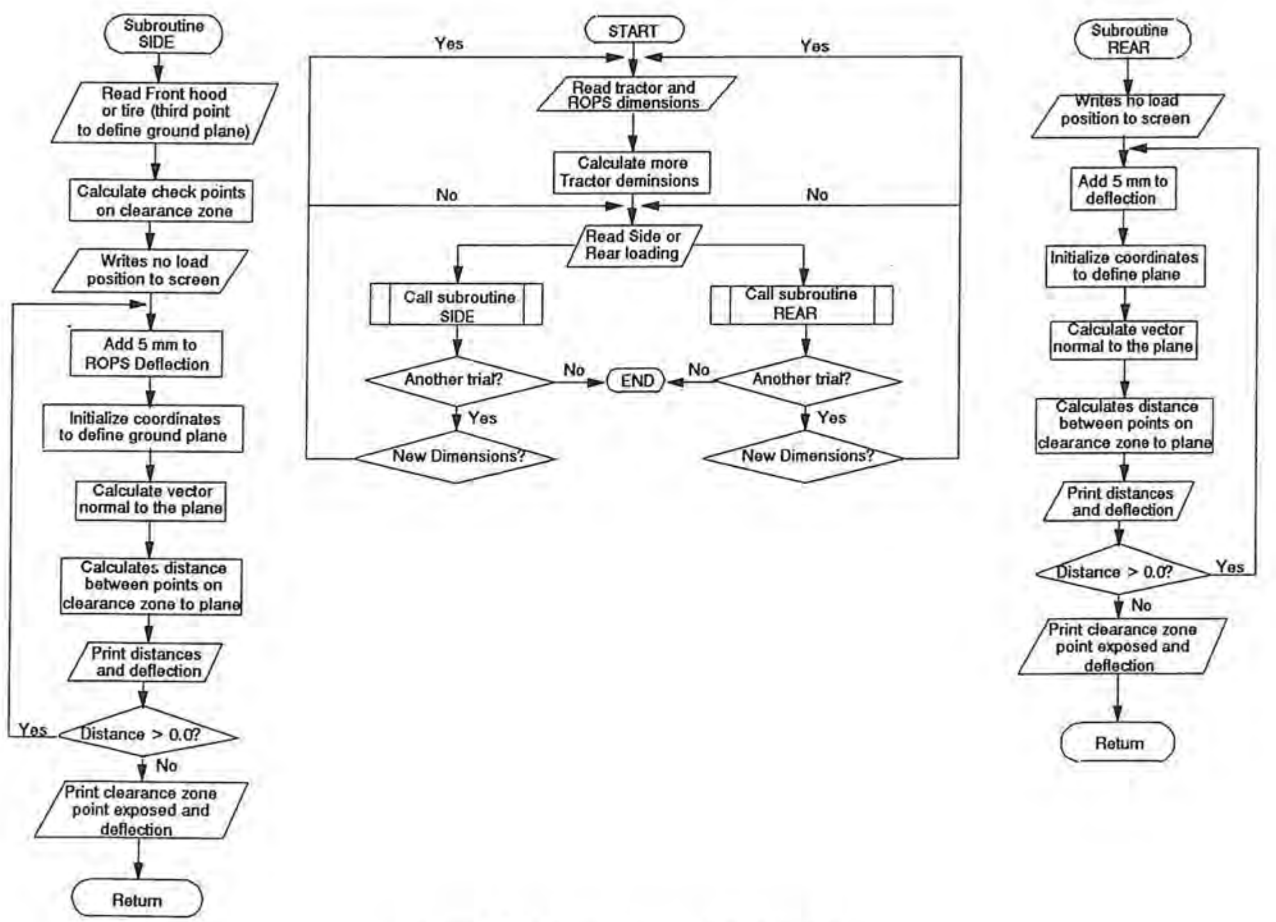

Figure 3–Flowchart of exposure criteria model.

Table 1. Comparison of test and model results

Contact	ROPS Horizontal Deflection at Exposure (mm)	
	Hood Contact Point	Front Tire Contact Point
ROPS 2-post test	316	351
ROPS 1-post test	313	330
Computer model	340	360

the front hood point rather than the front tire point. Different tractors will have different dimensions and may result in the front tire defining the ground plane. However, a majority of tractor front axles oscillate or swivel vertically in the center. For these tractors the front tire would not support the force of the tractor, thus resulting in the front hood making contact with the ground.

Using the hood as the contact point, the difference between the predicted and measured values for the ROPS deflection at exposure was 24 (7.1%) and 27 mm (7.9%) for the two-post and one-post ROPS, respectively. Although this difference is small, some of the error may be accounted for by observing the location of the ROPS load point during loading.

Figure 7 describes the location of the ROPS load point during loading for the one-post and two-post ROPS laboratory tests. Also shown in figure 7 is the model prediction of the ROPS load point using the assumption of a constant ROPS length hinged at the mounting point. It appears that for a given ROPS horizontal deflection, the laboratory results indicate the load point dropping below the model prediction. This could explain why the laboratory results indicated a smaller permissible ROPS deflection than the model results.

To evaluate the differences between the model and the test results, the ROPS height from the test was inserted in a modified version of the model. As illustrated in figure 8, at 300 mm horizontal deflection (1483 mm ROPS height), the modified version calculated a distance from the ground plane to point 15 on the clearance zone to be 13 mm. This can be compared to the normal model value (using a TOPS height of 1490 mm) of 18 mm and the two-post ROPS laboratory test measurement of 8 mm. For the ROPS

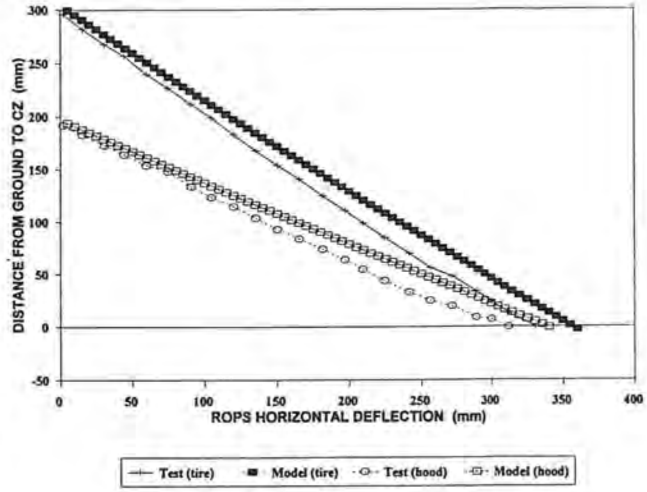

Figure 6–Model and laboratory test results from the one-post ROPS using point 15 of the clearance zone (CZ).

deflection evaluated when the actual ROPS load point was utilized in the model, the predicted distance from the ground plane to the clearance zone more closely matched the laboratory measurements. This indicates the model may more accurately predict the laboratory results if the actual ROPS height can be incorporated.

Conclusions and Recommendations

The following conclusions can be made from this study:

- A model was developed to describe the "exposure" criteria for ASAE Standard S519.
- The model proved effective in predicting maximum allowable ROPS deflections when considering the exposure criteria.
- The model results were less conservative than the laboratory results.
- Utilizing actual ROPS height measurements in the model can improve its accuracy.

For computer-assisted ROPS design, a finite element analysis can be used to generate a force versus deflection

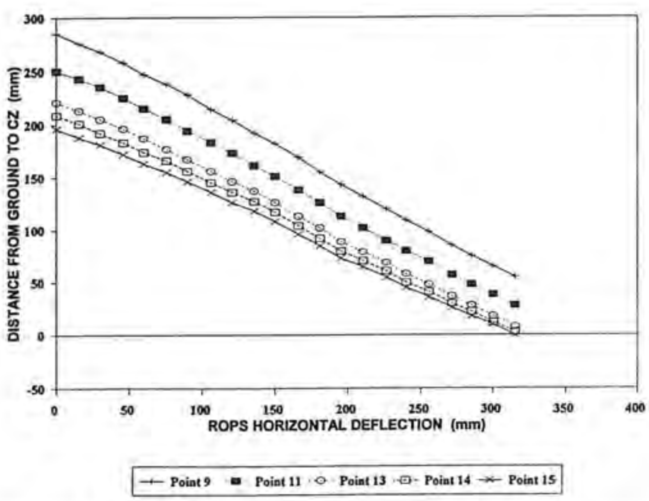

Figure 5–Measured distance from ground plane to clearance zone (CZ) using the front hood as a contact point and a two-post ROPS.

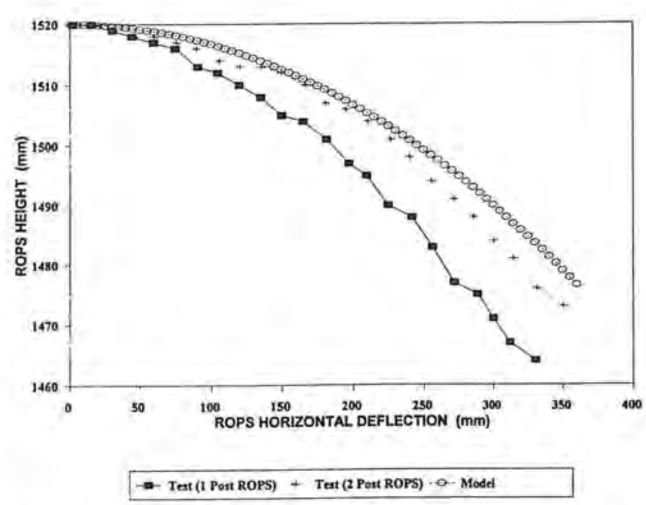

Figure 7–The ROPS load point location for the laboratory tests and model.

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Testing of Roll-Over Protective Structures (ROPS) Designed for Pre-ROPS Tractors

by

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Summary:

Tractor roll-overs are a major cause of agricultural related deaths each year. All new tractors are manufactured with ROPS, but many tractors produced prior to 1970 do not have ROPS as an option and were not designed to structurally support a ROPS during an overturn. Computer modeling, static and field tests were conducted for a ROPS designed for a pre-ROPS tractor. It was determined that ROPS and mounting techniques could be developed to successfully protect an operator of a pre-ROPS tractor in the event of a roll-over. Design and testing were subject to ASAE Standard S519.

Keywords:

Roll-Over Protective Structure (ROPS), Finite Element, Tractor Safety

Introduction

Tractor overturns are a major cause of agricultural-worker deaths each year. In 1991, nearly 31 percent of U.S. agriculture work deaths were tractor-related. Of the tractor-related fatalities, 47 percent or over 200 total were caused by tractor overturns (National Safety Council, 1992). In addition, other serious non-fatal injuries also result from overturns of tractors without roll-over protective structures (ROPS). One out of every seven agricultural work deaths in 1991 was due to a tractor overturn (National Safety Council, 1992). These deaths and serious injuries may have been prevented if the tractors had been equipped with ROPS, and the operator was wearing a seat belt.

A roll-over protective structure (ROPS) is a structural frame designed for protection of the operator in the event of a vehicle overturn. ROPS are designed to absorb energy resulting from the impact of the vehicle with the ground surface during an overturn and protect the operator from serious injury. ROPS utilization is shown to have a dramatic impact in reducing fatalities during vehicle overturns (Woodward and Swan, 1980).

Required installation of ROPS has significantly reduced the tractor rollover fatalities in Sweden. In the early 1950's, Sweden began the initial ROPS design work (Bucher, 1966; Sullivan, 1975; Watson, 1967). The first ROPS were made available for tractors in the 1960's and have since been included in the entire design of many tractors.

An agreement between North American tractor manufacturers resulted in all new tractors sold after 1984 be manufactured with ROPS. Also, retrofit ROPS are currently available for tractors manufactured with ROPS as an option. Although some tractor manufacturers had ROPS-equipped tractors earlier, many tractors manufactured prior to 1970 did not have ROPS as an option, and thus, the axle mounts were not designed to structurally support a ROPS during an overturn. Such tractors are referred to as pre-ROPS tractors.

NIOSH (1993) estimates that of the 4.61 million tractors utilized in the United States, 61 percent were manufactured before 1971. Many of these, but not all, are considered pre-ROPS tractors. Of 898 Colorado tractors surveyed in 1991, 37 percent are more than 20 years old. Of these older tractors, only 11.5 percent were equipped with ROPS. Of all the tractors surveyed without ROPS, only 46 percent had ROPS available from the tractor manufacturer. A 1988 study of West Virginia tractors revealed an average tractor age of 19.3 years (Etherton and Myers, 1990). Only 7.2 percent of the tractors between the ages of 15 and 34 years are equipped with ROPS. By retrofitting farm tractors with ROPS, an estimated 2,800 rollover-related fatalities could be prevented in the United States (NIOSH, 1993).

Use of ROPS and seatbelts can have a dramatically positive affect on the possibility of a tractor operator surviving a tractor rollover accident. If ROPS can be successfully attached to the frames of pre-ROPS tractors, the control of this potential hazard can be attained. Fitting pre-ROPS tractors with ROPS is one of the most important safety concerns facing the agricultural industry. Reports of axle casting failures during ROPS testing and actual roll-overs indicate the tractor structure and not the ROPS is an area of concern.

movement (Ross and DiMartino, 1982). When the ROPS deforms under loading, it fails by entering the clearance zone before absorbing the necessary prescribed energy. This failure is referred to as the intrusion criteria. The ROPS also may deform such that the zone is not protected from the ground. This failure is referred to as the exposure criteria. It is also required that no sharp edges be exposed to the operator in the event of a roll-over.

The second major point made is the energy requirements. Standard S519 states that for longitudinal (rear) loading, the energy required for the ROPS to absorb is as follows:

$$E = 1.4(m_t)$$

where E is the necessary energy in Joules, and m_t is the mass of the tractor in kilograms. For transverse (side) loading, the prescribed energy is:

$$E = 1.75(m_t)$$

These energy equations apply to the static testing section of the Standard.

Standard S519 describes seat belt requirements. When a ROPS is used on the tractor the safest place during a field upset is secured in the seat. A seat belt should always be used in conjunction with a ROPS. However, if a ROPS is not present, it is generally accepted that one should not use a safety belt. The theory is that an operator has a better chance of surviving by escaping the tractor rather than being between the vehicle and the ground. According to ASAE Standard S519, a "ROPS equipped tractor shall be fitted with a type 1 seat belt assembly." According to SAE Standard J141, "type 1" refers to seat belt assemblies which provide pelvic restraint (a common lap belt) (SAE, 1973). The standard also details material requirements. The standard lists Charpy V-notch impact strengths, bolt grades, carbon contents and weld requirements.

This project requires a great deal of time to complete each of the phases necessary to comply with ASAE standard S519. Each of the phases are separate from one another, while striving for the same goal. The three phases are computer modeling, laboratory (static) testing and field testing. These three phases are discussed in separate sections where the apparatus, procedure and results are presented. After all three sections are complete, they are tied back together in the conclusion section where the significance of each phase will be made clear. These three sections all focus on the design and retro-fit of a ROPS for one particular pre-ROPS tractor. In cooperation with the manufacturer the identity of the make and model are confidential.

Finite Element Modeling of Pre-ROPS Tractors

Modeling is one technique used to evaluate failure potential of the ROPS-axle combination. Previous analyses of static ROPS testing investigated nonlinear elastic and elasto-plastic failure modes (Ashburner, 1973; Brown and McNabb, 1974; Coddington *et al.*, 1991; Srivastava et. al., 1978; Wang and Talaboc, 1987). Laboratory testing of simple model ROPS has been accurately simulated with elasto-plastic modeling techniques (Srivastava *et al.*, 1978). These analytical

Preliminary laboratory static testing of the ROPS attached to the pre-ROPS tractor axle was conducted in accordance with ASAE Standard S519. The load force, ROPS deflection and absorbed energy were monitored during the tests. The ROPS post was a 3"x3"-1/4" box tube, 1.5 meters tall. The 3"x3" box tube was welded to a 1" thick plate that sat on top of the fender mounting flange holes. The post was set to the side of the mounting holes so that remounting the fender was possible. The mounting holes in the ROPS plate were centered with the existing fender mounting flange holes in the axle housing. Two grade eight 5/8" bolts and grade five nuts were used to fasten the ROPS to the axle housing using the existing fender mounts.

This static test resulted in a mounting nut failure at a ROPS rear deflection of 13.5 cm, a rear load force of 12,900 N, and absorbed energy of 1,050 J (Figures 2 and 3). The threads of the nut near the applied load were completely stripped out and left wrapped in the threads of the bolt. The bolt was not affected and appeared in good shape. The loading had to produce very high stress on the mounting bolt to result in a stripped nut. It was determined that the strength of the nut (grade 5) must match the strength of the bolt (grade 8) to be an effective fastener.

The second ROPS-axle rear load static test used the same ROPS from test one. The residual deformation from the first test was negligible. The faulty nut was replaced with two grade five nuts, resulting in twice the strength of the original nut. The test resulted in the mounting bolt near the applied load breaking at a ROPS deflection of 28.4 cm, a load force of 17,800 N, and 3,820 J of energy absorbed (Figures 2 and 3). The tensile strength of the 5/8" grade eight bolt is 621,000 kPa (90,000 psi). The bolt broke at an estimated applied stress of 586,000 kPa (85,000 psi). Again, the stresses were very high on the mounting bolt with this mounting configuration.

As the ROPS is loaded, a large torque is applied to the mounting bolts. The finite element model indicated high stress levels at the mounting point of the ROPS. It appears the mounting of ROPS to a pre-ROPS tractor axle frame cannot be performed with just two mounting bolts using the existing fender mounts.

For the third ROPS-axle static rear test, the ROPS mounting was modified from the previous tests. The same type of 3"x3"-1/4" box tube and gusset dimensions were used for the ROPS construction for this test, however, the mounting base consisted of two pieces of 9.5" x 6" -1" plate. The post was welded to the top plate, and the bottom plate was positioned on the bottom of the axle housing. A total of 12 holes were drilled in the two plates to accommodate the 6 bolts. The first two bolts were 5/8" x 8" grade eight bolts and nuts. These bolts pass through both plates and the fender mounting flange holes (identical to the first two tests). The other four bolts and nuts were 3/4" x 8" grade eight that pass through both plates on both sides of the axle housing.

The static test was intentionally stopped at a ROPS deflection of 40.9 cm, a load force of 19,800 N, and an absorbed energy of 6,250 J (Figures 2 and 3). This test resulted in no structural fracture, deformations in the axle, or bolt breaks.

The rear overturn bank for a rear upset test was constructed of top soil with a front slope of 60 degrees (173 percent grade). The width was 6.1 meters (20 ft) and the height was 2.4 meters (8 ft). The landing area had a cone index greater than 1,500 kPa. ASAE Standard S519 was used to design the overturn bank.

The tractor was driven at the test hill at a speed of 5 km/hr using the remote control system. As the tractor climbed the hill it rolled over backward under its own power.

With this ROPS/axle combination, the ROPS experienced an elastic deflection of approximately 4 cm. The plastic (permanent) deflection was undetectable, and considered negligible. This deflection is acceptable according to ASAE Standard requirements. It was also observed that no part of the normal operator area was intruded by the ROPS or exposed to the ground. The axle experienced no noticeable deformation or fatigue.

The side roll test was run with the same vehicle and ROPS as the rear roll test. The side over-turn bank was approximately 1.5 meters tall at a slope of 50 degrees. A steel ramp (specified by ASAE S519) was placed at an angle of 12 degrees from the over-turn bank. The tractor was run toward the bank at a speed of 16 km/hr (maximum vehicle velocity).

The right side of the tractor climbed the ramp and the left side descended down the over-turn bank, and the tractor rolled over on its side. This same ROPS experienced a side elastic deformation of approximately 3 cm, and a permanent deflection of approximately 0.5 cm. This deflection also is acceptable according to ASAE Standards and no part of the operator area was intruded or exposed.

These field tests suggest that the designed ROPS/axle configuration for the pre-ROPS tractor is adequate to support an actual tractor roll-over with regard to ASAE standards by passing both rear and side upset tests.

A second set of field tests were performed on a retro-fit ROPS. This ROPS was designed for a newer, larger tractor than the pre-ROPS tractor, but was the only model from the manufacturer that attached without major modifications. The only modification necessary was four new bolts were required to attach the fenders to the mounting plates of the ROPS. This modification did not alter the strength or mounting of the ROPS. A seat belt was supplied with the ROPS. It was unnecessary to laboratory test the retro-fit ROPS because it was certified by the manufacturer for a larger tractor (greater energy absorbing potential).

The tractor was driven at the rear roll test hill at a speed of 5 km/hr using the remote control system. As the tractor climbed the hill, it rolled over by its own power. The retro-fit ROPS experienced an elastic deflection of approximately 4 cm. The permanent deflection was undetectable and considered negligible. This deflection is acceptable according to ASAE standard requirements. It was also observed that no part of the normal operator area was intruded by the ROPS or exposed to the ground.

Acknowledgments

The ROPS project was largely funded by the National Institute of Occupational Safety and Health (NIOSH). All research was conducted at the Agricultural Engineering Research Center (AERC) on the Colorado State Foothills Campus.

Craig Thomas (CSU graduate) and Monte Dickson (CSU graduate student) both contributed to this effort. Their knowledge and work are greatly responsible for the completion of this portion of the project. This project would not have been possible without the help of Brian Neubauer (CSU graduate), Andy Rockwell (graduate student), Jason Lorenz (student), and the expertise of Doug Whitt (AERC Facility Supervisor).

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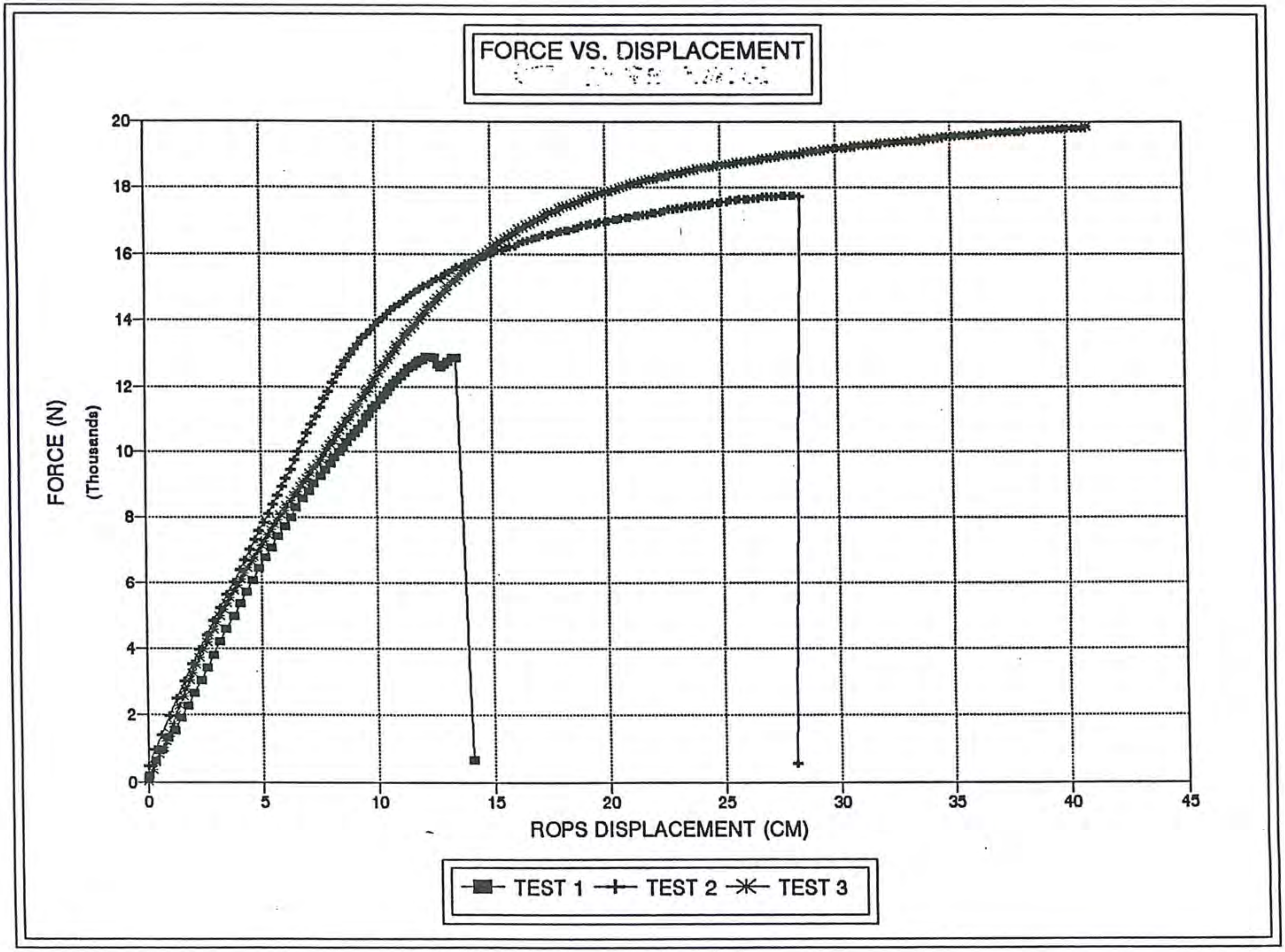

FIGURE 2. Load Force versus ROPS Displacement

PROCEEDINGS OF THE NIOSH SYMPOSIUM ON EFFORTS TO PREVENT INJURY AND DISEASE AMONG AGRICULTURAL WORKERS

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July 1994

Roll-Over Protective Structure (ROPS) Design and Testing for Pre-ROPS Tractors

By *Paul D. Ayers, Ph.D.*
Colorado State University

MR. MYERS: Our next speaker will be Dr. Paul Ayers. He is with the Department of Agriculture and Chemical Engineering at the Colorado State University. He will be giving a presentation on Roll-Over Protective Structures Design and Testing for Pre-ROPS Tractors.

DR. AYERS: Thank you, John. It is a pleasure to be here.

What I would like to report on today is some preliminary research that we are doing at Colorado State University on engineering controls. This is work that is being done at the High Planes InterMountain Center for Agricultural Health and Safety.

I think most of us understand the hazards associated with tractor over-turns. Many times it has been mentioned in this meeting that overturns are the primary cause of agricultural fatalities. I think it is safe to say that many of the fatalities or serious injuries that occur during a tractor overturn would not have occurred if a roll-over protective structure and a seat belt were utilized while operating the tractor.

Some of the survey work done at Colorado State University shows, as many states have shown, that there are many tractors out there that do not have ROPS. We conducted a survey in 1985 and in 1991 to look at the trends of ROPS availability on tractors in Colorado. What we are seeing is some of the older tractors still do not have ROPS on them, and this is the problem we are going to try to address.

We have a significant data base of 1,200 tractors from these surveys where we accumulated make and model information. Four-hundred and twenty-nine tractors were identified in the survey as not equipped with roll-over protective structures. By looking at some of the ROPS available in the country, we were able to estimate that 46 percent had ROPS available from tractor manufacturers. The tractor operators could have go out and retrofit those tractors with roll-over protective structures. However, the no ROPS are available on the remaining 54 percent of the tractors.

When looking at ROPS availability in pre-ROPS tractors, it is difficult to put an age on the tractor in terms of when ROPS were available. Some of the tractor makes had ROPS available at an earlier year, and others had ROPS available at a later year. When we are looking at finding ROPS in tractors, I use the term pre-ROPS tractors as tractors and axles were designed to support roll-over protective structures.

Here is a typical box beam with a roll-over protective structure attached. This box axle type is very common for attaching ROPS to axles. This would be what I would refer to as a post-ROPS tractor.

This, however, is an axle of a tractor that was not designed to support a ROPS. You can see that the mounting bolts there are specifically for the fender, so regardless of the age of the tractor it would be considered a pre-ROPS tractor. This is my definition of post- and pre-ROPS tractors. Based on the axle design and whether or not the tractor was originally designed to support a ROPS.

One of the problems is that there are a lot of pre-ROPS tractors with no ROPS available. In many states farmers or farm operators build their own roll-over protective structures for these pre-ROPS tractors. Some of them do a fairly decent job, and some of them do a fairly poor job using construction material that is available on their site. This is a problem I am trying to address, particularly the mounting of ROPS to axles. As you can see in this slide, some of the mounting bolts are actually missing, and if they were all there, I would question the structural capability of that roll-over protective structure to support and protect the operator during an over-turn.

The area we are trying to address is looking at the design of ROPS and the mounting structures on pre-ROPS structures. We initially looked at some computer aided design work of ROPS deflection to try to incorporate the new standards -- the ASAES 519 and SAE 2194 standards which were recently adopted involves the operator being protected and the ROPS not intruding into the clearance zone as depicted by the blue lines. Also, the ROPS standard states the clearance zone cannot be exposed to the ground surface when the tractor rolls over. We are attempting to look at those two failure criteria when designing our ROPS for pre-ROPS tractors. The concept is to look at the energy that is absorbed by the ROPS prior to (1) the ROPS intruding into the clearance zone or (2) the ROPS deflection exposing the clearance zone to the ground point.

This is an illustration of a clearance zone in blue and the ROPS deflection. We are attempting to allow the ROPS to absorb energy before the clearance zone is exposed. One way to do this is to define a ground plane using a triangle, so if this tractor had rolled to the side, it would define where the ground is located. Once the ground plane hits the clearance zone, then the ROPS fails by not absorbing the appropriate energy. We are using computer aided design to investigate the new ASAE standard for defining the exposure criteria.

We also have looked at some finite element analyses of ROPS axle designs in preliminary work, trying to define where the potential problem is, whether it is the axle housing itself or whether it is going to be the mounting area. In looking at the finite element analyses it is apparent that the major stresses occur at the mounting area in this type of pre-ROPS tractor. I repeat that we are only looking at one pre-ROPS tractor at this moment. There are a number of different axle categories, but we are investigating the bell housing type of axle.

We have a static test facility at the Agricultural Engineering Research Center in which a ROPS, shown in white here, is deflected using the static test as defined by SAE and ASAE. In this case, the hydraulic cylinder is extended and the deflection and the force on that roll-over protective structure are monitored. This determines the energy absorbed by the roll-over protective structure.

This is a single two post ROPS with no axle attachments. We calculated and measured all of these parameters, force and deflection, with a data analysis system. We were then able to mount the actual pre-ROPS tractor axle to the structure itself using the existing mounting bolts originally designed for the fender. The ROPS was attached to those mounting bolts, and a static test was run. We also instrumented with strain gauges to monitor deflections.

This is a plot of some of our test results on the pre-ROPS tractor axle. This is a plot of force applied to the top of the ROPS versus the ROPS displacement. Again, this is the displacement at which the load is being applied.

The energy absorbed by the ROPS is basically the area under the curve. The first test where we used the two mounting bolts saw a bolt failure at a very fairly low force, and thus the area under the curve is fairly small, not meeting the ASAE standards. We attempted to modify that mounting support and ran the test again. We saw another force deflection curve with a mounting failure at this point. You can see that by modifying the axle mounting, we are able to have the ROPS absorb more energy.

It was decided to continue to modify the mounting area. In the first test there were only two bolts. For this test there were a total of six bolts supporting the ROPS to the axle giving us this final test which did pass the ASAE standard with no bolt or mounting failure. That static test of the pre-ROPS tractors with the mounting modification would have passed the ASAE and SAE static testing.
Static testing is commonly used in determining whether a ROPS will protect an operator when the tractor rolls over. However, it is also recommended that either field upset or dynamic tests be conducted. Obviously, when a tractor rolls over, this static test is a fairly slow deformation type of test and really does not represent the forces on the ROPS during an actual roll-over.

The next step of the project was to conduct an actual roll-over. This is our pre-ROPS tractor with our designed ROPS. The tractor is remotely controlled. The structure in the front was put on to help protect the tractor engine.

A remote control starts the tractor, turns on the fuel, operates the clutch, and the brake. The operations are conducted using pneumatics or air pressure.

This is a picture of a pneumatic cylinder on the clutch pedal itself so we are able to slowly release the clutch pedal. On the return, it is spring-loaded so that it automatically goes down.

On the other side is a brake pedal. We do have a default, so if the cord is damaged, we do not have a runaway tractor. The brake goes on, the clutch pedal comes off, and the fuel cuts off if something does happen.

The mounting frame shown earlier has dual purposes. One, the sliding bracket is used to monitor deflection of the ROPS during the roll-over. It monitors both the elastic and the plastic deflection. In addition, this structure is designed to depict or describe the clearance zone. If that part of the structure hits the ground, it will indicate that the ground plane has intruded into the clearance zone, and the ROPS has failed the test. So it has a dual purpose of monitoring the deflection and defining the clearance zone. We conducted the field upset test. I do have a videotape of that if anybody is interested.

We did a rear upset test. Our preliminary results are the ROPS structure would have protected the operator, did not intrude into the clearance zone, nor did it expose the clearance zone to the ground plane. Those are fairly encouraging results. We were able to monitor the deflection of the ROPS at that point, so I feel fairly comfortable that if an operator had been sitting in there wearing the seat belt during the roll-over he/she would have avoided fatality or serious injury.

We do have some graduate students that we would like to put in there to test this in real life. That may encourage them to complete their research at an earlier date.

In conclusion, I would like to say that these are preliminary results in which we investigated ROPS design for just one axle category, but I think they were fairly encouraging in showing that ROPS can be designed and installed on pre-ROPS tractors to protect the operator. Thank you very much. ■

DEPARTMENT OF HEALTH AND HUMAN SERVICES

Public Health Service
Centers for Disease Control
and Prevention (CDC)

Memorandum

Date: May 31, 2001

From: Roy M. Fleming, Sc.D., Director, Research Grants Program RMF
Office of Extramural Programs, NIOSH, D30

Subject: Final Report Submitted for Entry into NTIS for Grant 5 R01 OH003163-02.

To: William D. Bennett
Data Systems Team, Information Resources Branch, EID, NIOSH, P03/C18

The attached final report has been received from the principal investigator on the subject NIOSH grant. If this document is forwarded to the National Technical Information Service, please let us know when a document number is known so that we can inform anyone who inquires about this final report.

Any publications that are included with this report are highlighted on the list below.

Attachment
cc: Sherri Diana, EID, P03/C13

List of Publications

Liu J, Ayers PD: Applications of Tractor Stability Index in Development of Control Strategies for Protective Structures. Journal of Agricultural Safety and Health. Special Issue (1): 171-181, 1998

Li Z, Ayers PD: Strength Test for Pre-ROPS Tractor Axle Housings. Journal of Agromedicine Vol. 4, No. 3/4, pp. 303-307 (Also in Agricultural Health and Safety: Recent Advances, ed. Kelley J. Donham et al., The Haworth Press), 1997

Ayers PD: ROPS Design for Pre-ROPS Tractors. Journal of Agromedicine Vol. 4, No. 3/4, pp. 3 09-3 1. (Also in Agricultural Health and Safety: Recent Advances, ed. Kelley J. Donham et al., The Haworth Press), 1997

Li Z, Ayers PD: Strength Test for Pre-ROPS Tractor Axle Housings. ASAE Paper No. 965030. ASAE, St. Joseph MI 49085, 1996

Ayers PD, Dickson M, Warner S: Model to Evaluate Exposure Criteria during Roll-over Protective Structure (ROPS) Testing. Transactions of the ASAE 37(6): 1763-1768, 1994

Johnson CK Ayers PD: Testing of Roll-over Protective Structures (ROPS) Designed for PreROPS Tractors. ASAE Paper No. 94-5003. ASAE, St. Joseph, MI 49085, 1994

Title: Investigation of ROPS Design for Older Tractors
Investigator: Paul David Ayers, Ph.D.
Affiliation: Colorado State University
City & State: Fort Collins, CO
Telephone: (303) 491-6172
Award Number: 5 R01 OH003163-02
Start & End Date: 6/1/1994–5/31/1998
Total Project Cost: $268,815
Program Area: Control Technology
Key Words:

Abstract:
Tractor overturns are a major cause of agricultural-worker deaths each year. These deaths and serious injuries may have been prevented if the tractors had been equipped with rollover protective structure (ROPS), and the operator was wearing a seat belt. Many tractors manufactured prior to 1970 did not have ROPS as an option, and thus the axle mounts were not designed to structurally support a ROPS during an overturn. If ROPS were available for these pre-ROPS tractors, then rollover protection will be more readily available and lives could be saved.

A database of tractors in use on U.S. farms (Myers and Snyder, 1995) was used to define the major axle categories for pre-ROPS tractors. The first major axle category includes the axle design for the John Deere A, B, G, 50, 60, 70, 520, 620, 720, 530, 630, and 730 tractors. This axle category consists of about 920,000 tractors sold with approximately 150,000 still in operation. The axle housings, and thus ROPS mounting locations are very similar for these tractor models. Axle drawing for these tractors have been obtained from Deere and Co. Axle housing dimensions and bolt hole locations were identified to assist in the ROPS construction guidelines.

The second major axle category selected covers the Farmall H, M, Super H, Super K 300, 400, 350, 450, 460 tractors. Again, these model tractors have very similar axle housings and axle housing drawings were constructed. Although ROPS for some of these tractors are listed as being available through Saf-T-Cab, Saf-T-Cab would like a more economical ROPS design (two post). Also, this tractor axle category makes up a large number of tractors in operation (approximately 278,000). Again, axle housing dimensions and bolt hole locations were identified to assist in the ROPS construction guidelines.

Two-post ROPS have been designed, constructed and tested for the John Deere A and Farmall M tractors. Energy calculations and allowable deflections were used along with the exposure criteria model to design the ROPS dimensions and select the material. The exposure criteria model was modified to assist in the ROPS design for the two tractors. The static lateral, longitudinal and vertical tests were conducted using the ROPS testing apparatus to ensure the requirements stated in ASAE S519 were satisfied. Both John Deere A and Farmall M tractors were purchased and modified for field upset testing. The modification includes structural support, battery protection, gas tank redesign and installation of a pneumatic power source for starting, braking and clutching. Pneumatic

tanks, control valves and cylinders were installed and are radio controlled to provide remote operation of the tractor. The ROPS deflection measuring system was installed. The lateral and longitudinal field upset sites were constructed in accordance with ASAE S519. Field upset testing was conducted for the John Deere A and the Farmall M in 1996 and 1997, respectively. The designed ROPS for both tractors satisfied the ASAE S519 test requirements.

Initially, vibrational loading was a concern when mounting ROPS on pre-ROPS tractors. However, after discussions with Dan Lockie of Saf-T-Cab, Dale Baker and Joe Oliver of Case IH, and Murray Madsen of Deere and Company, axle strength during the rear upset tests is more of a concern. The concern in the industry is the ultimate strength of the tractor axle housing when subjected to rear (longitudinal) loading. In rear loading, if the axle housing fails, the housing will rotate with respect to the axle and the operator will be crushed. To address this concern, an axle strength test apparatus was constructed. This apparatus consists of a 4-inch diameter, 24-inch stroke hydraulic cylinder attached to a 7-foot length I-beam. A torsional load is placed on the axle housing until failure or the 20,000 pound limit of the load cell is reached. The longitudinal torsional strength of 17 pre-ROPS axle housings (8 pre-ROPS model tractors) were tested. The longitudinal strength test were repeated four times for the Ford 8N and Farmall M pre-ROPS axle housings. Torsional axle housing strength test results of John Deere A, Ford 2N, Farmall H, C, 450 and 460 pre-ROPS axle housings were also obtained.

Guidelines of ROPS design which focus on axle housing support need to consider the design margin between longitudinal yield torque of the axle housing and maximum torque subjected during ASAE Standard S519 longitudinal static test. This design margin is determined to evaluate the appropriateness of the axle housing to support the designed ROPS. For example, the design margins for the Farmall M ROPS/axle housing combination is described. Static longitudinal tests conducted in accordance with ASAE S519 at Colorado State University revealed an estimated maximum torque on the axle housing as 36,000 Newton-meters. The strength torques of the four Farmall M axle housings were 51,436, 54,857, 46,520 and 49,574 Newton-meters. Their design margin are 1.43, 1.52, 1.29 and 1.38. These design margin calculations are only valid for the ROPS design tested. A change in ROPS design would likely produce a change in the design margin. The design margin of the Farmall M axle housing has a population mean of 1.41 with the standard deviation of 0.10. The 95% confidence interval of the design margin is determined to range from 1.25 to 1.57. The probability of the design margin less than one (the strength torque of the axle housing is equal to the maximum torque applied during ASAE Standard S519 longitudinal static test) is less than 0.35%. The test results indicate that the Farmall M axle housings tested can successfully support the ROPS design tested. Initial satisfactory results were found for the Ford 8N and John Deere A axle housings, encouraging commercial ROPS design for these tractors. These guidelines can be used to evaluate the appropriateness of axle housing support during ROPS design for pre-ROPS tractors.

A Fortran program was developed to determine if the operator clearance zone is exposed to the ground surface as the ROPS is deflected during the static test. The model results were compared to actual ROPS static tests to evaluate its accuracy. In actual testing the clearance zone was exposed to the ground plane at a horizontal ROPS load point deflection within 24 mm of the model prediction. This model provides guidelines in ROPS design (particularly sizing and dimensioning) when considering the evaluation of the exposure criteria as defined in ASAE S519.

Publications

Liu J, Ayers PD: Applications of Tractor Stability Index in Development of Control Strategies for Protective Structures. Journal of Agricultural Safety and Health. Special Issue (1): 171-181, 1998

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