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Development and Evaluation of a Computer- Based ROPS Design Program

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Abstract

Tractor overturn is the leading cause of agricultural fatalities in the U.S. Most of these fatalities can be eliminated using a rollover protective structure (ROPS) and a seatbelt. Unfortunately, not all agricultural tractors designed to support ROPS have ROPS designs. A computer-based ROPS design program (CRDP) was developed and successfully tested to provide quick and simple two-post, rear axle-mounted ROPS designs based on SAE Standard J2194. The program uses the tractor dimensions and mass to calculate the dimensions needed for ROPS components. Excel was used as the framework to provide the input, calculation, and ROPS drawing worksheets. Three ROPS (for Massey Ferguson 265, Long 460, and Allis Chalmers 5040 tractors) were designed and constructed using the CRDP. Static rear, side, and vertical tests were conducted based on SAE J2194 on two of the ROPS. All ROPS performance deflection (RPD) tests were less than the ROPS allowable deflection (RAD), indicating that the ROPS passed the static tests. The third ROPS was successfully mounted on the tractor axle housing within one hour, demonstrating the ease of installation using a bolted corner bracket design. Although the CRDP provided quick and simple ROPS designs, this program does not eliminate the requirement to conduct and pass the performance tests for ROPS designs specified in OSHA and SAE standards.

Keywords

ROPS; Safety; Standards; Tractor

Tractor overturn is the leading cause of occupational fatalities on farms in the U.S. (Myers and Hendricks, 2010). Rollover protective structures (ROPS) have been proven effective to reduce fatalities during tractor overturns. A ROPS, as described in SAE Standard J2194, is a protective structure designed to minimize the frequency and severity of operator injury resulting from accidental tractor upset (ASABE, 2009). ROPS are designed to absorb the energy resulting from the impact of the tractor with the ground surface during a tractor overturn, protecting the operator zone from intrusion of outside objects and exposure to the ground plane.

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While ROPS are prevalent on agricultural tractors in the U.S., an estimated 1.6 million tractors are still not equipped with ROPS. ROPS are installed on approximately 51% of all U.S. agricultural tractors, but this is not sufficient to reduce fatality rates (Loringer and Myers, 2008). Even with the current ROPS research, retrofit, and social marketing programs, ROPS retrofitting is still not progressing. Purschwitz (2008) described the difficulties and challenges in tractor ROPS retrofitting, including available ROPS designs.

A large number of tractors that were originally designed to support a ROPS do not have current ROPS designs, and thus have no ROPS availability. The costs of low-production ROPS are high, as the design costs are not spread out over a large number of units sold. In a relatively small four-county ROPS retrofitting program conducted by the New York Center for Agricultural Medicine and Health (NYCAMH), 76 tractor models and 99 ROPS requests could not be accommodated due to lack of ROPS availability (Julie Sorensen, NYCAMH, personal communication 2008). These tractors included both pre-ROPS tractors (manufactured prior to ROPS availability) and post-ROPS tractors (manufactured to fit a ROPS). Many of these tractors can be retrofitted with a two-post ROPS.

The recommendations from the National Agricultural Tractor Safety Initiative indicate that “ROPS must be available” (Reynolds, 2008). Cost-effective ROPS (CROPS) can be made quickly, using mostly off-the-shelf materials, but still need a technically valid design for a specific tractor (McKenzie and Harris, 2010). CROPS research with NIOSH has shown that ROPS designs can be simple and easy to manufacture but must be specific for each tractor model series.

Although some ROPS designs are simple, the process of designing a ROPS is not. ROPS designs require a balance of (1) material strengths and allowable deflections to meet energy criteria, (2) elastoplastic material behavior to reduce peak moments at the mounting brackets, and (3) positioning and alignment to meet appropriate operator protection. The ROPS design process is not a straightforward procedure and requires experience and engineering analysis to develop a feasible design. Once an appropriate ROPS design is developed, the construction of the ROPS, while requiring skill, is an easy process. Testing of the ROPS design is required to ensure that the design meets appropriate OSHA regulations and SAE ROPS performance standards. This testing certifies that ROPS constructed according to the design will meet the standards, but the tested ROPS cannot be used.

To assist with retrofitting of ROPS on tractors, a current need is to develop and demonstrate a computer-based ROPS design program to ensure ROPS availability for all post- ROPS tractors. The program would provide two-post ROPS retrofit designs for tractors that were originally designed to receive a ROPS but for which ROPS designs are lacking. The designs must be based on appropriate OSHA 1928.52 regulations and/or SAE Standard J2194. A computer-based ROPS design program should not require specialized or expensive software and should provide a design (and associated mechanical drawings) that is easy to construct by ROPS manufacturers and/or local custom fabricators. An inventory parts list and associated material costs would provide support to ease material acquisition and feasibility. Such a program does not eliminate the requirement to conduct and pass the ROPS performance tests specified in OSHA and SAE standards.

Previous guidelines for tractor ROPS design and construction were developed by Thomas and Ayers (1995). Their approach described the (1) material types, (2) weld quality and procedure, (3) gussets and cross members, (4) fasteners and mounting, (5) sizing of ROPS, (6) seatbelts, and (7) cost of materials associated with ROPS construction. These guidelines provided general design parameters and would need to be modified for each specific tractor. These guidelines were used to successfully design, construct, and test ROPS for five tractor models, for which previous ROPS designs did not exist, under the NIOSH R01 OH003612 project titled “ROPS Design and Testing for Agricultural Tractors” (Ayers, 1997, 2003). Mechanical drawings were developed for these ROPS designs, and several of the tractor models now have commercial ROPS available.

To assist in the ROPS design process, a model for evaluating the exposure criteria during ROPS testing was developed, validated, and implemented (Ayers et al., 1994). This model uses the tractor dimensions, ROPS mounting points, and ROPS deflection to determine the allowable ROPS deflections to meet the SAE J2194 ROPS performance standards (ASABE, 2009).

ASABE ROPS standards (SAE J2194) define ROPS design requirements and test standards (ASABE, 2009). ROPS are designed to absorb the energy of the overturning tractor prior to exposing the operator to danger. This danger comes in the form of operator exposure to the ground plane and intrusion of the ROPS into the operator zone. The ROPS design process includes parameters such as the tractor mass, dimensions, and ROPS mounting points. The energy absorption required by the ROPS is directly related to the tractor mass. Predicted energy absorption is based on the elastoplastic stress-strain or force-deflection relationships for the ROPS structure. Existing elastoplastic deformation models predict the energy absorbed during the deflection of a specific dimensioned ROPS (Easter, 1977; Woodward and Swan, 1980). However, these models only test existing ROPS designs; they do not actually design a ROPS. A computer-aided design approach (ESTREMA) has been developed to aid in the design of four-post ROPS but does not include two-post ROPS designs (Mangado et al., 2007). No two-post ROPS design programs are currently available. The objectives of this study are to develop and evaluate an Excel program to assist in the design of two-post, rear axle-mounted ROPS for tractors.

Development of Computer-Based ROPS Design Program

A computer-based ROPS design program (CRDP) was developed to quickly and effectively develop ROPS designs based on a tractor’s mass and dimensions. Based on previous ROPS design experience, the model input parameters consist of 46 tractor dimensions and the tractor mass. The ROPS designs are based on 28 ROPS dimensions. An empirical approach was used to generate relationships between the ROPS and tractor dimensions, with an example shown in figure 1. The model was derived by examining existing ROPS designs based on SAE J2194 and developing relationships with the tractor dimensions. The model parameter inputs were determined for 15 tractor/ROPS combinations with two-post rear axle housing mounts and have been included in a tractor/ROPS dimensions database.

The CRDP uses the tractor dimensions and mass inputs (example shown in fig. 2) and the derived relationships between the ROPS and tractor dimensions to define the final ROPS dimensions. The final framework for the CRDP uses Microsoft Excel. The program requires tractor dimension inputs and provides ROPS design outputs. The 28 required ROPS dimensions are incorporated into ROPS output CAD drawings (within Excel), which are used for ROPS construction. The final ROPS construction drawings are available in the CRDP. This includes drawing of the posts, crossbeam, baseplates, corner braces, and strapping, and an assembly drawing (figs. 3 and 4). The CRDP uses a bolted corner bracket design based on the NIOSH CROPS design (McKenzie and Harris, 2010; Keane and McKenzie, 2013). An assembled drawing and parts list can be generated (fig. 5). To assist in the ROPS construction, an Excel worksheet provides a material list and expected pricing (fig. 6). Steel grades are not specified; however, ASTM A500 Grades B and C, ASTM

Evaluation of Computer-Based ROPS Design Program

Using the CRDP and acquired tractor dimensions, ROPS were designed for three tractors (Massey Ferguson 265, Allis Chalmers 5040, and Long 460) and successfully constructed by a local fabricator. The Allis Chalmers 5040 and Long 460 tractors were chosen because they were identified as a common ROPS request for the NYCAMH ROPS retrofit program, and current ROPS designs were not commercially available. The Massey Ferguson 265 was selected because this tractor is currently available in-house, and the ROPS assembly and mounting could be readily evaluated. Using the CRDP, the ROPS materials were determined and acquired. The material and construction costs for each ROPS were documented and ranged from $500 to $600.

The bolted corner bracket design and the detailed axle housing bolt groove measurements provided easily assembled ROPS without the need for mounting modifications or construction. The ROPS design for the Massey Ferguson 265 was validated by successful mounting the ROPS on the rear axle housing of the tractor. ROPS mounting by untrained technicians was completed in less than one hour, without modification.

According to SAE J2194, ROPS must pass sequences of static tests, including rear, side, and vertical load tests. The ROPS must absorb predefined levels of energy during the rear and side load tests and tolerate a specific force under vertical loads, before the driver’s clearance zone is infringed by the ROPS or the ground surface. The required energy absorbed and force to resist are a function of the tractor mass (ASABE, 2009).

The ROPS performance criteria for the Long 460 and Allis Chalmers 5040 tractors are shown in table 1. The required energy for a ROPS designed for the Long 460 tractor is equal to 2844.8 J and 3556.0 J under rear and side loads, respectively. The Allis Chalmers 5040 absorbed energy must be equal to 2578.8 J and 3223.5 J for rear and side loads, respectively. The vertical force to withstand was 40,640 N for the Long 460 and 36,840 N for the Allis Chalmers 5040.

The ROPS for the Long 460 and Allis Chalmers 5040 tractors were sent to Femco Manufacturing, Inc., in McPherson, Kansas, for experimental tests. The static load tests were conducted on the ROPS using the SAE J2194 standard test procedure. The Long 460 ROPS was inadvertently tested to the energy and force requirements associated with only 90% of the tractor reference mass. These test results were extrapolated to meet the energy and force requirements for the full tractor reference mass.

Conclusion

A computer-based ROPS design program (CRDP) was developed and successfully tested to provide a quick and simple tractor two-post, rear square axle-mounted ROPS design based on SAE Standard J2194. Relationships between tractor and ROPS dimensions were established. The program uses the tractor dimensions and mass to determine the dimensions needed for the ROPS components. The program uses Excel as the framework, which provides the input, calculation, and ROPS drawing worksheets. Three ROPS were designed and constructed using the CRDP. Based on SAE J2194, static rear, side, and vertical tests were conducted on two of the ROPS. All ROPS deflections during the performance tests were less than the ROPS deflections that expose the operator zone to the ground plane or intrude into the operator zone, indicating that the ROPS passed the static tests. The third ROPS was successfully mounted on the tractor axle housing within one hour, demonstrating the ease of installation using the CROPS bolted corner bracket design. The CRDP provided quick and simple ROPS designs for tractors originally designed to support ROPS (post-ROPS tractors). This program does not eliminate the requirement to conduct and pass the ROPS performance tests specified in OSHA and SAE standards.

Acknowledgements

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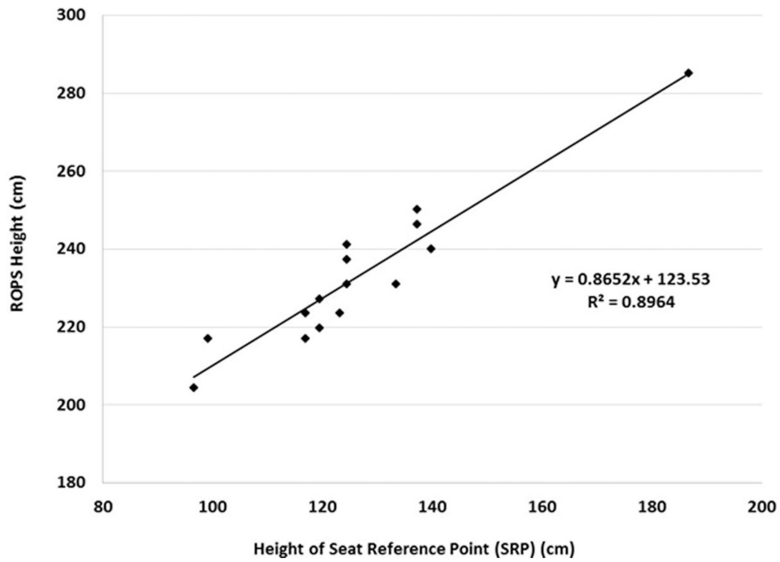
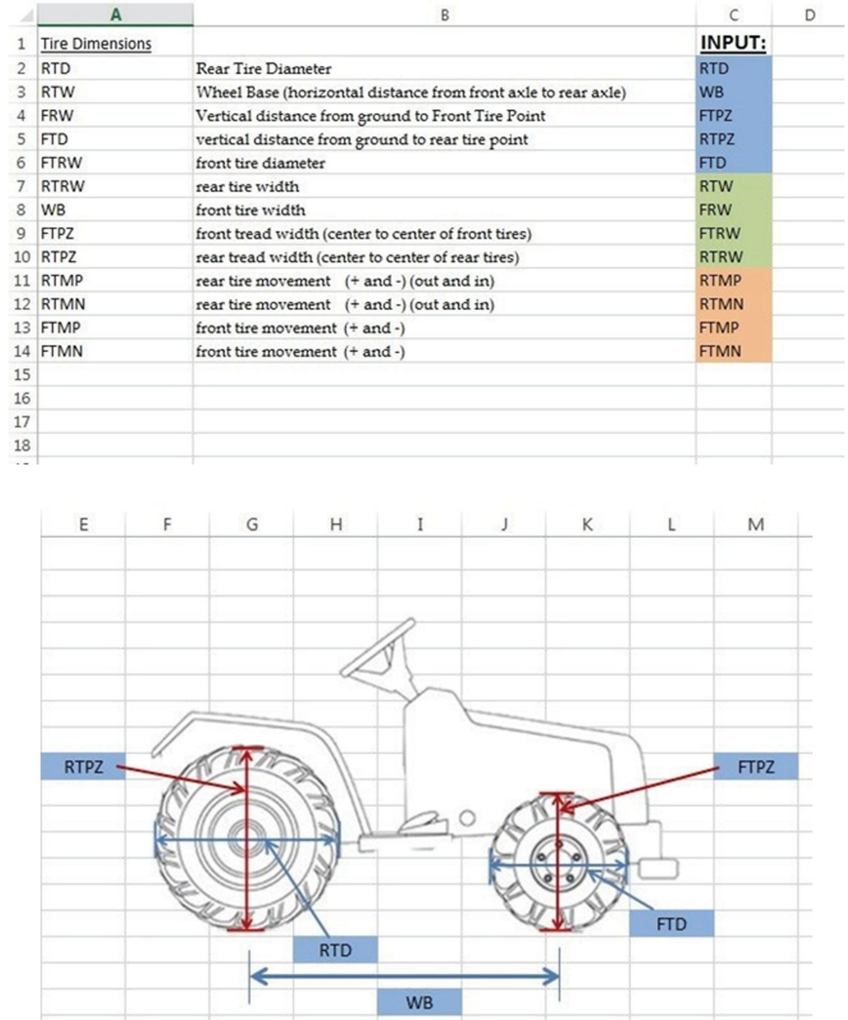


Figure 1. Example of relationship between ROPS and tractor dimensions.

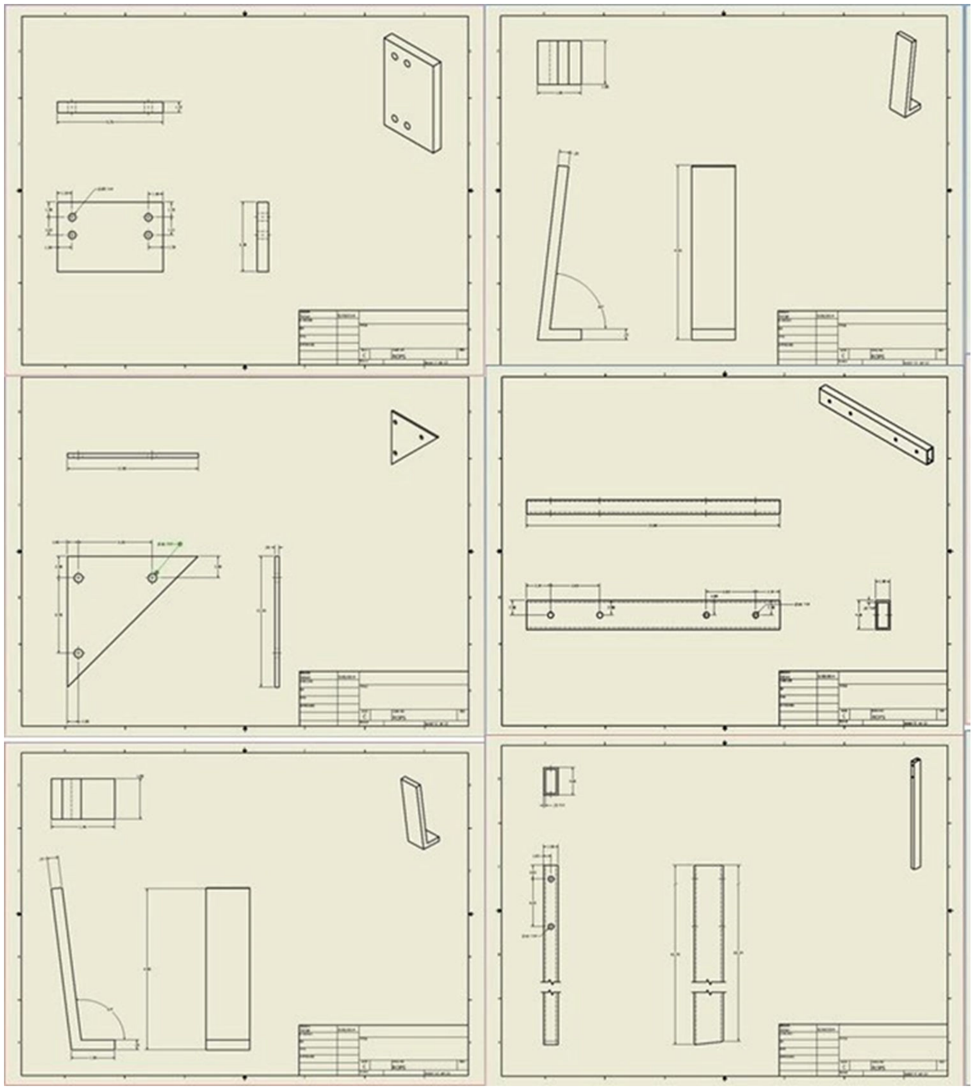
A513 Grade A, and ASTM A36 are common for ROPS construction. The steel must be either Charpy-approved or the ROPS must be cold tested.



	A	B	C	D
1	Tire Dimensions		INPUT:	
2	RTD	Rear Tire Diameter	RTD	
3	RTW	Wheel Base (horizontal distance from front axle to rear axle)	WB	
4	FRW	Vertical distance from ground to Front Tire Point	FTPZ	
5	FTD	vertical distance from ground to rear tire point	RTPZ	
6	FTRW	front tire diameter	FTD	
7	RTRW	rear tire width	RTW	
8	WB	front tire width	FRW	
9	FTPZ	front tread width (center to center of front tires)	FTRW	
10	RTPZ	rear tread width (center to center of rear tires)	RTRW	
11	RTMP	rear tire movement (+ and -) (out and in)	RTMP	
12	RTMN	rear tire movement (+ and -) (out and in)	RTMN	
13	FTMP	front tire movement (+ and -)	FTMP	
14	FTMN	front tire movement (+ and -)	FTMN	
15				
16				
17				
18				

Figure 2. Example of tractor dimension input requirements.

The ROPS allowable deflection (RAD) is defined as the maximum deflection of the ROPS without violating the intrusion or exposure criteria. The model developed by Ayers et al. (1994) was used to determine the RAD based on the tractor dimensions. The ROPS performance deflection (RPD) is determined during the static tests. The RPD is the ROPS deflection at the point at which the ROPS absorbs the predefined level of energy in the rear or side tests, or the ROPS deflection under the vertical load. In order to meet the SAE J2194 requirements, the RPD must be smaller than the RAD.



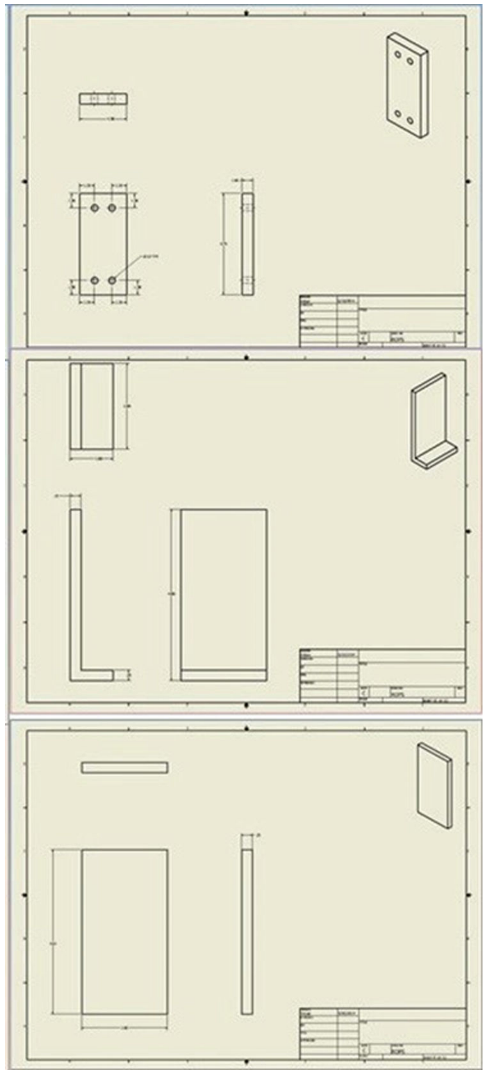


Figure 3. Example of drawings for ROPS parts.

The static side load test results for the Allis Chalmers 5040 ROPS are shown in figure 7. The area under the force-deflection curve equals the absorbed energy. In this test, the RAD is 29.5 cm and the RPD is 21.3 cm, indicating that the ROPS passed the static side load test. The static rear load test results for the Allis Chalmers 5040 ROPS are shown in figure 8. The RAD of 42.0 cm is greater than the RPD of 21.6 cm, indicating that the ROPS passed the rear load test. Similar results were found in the side and rear load tests for the Long 460 ROPS, as shown in figures 9 and 10. For the vertical tests, the Long 460 ROPS and the Allis Chalmers 5040 ROPS produced deflections of 0.7 and 2.1 cm, respectively. The RAD values for the two tractors were 7.2 and 6.8 cm, indicating that the actual ROPS deflection was lower, and the operator was protected. The ROPS deformation during the rear and side load tests revealed the accepted elastoplastic failure characteristic, without overload failure. In all tests, the RAD was greater than the RPD, indicating that both ROPS passed the SAE J2194 side, rear, and vertical tests.

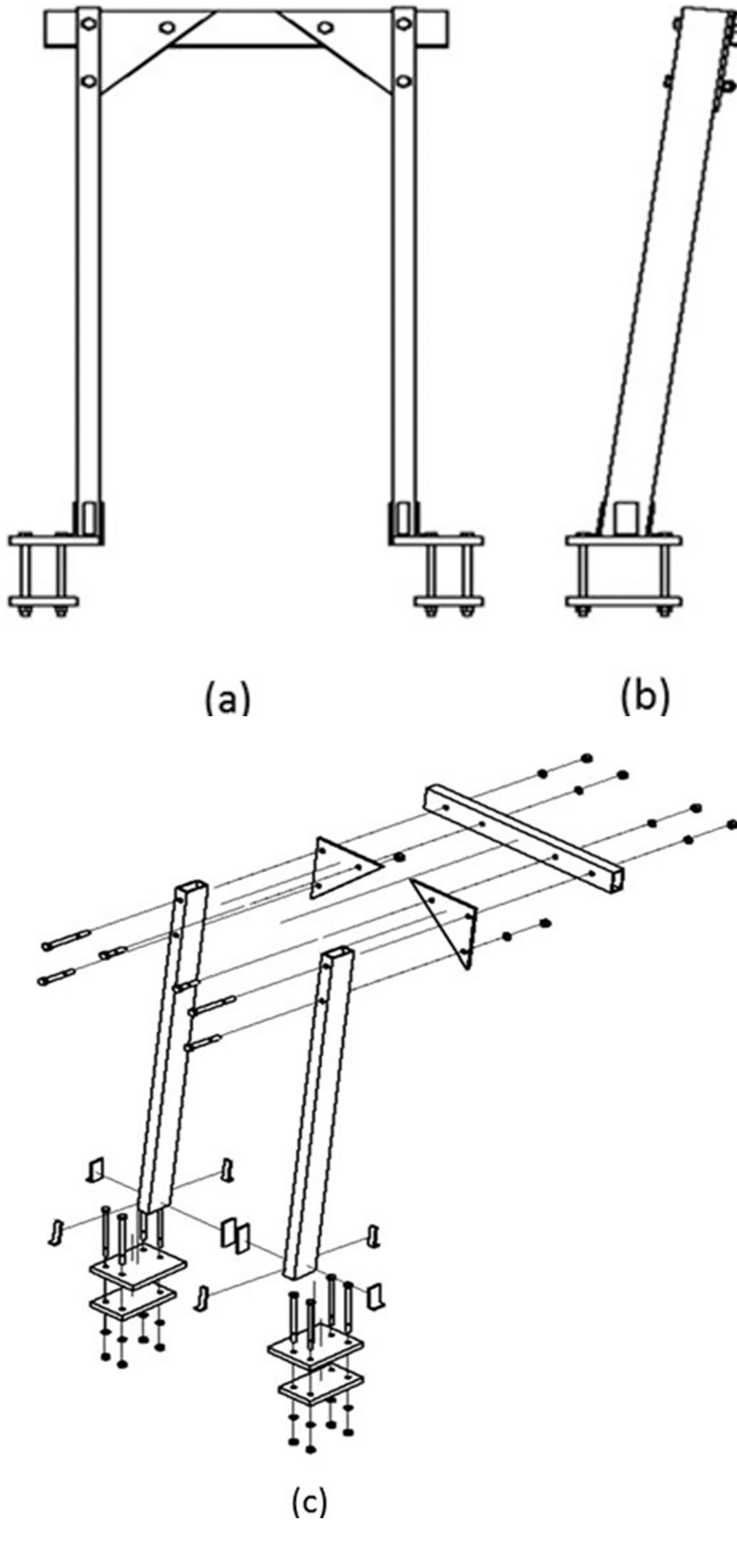


figure 4.
ROPS assembly drawings: (a) front, (b) side, and (c) exploded views.

PARTS LIST			
ITEM	QTY	PART NUMBER	DESCRIPTION
1	2	Post	
2	1	Crossbeam	
3	2	Top Baseplate	
4	2	Bottom Baseplate	
5	2	Corner Brace	
6	2	ANSI/ASME B18.2.1 - 3/4-10 UNC - 7.5	Hex Bolt - UNC (Regular Thread - Inch)
7	6	ASME B18.21.1 - 3/4	Regular Helical Spring Lock Washers(Inch Series)
8	6	ANSI B18.2.2 - 3/4 - 10	Hex Nuts (Inch Series) Hex Nut
9	2	ANSI/ASME B18.2.1 - 3/4-10 UNC - 5.5	Hex Bolt - UNC (Regular Thread - Inch)
10	2	ANSI/ASME B18.2.1 - 3/4-10 UNC - 3.5	Hex Bolt - UNC (Regular Thread - Inch)
11	2	Straight Strapping	
12	2	L Strapping	
15	8	ANSI/ASME B18.2.1 - 5/8-11 UNC - 9.5	Hex Bolt - UNC (Regular Thread - Inch)
16	8	ASME B18.21.1 - 5/8	Regular Helical Spring Lock Washers(Inch Series)
17	8	ANSI B18.2.2 - 5/8 - 11	Hex Nuts (Inch Series) Hex Nut
18	2	Acute Strapping	
19	2	Obtuse Strapping	

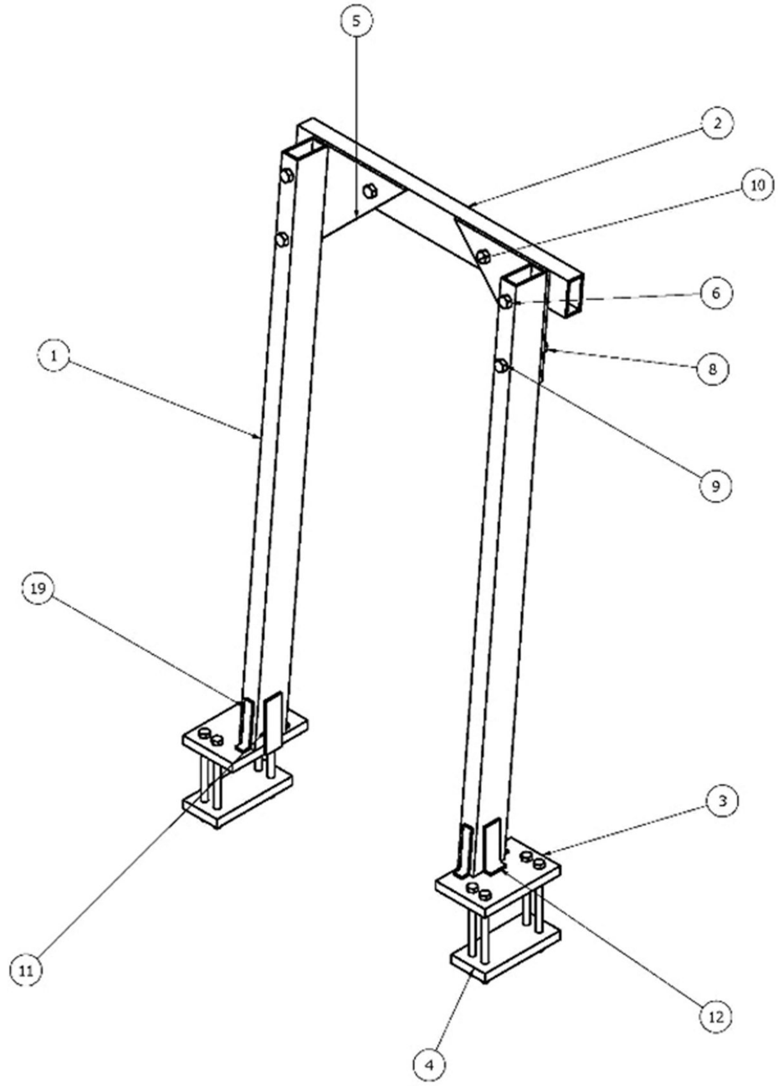


Figure 5. Example of ROPS parts list.

The intended users of the CRDP are experienced ROPS manufacturers who are familiar with the required ROPS standards and testing procedures. Material selection, mounting bolt prestress, welding quality, and manufacturing quality control are critical components not addressed in the design program.

Figure 5. Example of assembled ROPS with references to parts list.

	A	B	C	D	E	F	G
1	**Summary of Materials and Cost**						
2	Length in inches						
3	**ROPS Tubing**						
4	Quantity	Thickness	Width	Depth	Length	Part	Price
5	2	0.1875	2	3	69.8	posts	$153.48
6	1	0.1875	3	2	38.8	crossbeam	$62.28
7							
8	**Baseplates**						
9	Quantity	Thickness	Length	Width	Part		Price
10	2	0.75	8.875	6.28125	Top Baseplate		$60.69
11	2	0.75	8.875	5.8125	Bottom Baseplate		$56.16
12							
13	**Corner Braces**						
14	Quantity	Thickness	Length	Width			Price
15	1	0.375	12	12			$40.32
16							
17	**Strapping**						
18	Quantity	Thickness	Length	Width	Part		Price
19	1	0.25	20	1	Baseplate Strapping		$3.45
20	1	0.25	20	1	Baseplate Strapping		$3.45
21							
22	**Fasteners**						
23	Quantity	Diameter	Grade	Length	Part		Price
24	14	0.5	8	10	Baseplate Bolt		$86.59
25							
26						Total:	$466.42
27							
28							
29							

... | Diagram 7 | Diagram 8 | Diagram 9 | Diagram 10 | Diagram 11 | Diagram 12 | Price Calc | **Supply List and Price** | Checklist

Figure 6.

Excel worksheet with ROPS material lengths, quantities, and approximate costs.

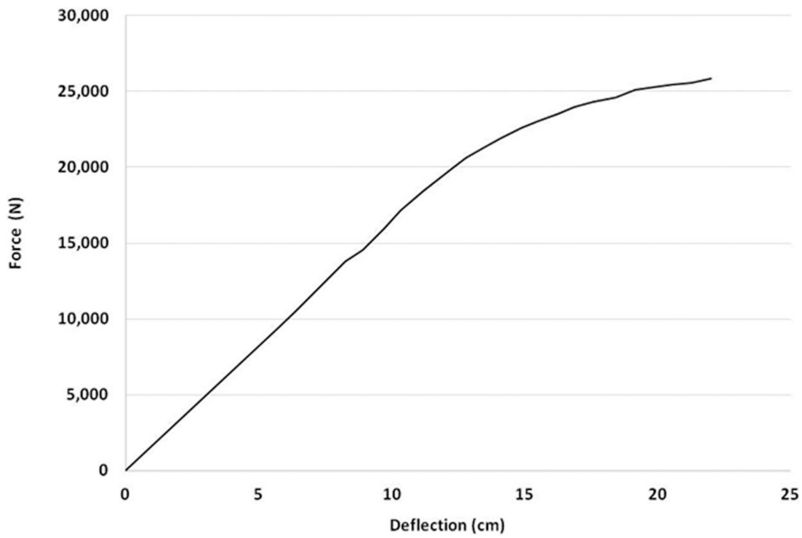


Figure 7.
Force-deflection curve for Allis Chalmers 5040 ROPS static side test.

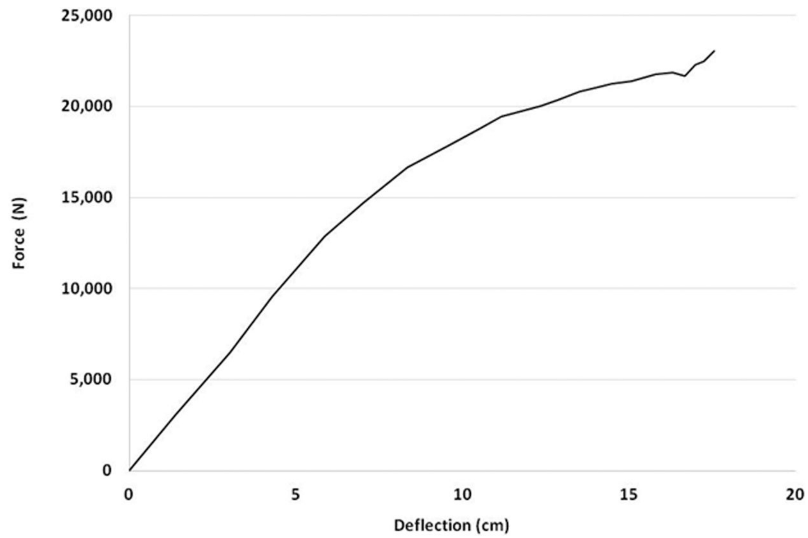


Figure 8.
Force-deflection curve for Allis Chalmers 5040 ROPS static rear test.

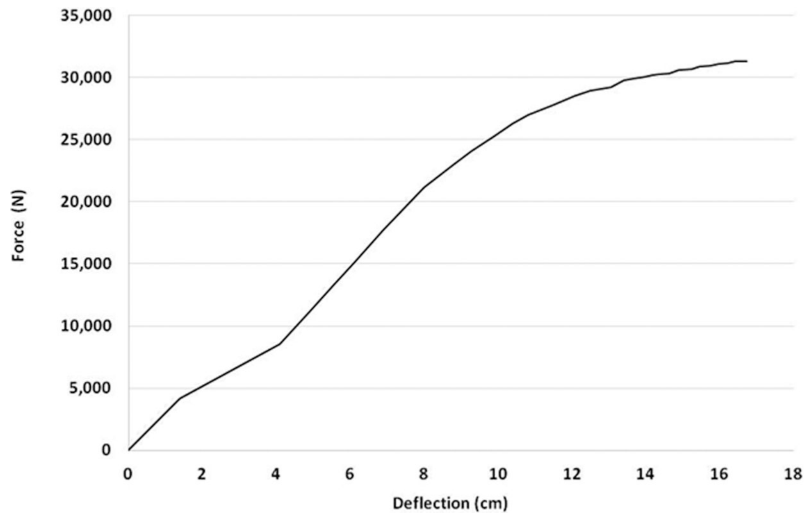


Figure 9.
Force-deflection curve for Long 460 ROPS static side test.

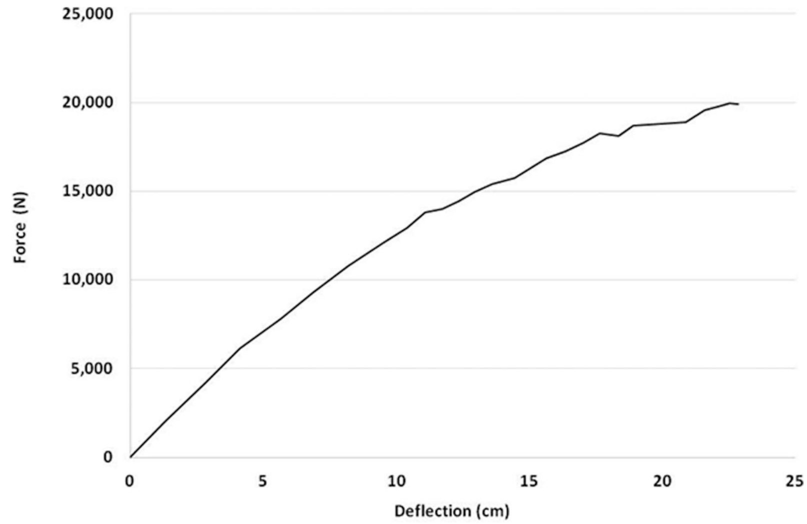


Figure 10.
Force-deflection curve for Long 460 ROPS static rear test.

Table 1.

Tractor mass, ROPS performance criteria, and performance and allowable deflections.

	Long 460	Allis Chalmers 5040
Tractor reference mass (kg)	2032	1842
Rear load test, absorbed energy (J)	2844.8	2578.8
Rear load test, RPD (cm)	18.6	21.6
Rear load test, RAD (cm)	40.0	42.0
Vertical load test, force (N)	40,640	36,840
Vertical load test, RPD (cm)	0.7	2.1
Vertical load test, RAD (cm)	7.2	6.8
Side load test, absorbed energy (J)	3556.0	3223.5
Side load test, RPD (cm)	17.8	21.3
Side load test, RAD (cm)	36.0	29.5