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SAFETY ALERT

Retractable Overhead Guards For Industrial Vehicles Without Seat Belts

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Abstract

"Struck By Overhead Guard" - an ironic tragedy. While intended to protect operators of industrial vehicles against the crushing and impact hazards associated with rollover, tip over and falling objects, Rollover Protective Structures (ROPS) and Falling Object Protective Structures (FOPS) on industrial vehicles have themselves become major instruments of death and mutilation. During vehicle rollover, operators sometimes jump, climb or are thrown from their seats into the trajectory of the guard's horizontal canopy or its uprights, whereupon these operators are crushed between the operating surface and the overhead guard. To protect operators against this contingency, the operator seat belt has become the intervention system of choice. Unfortunately, extremely low seat belt usage calls into question whether the overhead guard offers a net safety benefit. This paper introduces a new guard concept that eliminates the overhead guard hazard during rollover while maintaining falling object protection and rendering seat belts or other supplementary rollover safeguards unnecessary. The standard uprights are replaced by a midplane structural frame and the rigid canopy takes the form of a passive retractable mechanism. Also, the blind spots normally associated with the uprights no longer exist.

INTRODUCTION

Overhead guards in the forms of Rollover Protective Structures and Falling Object Protective Structures are supplied as standard or optional equipment for vehicles such as forklifts, tractors, bulldozers, compactors, turf trucks and front end loaders. These guards usually have structural uprights located on the right and left sides of the machine disposed to support a horizontal canopy located above the operator's head. When such an industrial vehicle rolls over onto its operating surface, its conventional overhead guard approaches the surface along the uprights and along the side of the canopy. Closure of the rigid guard with the surface creates an impact and crushing hazard that jeopardizes any operator who jumps or is thrown from the seat into the guard's path. Indeed, "struck by overhead guard" has become the predominant cause of death in forklift rollovers.[1] The response to this tragic and ironic circumstance was the introduction of the operator seat belt. Certainly, the simplest geometric considerations demonstrate that a seat belt can protect the operator's head and torso from the overhead guard during a rollover. Testing of forklifts reveals that occasionally a limb will be pinched by an upright.[2] On unimproved operating surfaces, the seat belt provides an effective countermeasure. The seemingly intractable problem is the low compliance with seat belt usage requirements on industrial vehicles. This has given rise to the following dilemma: Is it safer to provide no overhead guard protection or to provide it knowing that seat belt usage is low?[3,4]

From a designer's point of view, the issue is resolved if a value system, such as a safety code or standard, mandates an Overhead Guard/Seat Belt combination. On the other hand, without permission from a value system, an individual designer or manufacturer should not adopt the Overhead Guard/Seat Belt set as standard equipment.[5,6] To do so violates the Dangerous Safeguard Consensus because it introduces new hazards into the vehicle.[7] For some industrial vehicles it has not been established that the Overhead Guard/Seat Belt countermeasure leads to a net safety benefit.

PROPOSED GUARD CONCEPT

The overhead guard shown in Fig. 1 is one of the "proof of concept" designs used in our studies. Safety is achieved by eliminating the overhead guard crushing hazard. The proposed concept accomplishes this using four design elements: a midplane upright post with rollover struts, a midplane cantilever beam supporting the overhead canopy, a canopy mechanism and a passive canopy retractor.

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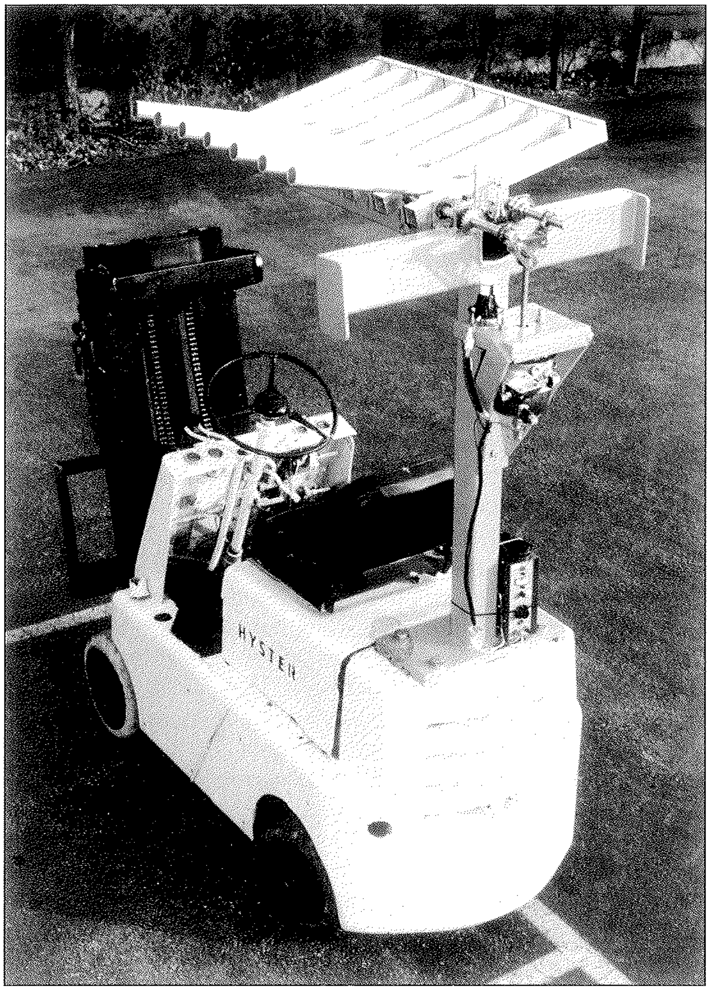
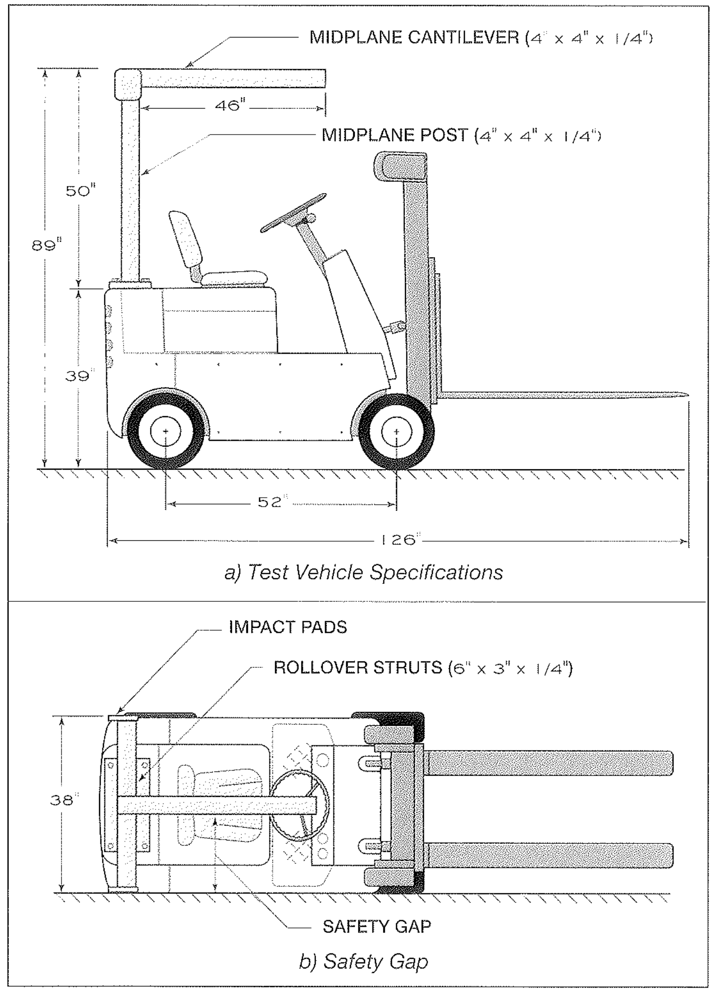


Figure 1 – Midplane Overhead Guard



a) Test Vehicle Specifications

b) Safety Gap

Figure 2 – Hyster Forklift with Midplane Structure

A. Midplane Upright with Rollover Struts

Figure 2 illustrates a candidate overhead guard mounted on the counterweight of a Hyster forklift from which the canopy has been removed. When viewed from the rear, the post and the rollover struts appear as a "T." The transverse rollover struts are fabricated with end pads to distribute concentrated impact loads to the operating surface and to act as skids or sliders if longitudinal motion occurs concurrently with overturning. When a forklift rolls over onto a hard surface, the machine exhibits the orientation shown in Fig. 2b, where we observe the "safety gap" formed between the surface and the lowest portion of the post and the midplane cantilever. This gap is approximately equal to half of the vehicle width; clearly, crushing cannot occur. The absence of the conventional overhead guard uprights virtually eliminates any crushing hazard and any blind spots associated with them.

In general, the midplane post and cantilever must be proportioned to resist the FOPS and ROPS loading specifications associated with a specific vehicle application. In the case of a forklift there are no ROPS requirements or specifications since the mast will resist overturning; however, because the mast is inboard of the frame it will not restrict the rollover angle to 90°. Indeed, using blocks to artificially extend the effective width of the mast to the overall width of the forklift still did not restrict the rollover angle to 90°. Our testing demonstrated that the mast was too flexible in the lateral direction.

Using the T-Frame shown in Fig. 3, the Hyster test forklift was repeatedly overturned laterally onto a concrete pad. The forklift was slowly pulled to its balance point and released. In each test the maximum rollover angle was approximately 90°; a permanent set of 2–1/8 inches was measured along the centroid of the rollover strut as indicated in Fig. 3 after a single rollover. No cracks were observed, no repairs were performed and no penetration into the Deflection Limiting Volume (DLV) was suffered [see Appendix A]. The photograph in Fig. 4 shows the midplane frame after rollover; little frame distortion is observable. The safety gap, so essential to the proposed overhead guard concept, is clearly portrayed.

If a midplane frame is mounted on a wheel loader, specifications for ROPS service are described in the Society of Automotive Engineering standard SAE J1040 May 94. Table I applies the SAE specifications to an 8000 pound machine; the performance of the proposed midplane frame is calculated in Appendix B using limit analysis. Table I indicates that the overhead guard exceeds the SAE resistance specifications.

B. Midplane Cantilever

As the name implies, Falling Object Protective Structures must resist the impact of falling objects. In the case of a high lift rider powered industrial truck, the American National Standards Institute has characterized the overhead guard's load environment in the "Safety Standard for Low Lift and High Lift Trucks," ASME/

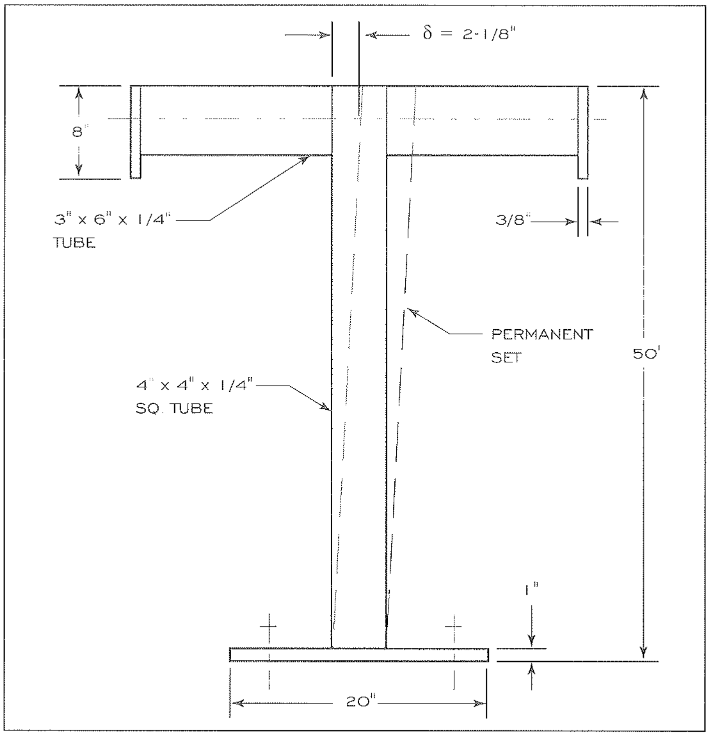


Figure 3 – Rear Elevation - Midplane Frame After a 90° Vehicle Rollover

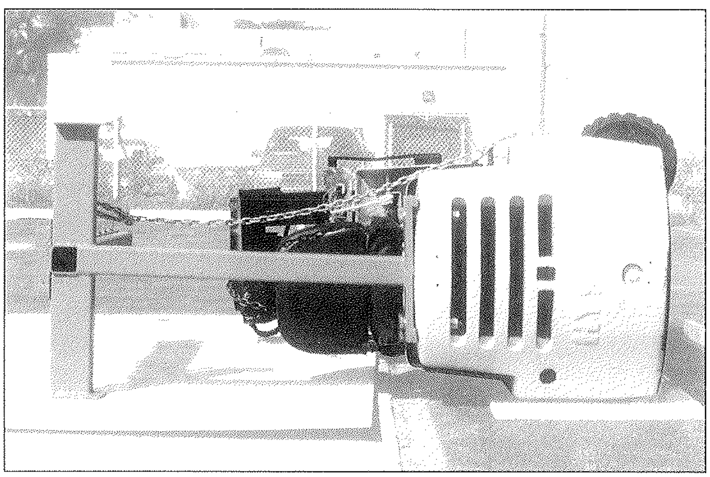
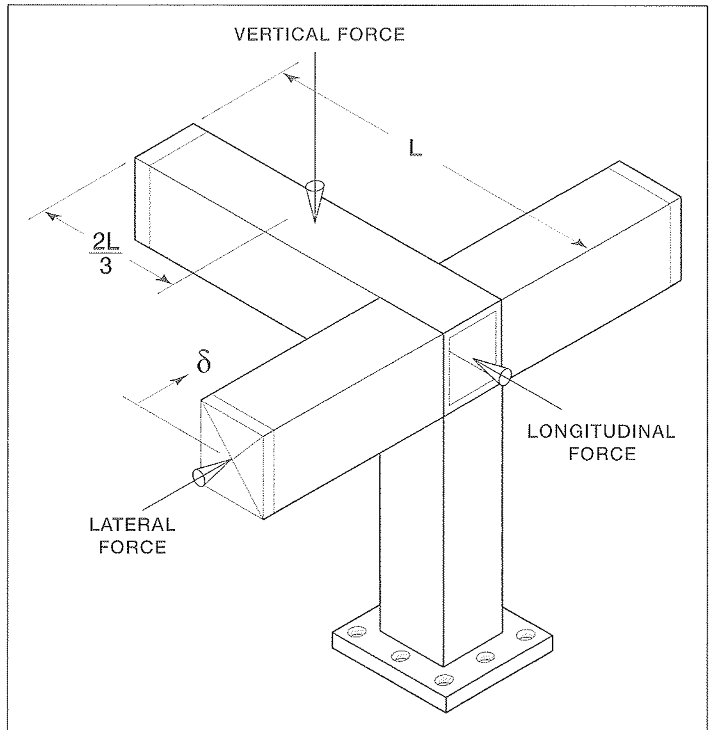


Figure 4 – Midplane Frame After Rollover - No Canopy

*Table I – Specifications for Overhead Guard**



Overhead Guard	SAE Spec. J1040 May 94	Midplane Frame (Calculations)
Machine Mass	3629 kg (8000 lbs)	3629 kg (8000 lbs)
Lateral Force	4895 lbs 21,772 N	5,169 lbs 22,993 N
Vertical Force	15,997 lbs 71,159 N	16,564 lbs 73,680 N
Longitudinal Force	3916 lbs 17,418 N	5,169 lbs 22,993 N
Lateral Energy	2,597 ft-lbs 3,520 Joules	

* Specifications cover Wheel Loaders, Wheel Tractors, Skid Steer Loaders, Backhoe Loaders and Wheel Log Skidders

ANSI B56.1-1993; sections 7.27.1 and 7.27.2. The standard requires a Cube Drop Test and an Impact Drop Test. The midplane cantilever directly addresses the Impact Drop Test; for the Cube Drop Test it acts in a secondary capacity as the foundation for supporting various candidate canopies.

In order to pass the Impact Drop Test, the overhead guard must withstand the impact of a bundle of 12 foot long 2″x4″s that has been dropped from a height that will generate a specified potential energy. Figure 5 shows a 1500 lbs. test load, 40 inches wide, that had been dropped onto the midplane cantilever from 5–1/3 feet. This produced a kinetic energy of 8000 ft-lbs. which the standard requires for a forklift with a 5000 lbs. rated capacity. The photograph in Fig. 5 captures the moment of impact. The test procedure reflected the protocol described in sections 7.27.1 and 7.27.2 of the B56.1-1993 standard. Figure 6 shows a photograph of the side elevation of the test vehicle after the 8000 ft-lbs. drop with four dimensions superimposed:

1. Height over the top of the steering wheel; 14-1/2 ″
2. Height over the Locating Point (LP) [Appendix A]; 38-3/8 ″
3. The permanent tip deflection; 10-1/2 ″
4. Distance from the post to the front of the seat back; 10 ″

Comparing these dimensions to the clearance shown in Fig.14 in Appendix A, it is clear that the DLV is never invaded. The B56.1 Drop Impact Test is satisfied by the "proof of concept" overhead guard.

C. Canopy Mechanisms

In contrast to conventional canopy structures, our proposed canopy is a mechanism that retracts or withdraws during a rollover

Figure 5 – Impact Drop Test

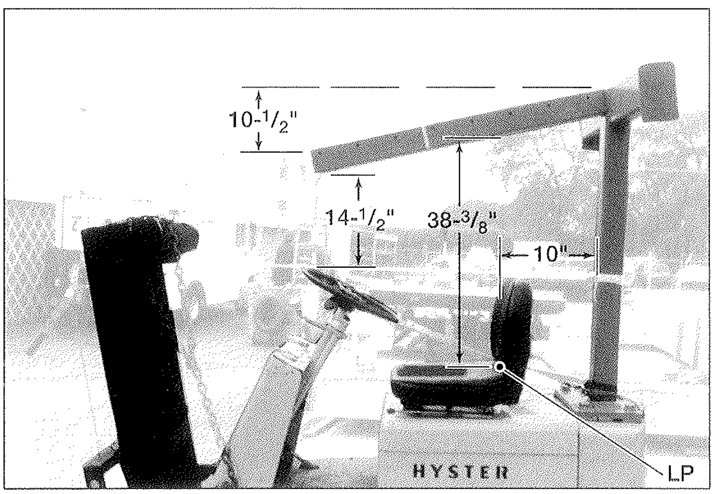


Figure 6 – Side Elevation After 8000 ft-lbs. Impact

scenario so as not to pose an impact or crushing hazard to escaping operators. Various concepts for retractable canopies are illustrated in Figure 7. The one chosen for our "proof of concept" study is shown in Figure 1. The left half of the canopy is comprised of a parallel array of hinged aluminum circular tubes (2 inch diameter x 3/16 inch wall thickness). Each will behave as a statically determinate beam when loaded in a downward direction and as a single degree of freedom mechanism when loaded in an upward direction. The right half of the canopy is a grillage formed by parallel square aluminum tubes (2 inch by 2 inch by 3/16 inch) that are hinged to the midplane cantilever on one end and are captured by a perpendicular channel at the other end. During a rollover, either the tube array or the grillage rotates upward (relative to an upright vehicle) by the action of the retraction system. This maintains a safety gap after the side of the vehicle impacts the ground.

To satisfy the requirement for a forklift FOPS, the canopy must withstand the ANSI B56.1-1993 Cube Drop Test, paragraph 7.27.2 (b). A one foot hardwood test cube weighted to 100 pounds (45kg) is dropped 10 times from a height of 5 feet (1,500 millimeters) onto the canopy. The cube must randomly strike the canopy with a flat surface within a 24 inch (600 millimeters) diameter circle over the operator's head without producing separation fractures and without exceeding 0.75 inches (18 millimeters) of permanent intrusion into the original head clearance. Figure 8a shows the test set up for a Cube Drop Test; Figure 8b shows the plan view of the test canopy after the test was completed. No fractures were observed and the maximum observed deformation did not intrude into the original head clearance. The round and the square canopy tubes both satisfied the standard.

D. Canopy Retraction Systems

There are, of course, an unlimited variety of energized systems that may be employed to remove, shift, or retract canopies during a rollover event. The idea is to prevent the canopy from entering the safety gap. To demonstrate the feasibility of this notion, two systems were fabricated for rotating canopies out of harm's way; a preloaded spring system and a counterweight system. Each of these cause the canopy rod shown in Figure 9 to rotate clockwise and lift the canopy elements or arms. Note that the individual arms may also be lifted by an external vertical force.

Figure 10 illustrates the elements of a preloaded spring system retrofitted on a Hyster forklift. A spring actuated parking brake chamber is used to pull downward on a simple linkage that rotates the canopy rod on the left in a clockwise direction (the canopy rod on the right rotates in the opposite direction) when the chamber is pressurized with air. The canopy is now deployed to act as a FOPS. Releasing air pressure from this fail to safety parking brake allows the spring to mobilize rotating the left rod counterclockwise and the right rod clockwise; a ratchet and pawl precludes backward rotation. This retracts the canopy, establishing and preserving the safety gap. A standard electric tilt switch used in aerial lifts provides the activation signal to a solenoid operated air dump valve that exhausts the air from the brake chamber. Two stages of a dynamic rollover test are captured in Figure 11. At a rotation angle of 10°, the tilt switch causes the lift system to deploy as shown in Figure 11a; this angle may be set at any desired value. The resting geometry of the canopy and the mid-plane frame is shown in Figure 11b where the safety gap is shown.

As depicted in Fig. 12, a counterweight system has been affixed to the canopy rods in lieu of the preloaded spring retraction system together with a double ratchet and pawl which constrains each rod's rotation to a single direction. Theoretically, the counterweights maintain the orientation of the canopy elements throughout a forklift rollover excursion. This was approximated in the static rollover test in Fig. 13. When the forklift assumes its full rotation, the safety gap is free of intruding canopy elements as shown in Fig. 13.

The exclusion of canopy elements from the safety gap was demonstrated by both static and dynamic rollover tests of the counterweight system and preloaded spring system. With one exception, the results of the static and dynamic rollover tests were similar. During the dynamic rollover tests, the impacting ROPS gave rise to transient elastic vibrations of the canopy

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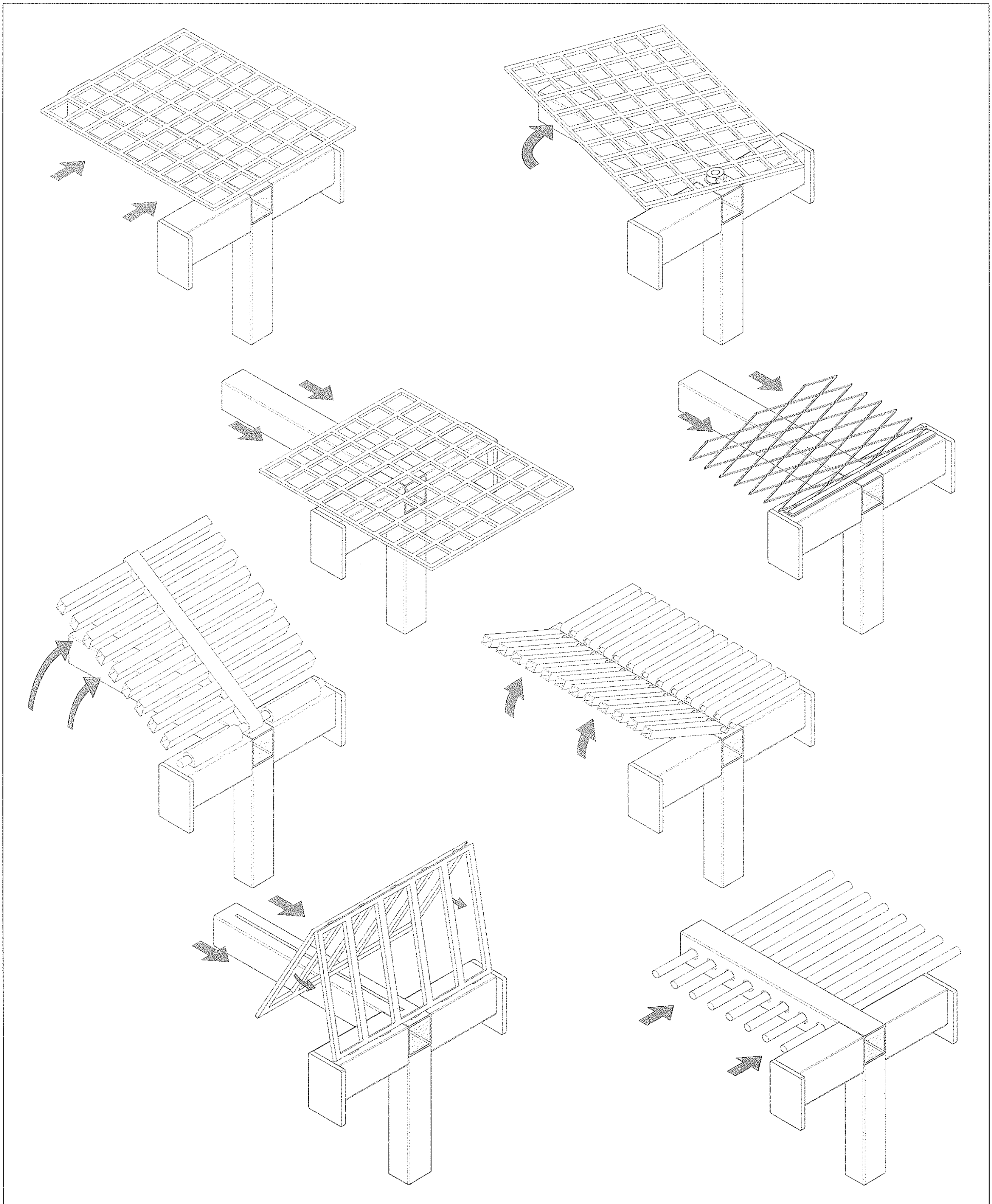
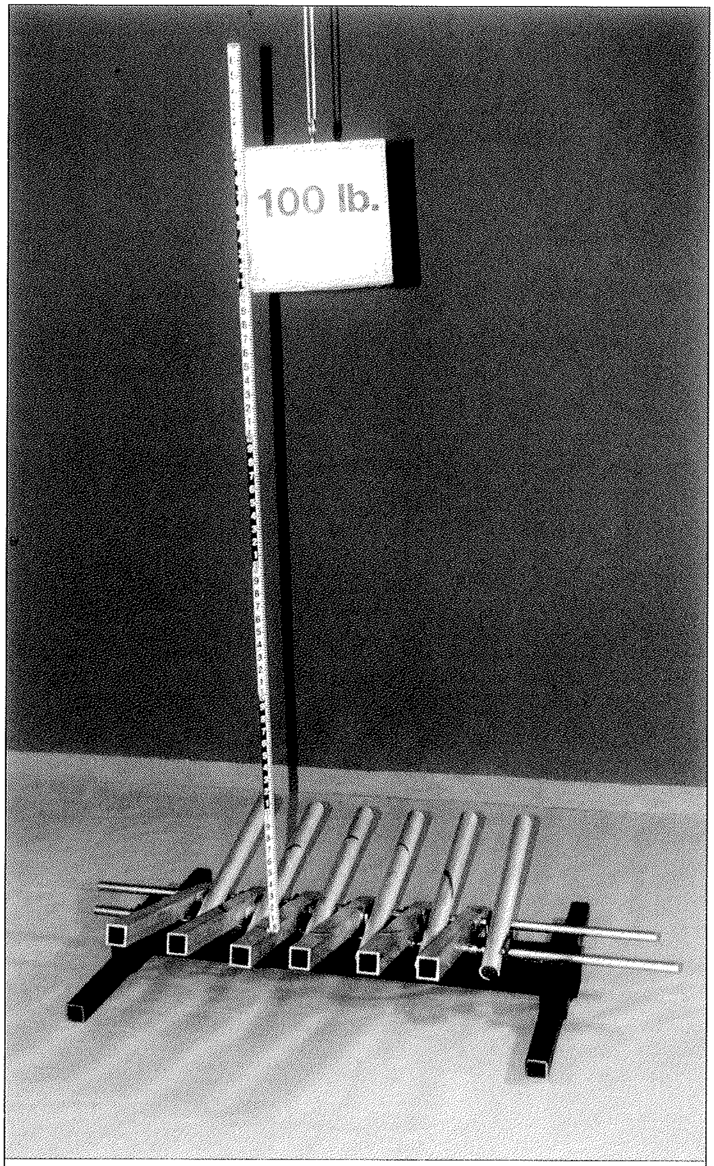
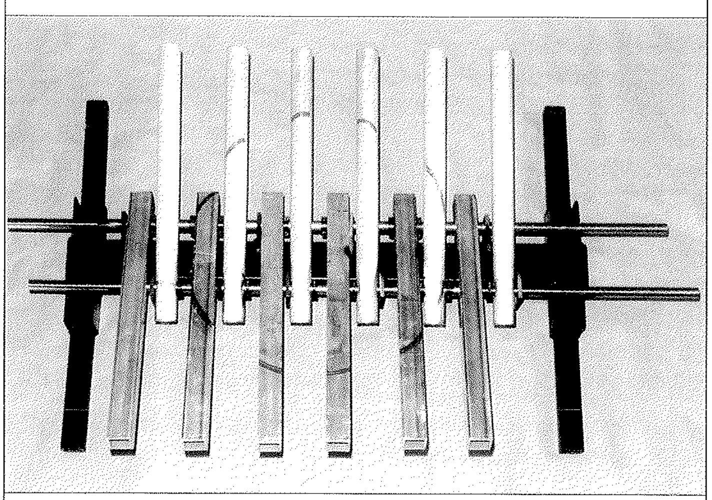


Figure 7 – Various Removable Canopy Concepts



a) Test Set Up



b) Plan View of Dual Canopy

Figure 8 – Cube Drop Test

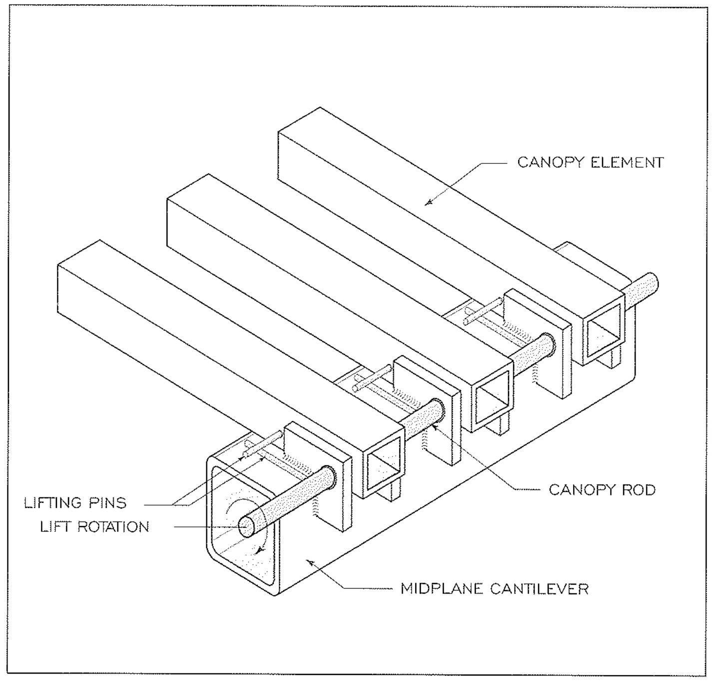


Figure 9 – Canopy Lifting Elements

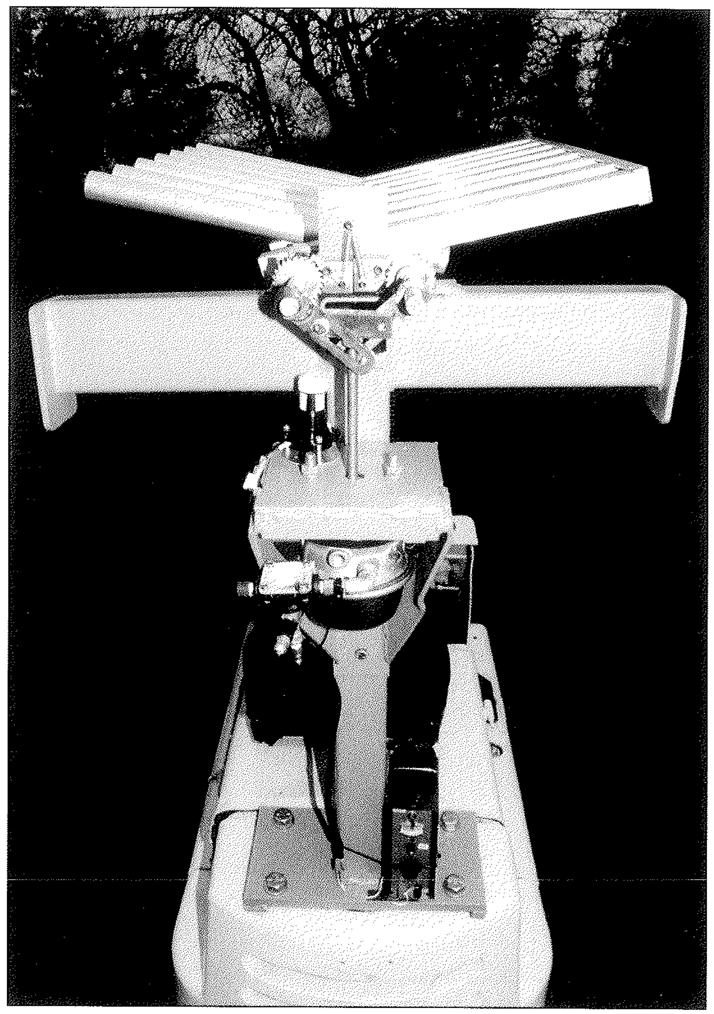
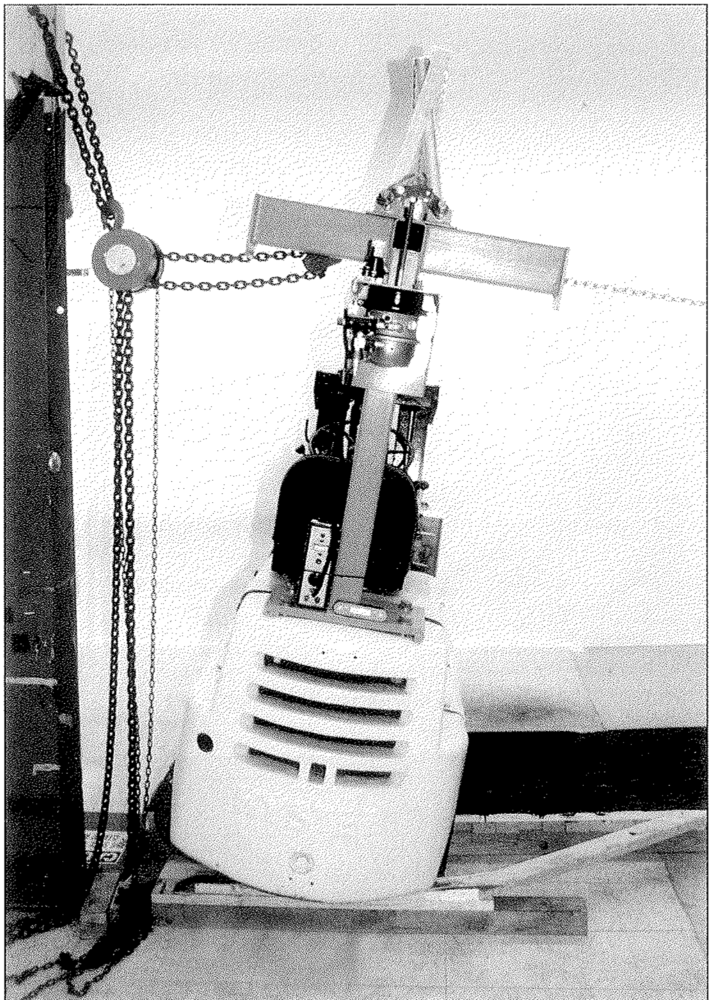
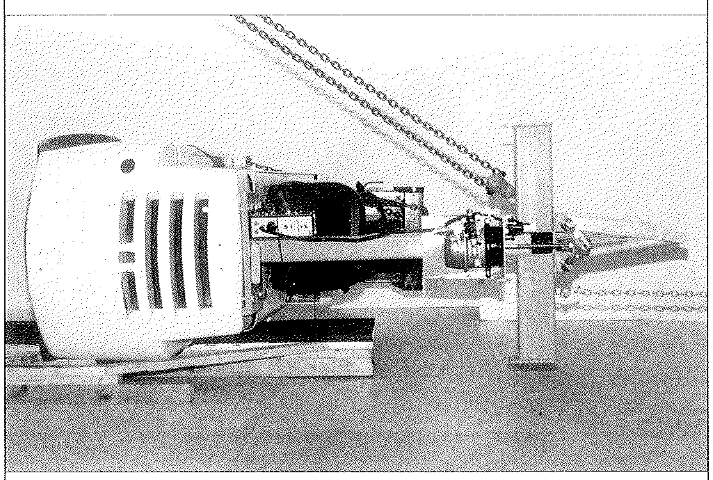


Figure 10 – Components of a Preloaded Spring Retraction System



a) Canopy Retraction Angle



b) Resting Configuration After Rollover

Figure 11 – Passive Preloaded Spring Canopy Retraction System

elements. The associated amplitudes are controlled primarily by the stiffness of the rods, lifting pins, and ratchets. The crushing hazard associated with the overhead canopy was completely eliminated by the two "proof of concept" designs.

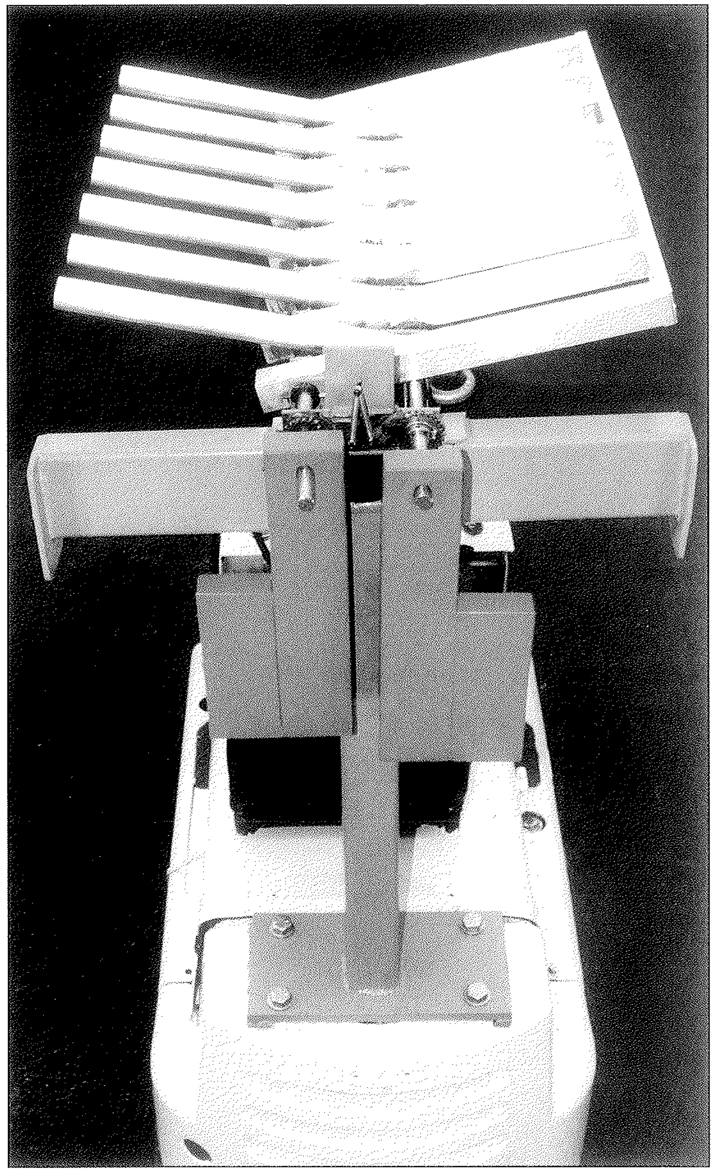


Figure 12 – Components of a Counterweight Canopy Retraction System

CONCLUSION

Is it possible to design a practical overhead guard that will serve as a ROPS and FOPS while eliminating the crushing hazard associated with the overturning of conventionally equipped industrial vehicles? This paper postulated that this question could be affirmatively answered if a midplane frame is used in conjunction with a passively retractable canopy. Several variations of such a design were fabricated and tested to demonstrate the validity of the concept. These so called "proof of concept" tests were conducted using an 8,000 pound forklift with a 5,000 pound lift capacity. The suitability of the retrofit overhead guard was evaluated against the following necessary conditions:

1. A rollover event on a hard surface must not result in a vehicle rotation greater than 90°.
2. The overhead guard must meet the performance criteria for rollover protective structures specified by SAE. Specifically, it must meet the strength and energy requirements for an 8,000 pound vehicle.

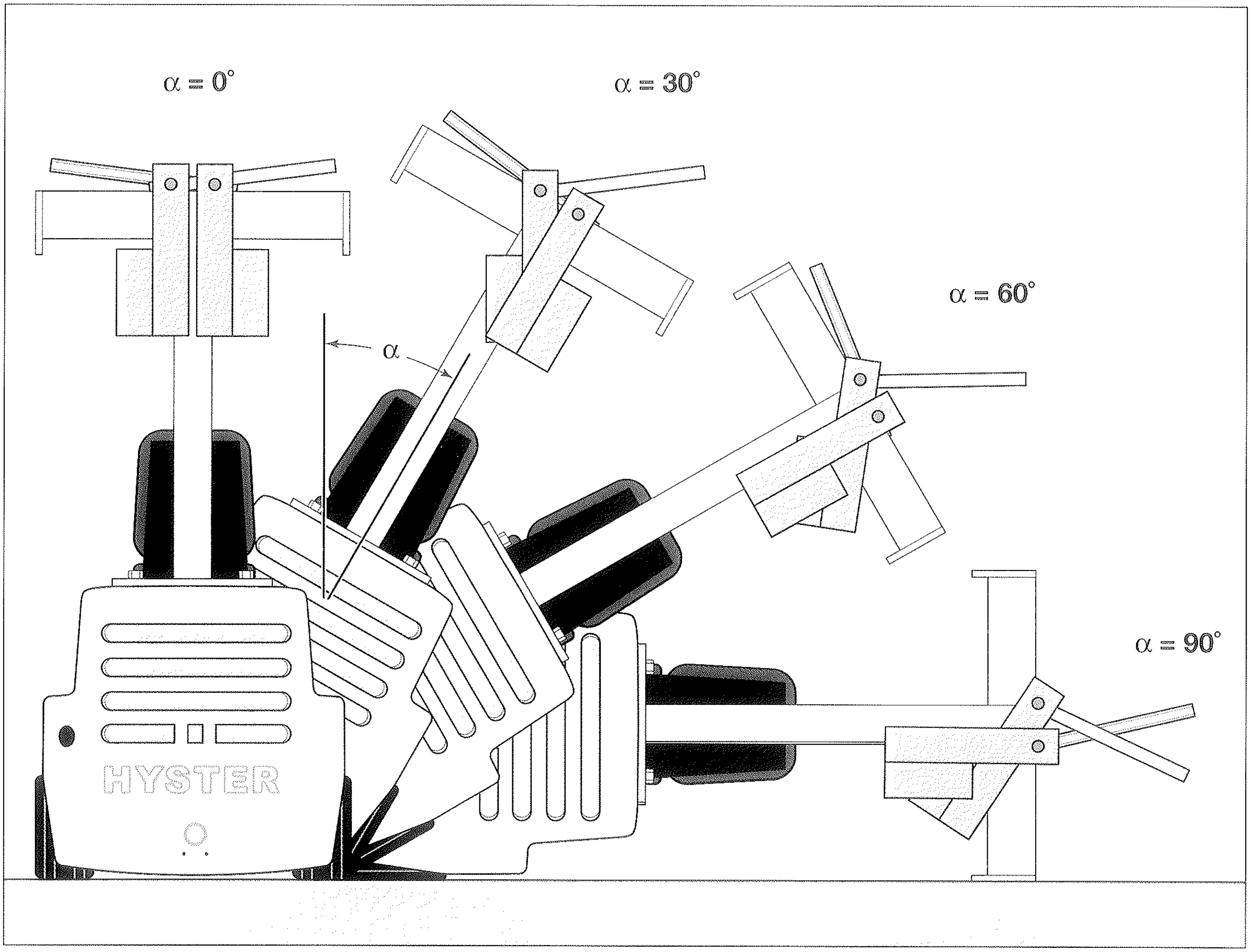


Figure 13 – Static Rollover Test of Counterweight Retraction System (Photographic Tracing)

3. The overhead guard shall not exceed the ANSI deformation specifications during an Impact Drop Test generating 8,000 foot pounds of energy.

4. The canopy elements must pass the Cube Drop Test required by ANSI for forklifts.

5. During a rollover excursion, the canopy elements must not invade the safety gap.

The candidate overhead guard and its variations all satisfy the necessary conditions which established "proof of concept." No attempt was made to optimize the guard design with respect to weight or cost. For economic reasons, the same candidate design was repeatedly tested under various failure provoking conditions. Overhead guards are not required to sustain multiple traumatic events; nevertheless, the basic design was sufficiently robust to meet the challenge of our testing protocol.

PATENT STATEMENT

There is a patent pending that covers the concepts described in this paper.

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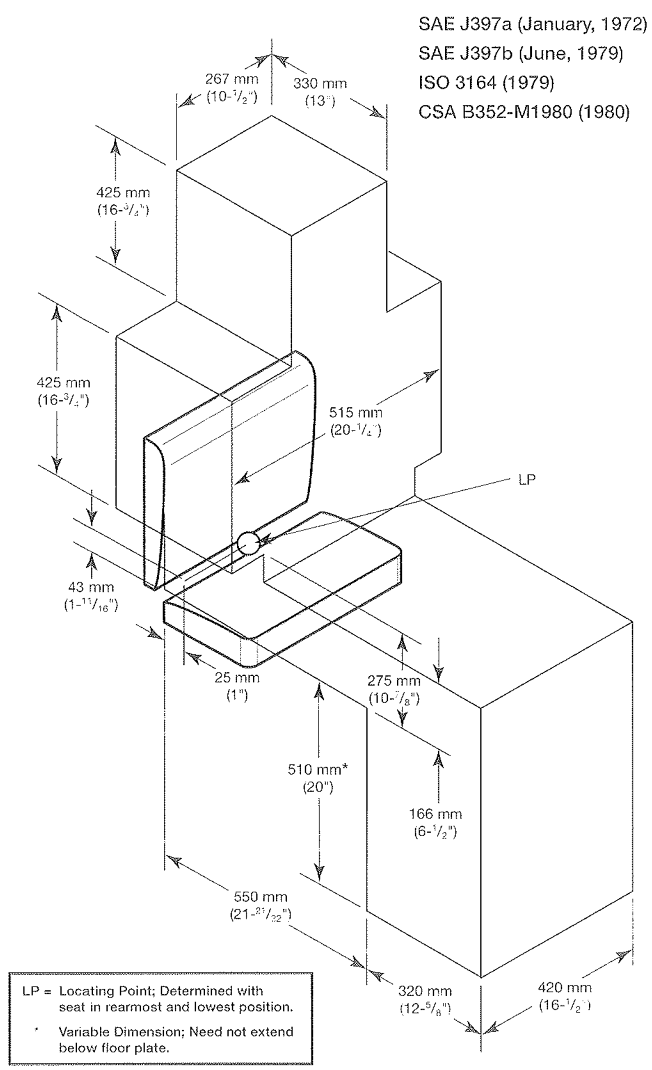
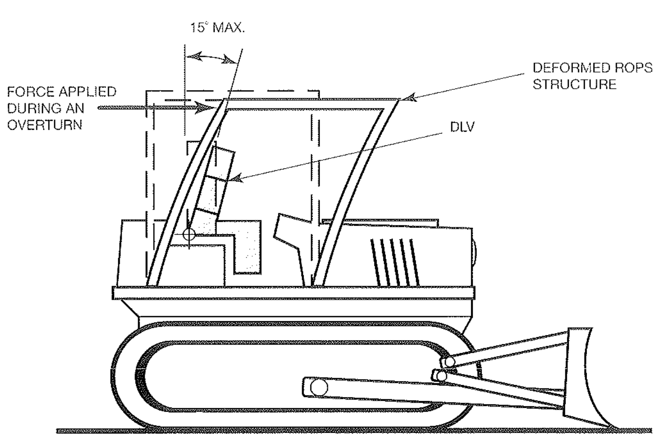


a) Deflection Limiting Volume of a Large Male Wearing Regular Clothing



b) Allowable 15° Rotation of DLV on a Crawler Tractor

Figure 14 – Deflection Limiting Volume (DLV)

APPENDIX A
(Definition of DLV)

The Deflection Limiting Volume (DLV) defined in Fig. 14a was first standardized in April, 1988 by SAE [A1] for use in the design of ROPS - FOPS for machinery such as crawler tractors and loaders, graders, wheel loaders and tractors, wheel log skidders, skid steer loaders, backhoe loaders, wheel industrial tractors, semi-mounted scrapers, water wagons, articulated steer dumpers, bottom dump wagons, side dump wagons, rear dump wagons, towed fifth wheel attachments, rollers, compactors, and rigid frame dumpers with full mounted bodies. The protective volume must not be invaded by the ROPS - FOPS when they are tested against SAE standards. The DLV must also not be invaded by a plane on which the vehicle is operating when it is oriented into any overturned attitude. Figure 14b indicates that the upper portion of the DLV may be rotated 15° forward in recognition of the fact that the human body is not rigid.

The Locating Point (LP) on the seat and on the DLV is defined in Fig. 14a. All testing with the Hyster forklift was performed with its seat in the rearmost and lowest position.

APPENDIX B
(Supporting Calculations for Table I)

Machine Mass, M (kg):

8000 lbf x 0.45359 = 3629 kg $\equiv M$

SAE Lateral Load Force (Newtons):

$6M$ = 21,772 N

SAE Vertical Load Force (Newtons):

$19.61\,M$ = 71,159 N

SAE Longitudinal Load Force (Newtons):

$4.8\,M$ = 17,418 N

SAE Lateral Load Energy (Joules):

$12{,}500\,(M/10{,}000)^{1.25} = 3{,}520$ J

<u>Plastic Moment, M_p (in-lbs):</u>

Solid Rectangle:

height H, width B:

$$M_p = \frac{BH^2}{4}\sigma_y \qquad \text{(See reference A2)}$$

σ_y...yield strength; 46 ksi for ASTM 4500

Square Tube:

$B = H$, $b = h$ (inside width and height):

$$M_p = \frac{\sigma_y}{4}\left(B^3 - b^3\right)$$

Square Tube:

4 x 4 x 1/4; B = 4", b = 3.5"

$$M_p = \frac{46{,}000}{4}\left(4^3 - 3.5^3\right) = 242{,}938\,in - lbs$$

<u>Limit Analysis</u> [A2] (See Figure 15)

- Upright Resistance (Lateral or Longitudinal): $P = M_p / L$

$$P = \frac{M_p}{L} = \frac{242{,}938}{47} = 5169\,lb.$$

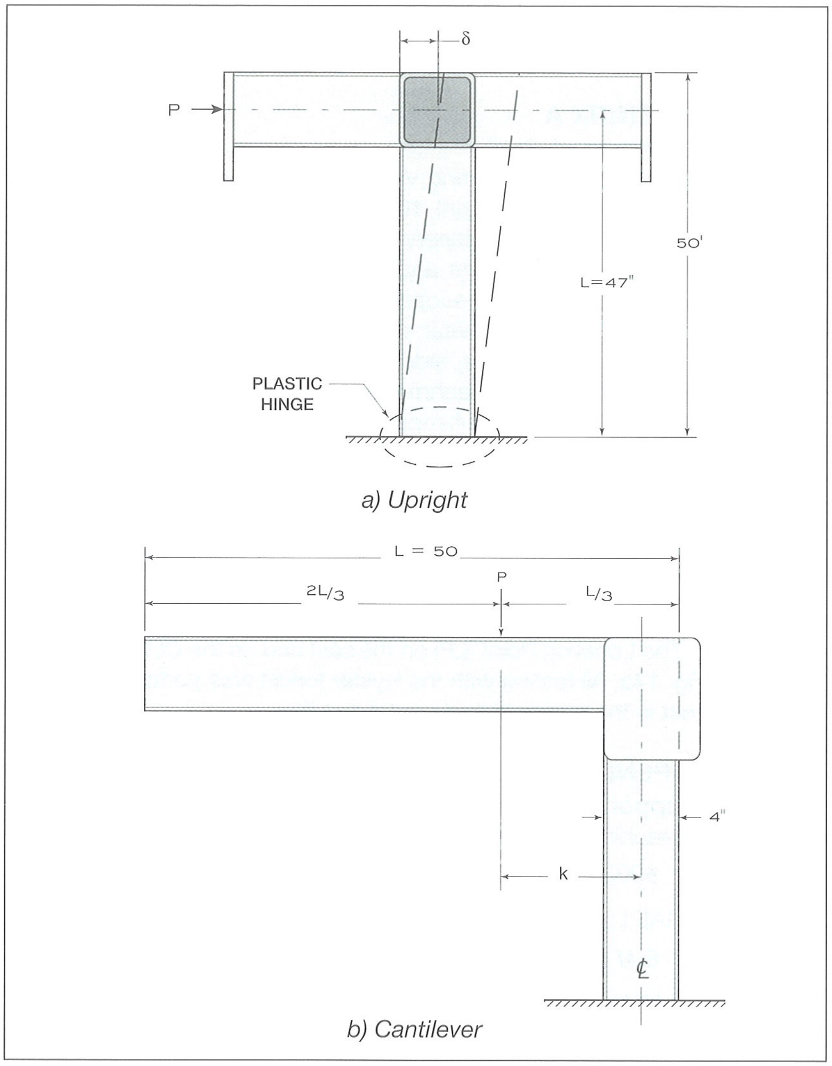


Figure 15 – Resistances

- Cantilever Resistance (Vertical): $P = M_p / k$

$$k = \frac{L}{3} - 2 = \frac{50}{3} - 2 = 14.67\ in.$$

$$P = \frac{M_p}{k} = \frac{242,938}{14.67} = 16,564\ lb.$$

Note: The plastic hinge may appear anywhere along the vertical centerline without changing the formula $P = M_p / k$.

- Lateral Displacement (Permanent Set): δ

For a rigid-perfectly plastic material, the absorbed energy U is simply $P\delta$. Using the SAE specified lateral force, 4895 lbf, and SAE specified lateral energy, 2597 ft-lbs, shown in Table I the associated lateral displacement is

$$\delta = \frac{U}{P} = \frac{2597}{4895} = 0.531\ ft. = 6.37\ in.$$

A single rollover of the "proof of concept" overhead guard produced an equivalent displacement, δ = 2-1/8 in.

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