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Forensic Engineering Analysis of Failed UTV Roll Cages

By Olof H. Jacobson, MS, PE (NAFE 496F), Stephen A. Batzer, PhD, PE (NAFE 677M), Mark H. Kittel, PE (NAFE 757M), Jesse A. Grantham, PhD, PE (NAFE 597S), Guy J. Barbera, PE (NAFE 732M), and Allen Molitoris, PE (NAFE 464C)

Abstract

Two cases were analyzed that involved pitchover/rollover accidents of the same model side by side utility terrain vehicle (UTV). In each case, the UTV ran over a bump on a dirt road and pitched over. The roll cages collapsed, and the drivers suffered significant injuries. Both roll cages collapsed in a similar manner. The design and failure modes of the roll cage structure were analyzed. Engineering analysis included dynamic analysis, laboratory testing, vehicle dynamic testing, finite element analysis, and a review of fundamental mechanical engineering design concepts. Roll cage design and applicable standards were evaluated. Reasonable alternative designs were identified and analyzed.

Keywords

Roll cage, ROPS, rollover, pitchover, design, testing

Vehicle Description

The subject UTV is a four-wheeled, side-by-side vehicle that is equipped with two bucket seats, a steering wheel, and pedals that are similar to automobile controls. The vehicle is equipped with a tubular steel roll cage and three-point automotive-style seat belts.

This UTV is an off-road vehicle with a short wheel base (76 inches), a narrow track width (48 inches), and a high center of gravity. The vehicle has correspondingly low yaw, pitch and roll moments of inertia, resulting in a higher probability of rollovers. The UTV was capable of speeds in excess of 65 mph and had a suspension configured for sporting use. The UTV's roll cage is a tubular steel structure that is bolted to the vehicle frame at four points. The geometry of the roll cage is based on open-sided rectangular shapes with no diagonal bracing. The B-pillars consist of dual tubes that are bent into Z-shapes.

The longitudinal roll cage side header tubes between the A and B pillars include a bolted connection on each side. An optional plastic roof was installed on top of the roll cage in one case. An undamaged exemplar roll cage is seen in **Figure 1**.

Figure 1
Undamaged exemplar UTV roll cage.

Case A Description

The UTV was descending a 7 percent grade on a two-track dirt forest service road. A water bar (a transverse mound of dirt that diverts water from the road) formed a bump across the road. Engineering analysis indicates the UTV was traveling 29 to 34 mph when it crossed the water bar. After crossing the water bar, the UTV pitched forward and rolled one time longitudinally (end-over-end). The UTV then landed on its wheels and swerved right before rolling over laterally 1¼ times and coming to rest on the driver's side.

Olof H. Jacobson, MS, PE, 10822 W. Toller Drive, Suite 150, Littleton, CO 80127; (303) 948-9515; oj@jacobsonforensic.com

The roll cage collapsed at the B-pillars, and the two bolted connections in the side header tubes failed during the first roof-to-ground contact. The vertical occupant space was reduced by more than 13 inches. The plastic roof separated from the roll cage near the end of the rollover motion.

The driver, who was using the seat belt, was partially ejected. His head struck the ground, resulting in a paralyzing spinal cord injury. His left arm and leg were pinned under the driver's side at rest, resulting in additional injuries.

Scene Geometry: The accident occurred on a two-track dirt road that is 7 feet wide. Sagebrush borders the road on both sides. The road slopes downward at a grade of 7 percent.

The road is relatively straight, approaching the water bar, and it curves slightly to the right downhill from the water bar. With respect to the plane of the road, the peak of the bump was approximately 1 foot high, and the entire bump was 8.4 feet long. A plan view of the accident scene is shown in **Figure 2**. Photographs of the accident site are shown in **Figures 3** and **4**.

UTV Motion: When the UTV crossed the water bar, the rear axle kicked up, and the UTV pitched forward in an end-over-end motion. The right front tire and bumper dug into the dirt and sagebrush to the left of the road 63 feet downhill from the water bar. The UTV continued its forward pitchover rotation, and the vehicle struck the ground on its roof with the rear end facing downhill. The UTV completed one full revolution in the forward pitchover direction and landed on

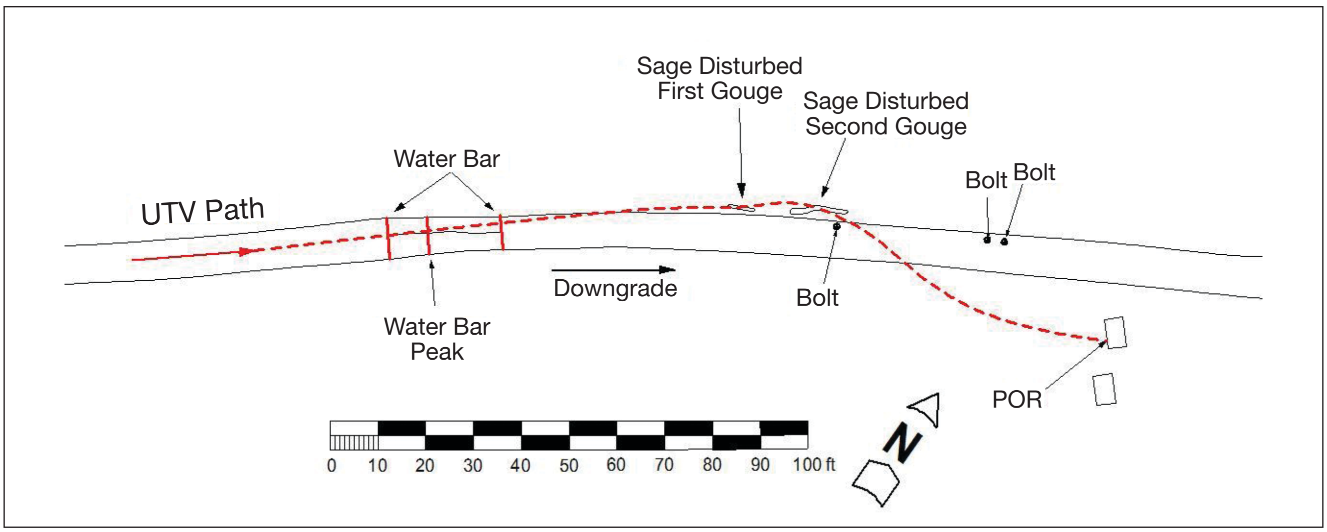

Figure 2
Case A: Scale drawing of accident scene.

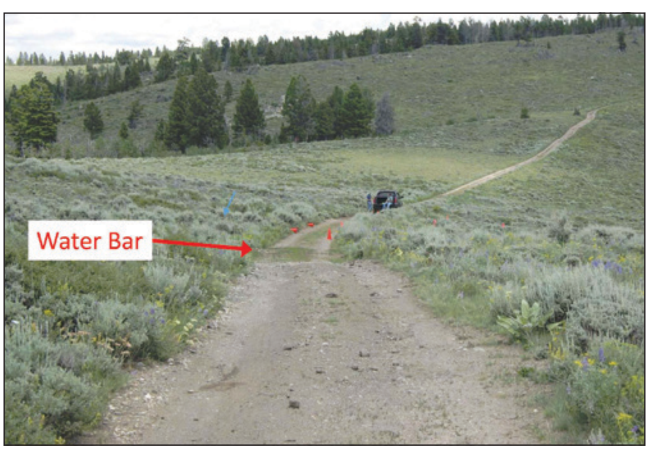

Figure 3
View of accident location, looking downhill in direction of UTV travel.

Figure 4
Side view of water bar. UTV traveled from right to left.

its wheels in a slightly clockwise orientation (i.e., rotated to face slightly toward the right). The UTV then swerved to the right and rolled over laterally with the driver's side leading. The vehicle rolled over laterally 1¼ times before coming to rest on the driver's side. The sequence of the rollover motion is shown in **Figures 5** through **7**.

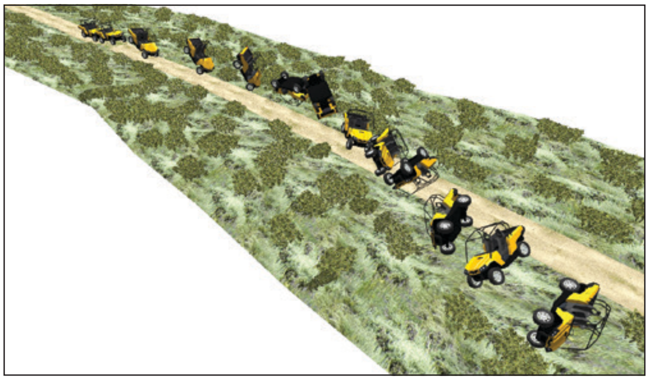

Figure 5
Case A: Overall vehicle motion.

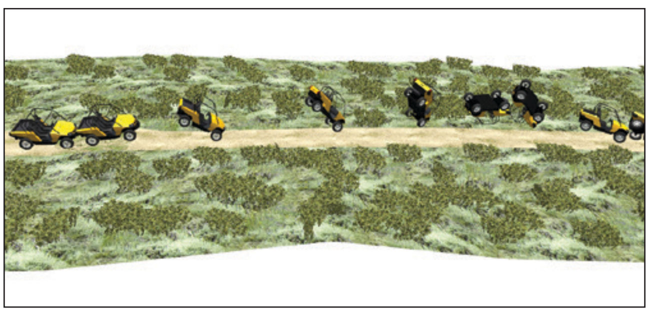

Figure 6
Case A: Initial pitchover motion.

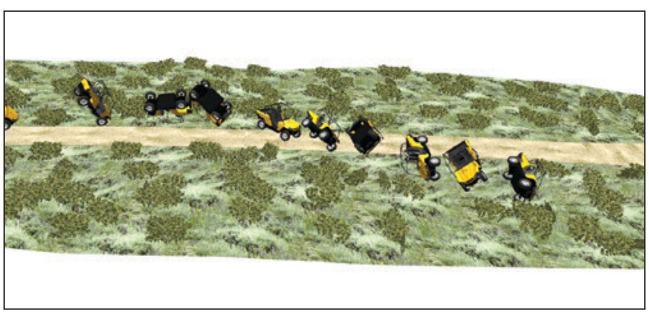

Figure 7
Case A: Final lateral rollover motion.

UTV Damage: The right front corner of the front bumper was scraped and deformed rearward. The right front wheel was folded under with the bottom of the wheel pushed inboard, including associated buckling of the lower suspension A-arm. This evidence indicates that the right front wheel rolled along the ground with the vehicle in a nose down attitude until the front bumper dug in as the vehicle continued to pitch forward onto the roll cage. Given the short wheelbase, the center of gravity of the UTV was not significantly higher during this nose down ground contact when compared to its initial height. The center of gravity did not subsequently fall a significant distance between the time the front end struck the ground and the time when the roll cage struck the ground. Analysis of the UTV geometry, the UTV damage, and geometry of the scrape marks on the ground indicates that the center of gravity did not fall a significant distance above the ground during the initial pitchover when the roll cage collapsed.

The plastic roof exhibited heavy scrapes in the longitudinal direction from rear to front, indicating that the UTV initially landed on its roof while traveling with the rear end leading (following a nose-down pitchover). A second set of lateral scrapes was present on the roof from right to left, indicating that the vehicle subsequently landed on its roof one time while rolling over laterally in a counterclockwise direction (from the driver's perspective) with the driver's side leading. The lateral scrapes were overlaid on top of the longitudinal scrapes, indicating that the lateral rollover occurred after the forward pitchover.

The roll cage collapsed at both B-pillars above the driver's head. The lateral roll cage cross member behind the driver's head buckled downward into a V-shape, and the B-pillars were deformed inward. The bolted connections in both side header tubes separated, and the bolts were found sheared in the bolt holes. Three of the four fractured bolt heads were found in the roadway. The fracture surfaces showed that the bolts failed in shear.

The permanent downward deformation of the roll cage above the driver's head measured 13 inches. The maximum dynamic deformation during the rollover was likely in excess of 13 inches. Roll cage damage is seen in **Figures 8** through **11**.

As described above, the UTV's center of gravity did not gain significant height above the ground during the initial forward pitchover. When the roof struck the ground, the roll cages collapsed and deformed but did not fully compress down to the body of the UTV. It is reasonable to conclude that increased roll cage strength would have reduced the exposure to occupant injuries. In the opinion of the authors, even a moderate increase in roll cage strength would have prevented the collapse of the roll cage.

Figure 8
Case A: Side view of roll cage damage.
Front half of roll cage has been temporarily placed on the vehicle.
(The A-pillars were cut at the front frame attachment points
after the accident by rescue personnel.)

Figure 9
Case A: Rear view of roll cage damage.

Figure 10
Case A: Failed bolted connection in side header tube.

Figure 11
Case A: Failed bolted connection in side header tube.

Case B Description

The accident occurred on an off-highway vehicle (OHV) trail that is developed and maintained for recreational vehicle use by the U.S. Forest Service. The UTV driver was in the lead of a group of off-road vehicles on a perimeter trail in an area with relatively smooth and level terrain. The driver and his passenger were both wearing helmets and seat belts.

The driver reported that he was traveling approximately 43 to 46 mph as he approached a low spot in the trail. He did not brake or accelerate as he entered the low spot. As the UTV came up the rise on the far side of the depression, the rear end of the vehicle unexpectedly kicked up vertically. The UTV pitched forward with the nose down, and it tumbled end-over-end.

The UTV passenger reported that the driver had accelerated up to approximately 40 mph, and his speed was consistent on the approach to the depression. Witnesses indicated that the UTV was traveling at a reasonable speed for the terrain, and they were surprised that the UTV pitched over.

Scene Geometry: The trail is relatively flat throughout the rollover path. A shallow dip is present at a small drainage channel that enters the trail from the left. The entry to the dip descends very gradually over a distance of 25 to 30 feet. The profile transitions to a slight rise, leaving the low spot over a distance of 10 to 12 feet, with the final 7 feet at a 14 percent upgrade. Photos of the site are seen in **Figures 12** and **13**.

UTV Motion: Engineering analysis indicates that the UTV was traveling at a maximum of 43 miles per hour as it traversed the slight depression in the trail. As the UTV came up the rise on the far side of the depression, the rear end of the vehicle kicked up vertically, and the UTV pitched forward with the nose down, tumbling end-over-end. The UTV completed two full rotations in the forward pitch direction (end-over-end) and came to rest on the driver's side. The UTV traveled 157 feet from the top of the dip to the point of rest.

UTV Damage: One corner of the front bumper was deformed rearward. The roll cage collapsed at the B-pillars above the driver's head, and the bolted connections in the side header tubes failed in shear. The front half of the roll cage collapsed downward at the bolted connections, and the bolts attaching the front of the roll cage to the frame had also failed in shear. The

Figure 12
Case B: Accident site.

Figure 13
Case B: Accident site.

deformed roll cage is seen in **Figures 14** and **15**. Note the similarity to the deformation pattern in Case A seen in **Figures 8** and **9**. The bolted connections failed in the same manner as in Case A.

Longitudinal scrape marks at the tops of the A-pillars and B-pillars indicate that the UTV was on its roof while pitching forward and tumbled end-over-end two times. The absence of scrape marks on the side header tubes between the A-pillars and B-pillars indicates that the bolted connections failed during the first pitchover, allowing the front section of the roll cage to deform downward during the first ground contact.

The permanent downward deformation of the roll cage at the B-pillars measured 2¾ inches on the driver's side and ½ inch on the passenger's side. The downward deformation of the header tubes of the forward portion of the roll cage (at the failed bolted connections) measured 10 inches on the driver's side and 6¼ inches on the passenger's side. The A-pillars were deformed downward 7 inches on the driver's side and 8 inches on the passenger's side. The maximum dynamic deformation during the pitchover was in excess of these static measurements.

The driver's head contacted the ground, but the passenger's head did not, as was evidenced by the scrapes on the driver's helmet and the absence of scrapes on the passenger's helmet. The driver sustained injury from the head contact, and his hands were injured due to impingement between the ground and the upper portion of the steering wheel during the pitchover. As the front portion of the roll cage collapsed, the top of the steering wheel protruded above the plane of the roll cage. The passenger was not injured.

When the rear end of the UTV unexpectedly kicked upward after coming off the bump, the UTV initially traveled on its front wheels for some distance prior to the front end tripping and beginning the pitchover. After the first full revolution of the pitchover motion, the vehicle landed on its wheels as it continued pitching forward. Since the vehicle would lose very little speed during the wheel contact with the ground, the calculated speed of 43 mph is a maximum — the actual speed could have been lower.

The level of B-pillar roll cage deformation in Case B suggests that when the roof struck the ground, the forces of contact were marginally greater than the

Figure 14
Case B. Side view of failed roll cage.

Figure 15
Case B. Rear view of failed roll cage.

strength of the roll cage. In the opinion of the authors, even a moderate increase in roll cage strength would have prevented the collapse of the roll cage. Such an increase in strength would include durable fastening of the front roll cage to the rear roll cage at the bolted header joints; the failure of these joints contributed to the driver's hand injuries.

The absence of injury to the passenger further indicates that increased roll cage strength would have reduced the exposure to occupant injuries.

History and Development of UTV Market

UTVs are a relatively new class of personal recreational vehicles that have evolved as a hybrid of two different products: low power utility vehicles and four-wheel all-terrain vehicles (ATVs).

Low power work site vehicles, often referred to as "mules," are four-wheel vehicles with low horsepower engines and low top-speed capabilities. These vehicles are typically used around farms, ranches, and work sites to haul tools/supplies and to transport personnel. Utility vehicles were initially manufactured in the late 1970s as work vehicles for hauling light loads and traversing mild terrain. Design features of traditional utility vehicles included relatively low power engines and limited suspension travel, or no suspension in some cases, which kept the operation of the vehicle to relatively low speeds due to uncomfortable ride quality and poor handling on rough terrain.

UTVs also evolved out of the four-wheel ATV product lines. These vehicles are technologically sophisticated, high-speed machines where the rider sits atop the vehicle, much like a motorcycle rider. The ATV is a "rider-active" vehicle where the rider's body position is an important part of maintaining vehicle control. When an ATV rolls over or pitches over, the rider is ejected.

In contrast to ATVs, the driver of a UTV is seated inside the vehicle. The driver is restrained with a seat belt and inside a roll cage. The driver cannot move his body to affect vehicle stability, and he or she should remain within the protective space of the roll cage during a rollover. The UTV is not "rider-active," meaning that the operator does not actively affect the vehicle's handling through body positioning, as is done on an ATV or motorcycle.

Since the occupants of a UTV are seated similar to an automobile, the opportunity exists to protect the driver with a properly designed occupant protection system, consisting of the seat belt, the seat, and the roll cage. With the occupant seated, safety considerations require that the UTV employ appropriate means of protecting the operator in the event of a crash or if the vehicle overturns.

The subject UTV is visually similar to a "mule" work vehicle, but it has been upgraded with a sophisticated, high-powered engine and sophisticated suspension to combine the cargo hauling and two-passenger capability of a traditional utility vehicle with the speed and off-road capability of an ATV.

The subject UTV employs a roll cage that is visually similar to the rollover protection system (ROPS) devices found on lower-speed work vehicles. However, in contrast to the engineering and technical sophistication of the rest of the vehicle, the roll cage portion of the occupant protection system is not comparable to the balance of the UTV. The roll cage on the subject UTV is not safe for the capabilities of the machine, and it is not safe for its foreseeable use. The subject UTV roll cage was defectively designed as it did not provide its intended function of reliable intrusion resistance. The roll cage should have been designed for the foreseeable use of the UTV, including the potential for rollovers and pitchovers. The roll cage should be adequate to protect the occupants during the foreseeable event of a rollover or pitchover.

Roll Cage Design

The roll cage consists of a tubular steel cage bolted to the UTV frame at four points. The geometry of the roll cage is based on open-sided shapes, which are approximately rectangular with no diagonal bracing. The B-pillars consist of dual Z-shaped tubes. The side header tubes include a bolted connection on each side. The roll cage is fabricated from steel tubing with a nominal outside diameter of 2 inches, a wall thickness of 0.131 inches, and a yield strength of 71,000 psi.

During the accident sequences investigated, both B-pillars collapsed and both bolted connections failed during the initial pitchovers. In Case A, the lateral cross member above the driver's head also buckled, allowing the B-pillars to deform inward. Three fundamental engineering deficiencies were identified in the subject roll cage:

- Z-shaped B-pillars
- Rectangular, open-sided truss geometry without diagonal bracing
- Single-shear bolted connections in the side header tubes

Failure of the subject roll cage in relatively low-speed rollover events is foreseeable, given the fundamental engineering deficiencies in the roll cage design. Details of the deficiencies are as follows:

1. **Z-shaped B-pillars:** From an engineering perspective, the Z-shaped B-pillars are an obvious potential failure point. Bends in a load-bearing column create a weak point where buckling will occur. This type of bent structure is normally avoided in engineering design. The use of straight vertical columns instead of the "dog leg" B-pillars would increase the strength of the B-pillars significantly.

   Testing of the subject roll cage resulted in a B-pillar buckling failure under a vertical load of 16,510 pounds (see testing section below). Analysis shows that the use of vertical columns with the same steel tubes would increase the buckling failure load to approximately 88,600 pounds, a more than five-fold increase over the original design. The use of straight vertical columns in place of the Z-shaped B-pillars would not change the cost of the roll cage. The use of straight vertical columns is economically feasible, technically feasible, and an obvious design choice to a mechanical engineer. Details of adapting the straight columns to the existing frame geometry could be overcome with proper engineering analysis. Fundamental engineering design principles should have been incorporated into the entire UTV design from the conceptual stage.

2. **Roll Cage Geometry:** The geometry of the roll cage is based on open-sided shapes, which are approximately rectangular with no diagonal bracing. A properly designed roll cage should be based on triangular trusses. Rectangular trusses can deform into parallelograms with relatively little resistance to deformation. Rectangular trusses are inherently much less rigid than triangular trusses. This concept is demonstrated graphically in **Figure 16**.

   Fundamental mechanical engineering design practice and numerous roll cage design standards require triangular trusses. This is accomplished with diagonal bracing. Diagonal braces can be included in a four-point mount design, or they can be added by utilizing six mounting points to the frame. Diagonal bracing is standard in roll cages designed for off-road racing vehicles where the probability of rollover is higher than in passenger cars. Longitudinal and lateral diagonal bracing should have been included in the UTV roll cage design. Fundamental engineering design principles should have been incorporated into the entire UTV design from the conceptual stage.

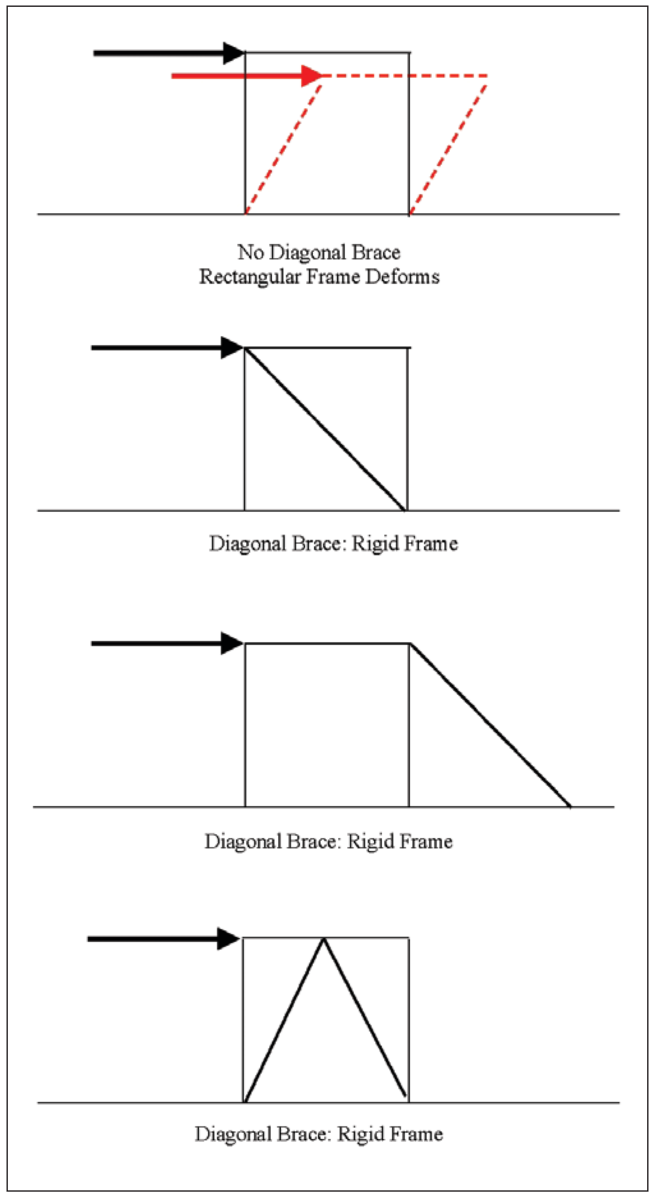

Figure 16
Schematic diagram of rectangular truss deformation vs. triangular truss stiffness.

3. **Bolted Connections:** In the two cases, both bolted connections in the side header tubes failed during the pitchovers. Engineering shows that the bolted connections would fail under a vertical load of approximately 1,200 pounds. The steel tubes without bolted joints would have supported a vertical load of approximately 3,500 pounds. This use of bolted connections weakened the longitudinal members of the roll cage by a factor of nearly three. (See **Appendix A**.)

   The bolted joints in the roll cage were loaded transversely, and the bolts failed in single shear. This is a fundamental design weakness. Bolts are typically loaded in tension, but if they must be loaded in shear, they should be loaded in double-shear. In addition, the cross-sectional area of the bolts should be sufficient to support the expected loads such that the strength of the bolted joints is consistent with the overall strength of the roll cage.

   If tube joints are necessary, the tubes could be joined by using one of several standard methods. For example, a reduced diameter tube end inserted inside a full diameter tube end locked together with through bolts would not load the bolt in shear, and the joint could be as strong as the base steel tubing. Other alternate designs include engineered products such as the Camburg Tube Clamp seen in **Figure 17**. In this design, if properly oriented, bending moments and resultant shear forces would be transferred through interlocking features and not through the bolts.

The use of vertical columns, diagonal bracing, and properly designed joints as described above would have prevented the collapse of the subject roll cages. These design concepts are economically feasible and technically feasible. These design concepts are widely known and accepted in mechanical engineering design and roll cage design.

Roll Cage Testing

An exemplar roll cage was tested in a laboratory setting. The cage was bolted to a steel base plate, and a downward vertical load was applied across the lateral member at the B-pillars. As the cage was deformed vertically, load and displacement data was recorded until the vertical force peaked and then began to decline, indicating that the stress had exceeded the yield strength of the steel tubing. The roll cage failed due to buckling in the bends in the Z-shaped B-pillars.

The test setup is shown in **Figure 18,** and the load displacement data is shown in **Figure 19**. The B-pillars buckled at a vertical load of 16,510 pounds.

Figured 17
Camburg tube clamp
(http://camburg.com/fabrication-parts/billet-tube-clamps/)

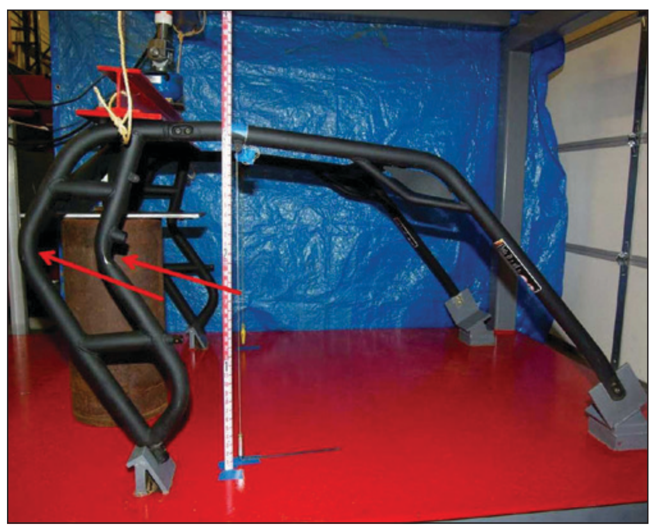

Figure 18
Laboratory testing of an exemplar roll cage.
Z-shaped B-pillars buckled at bends (arrows).

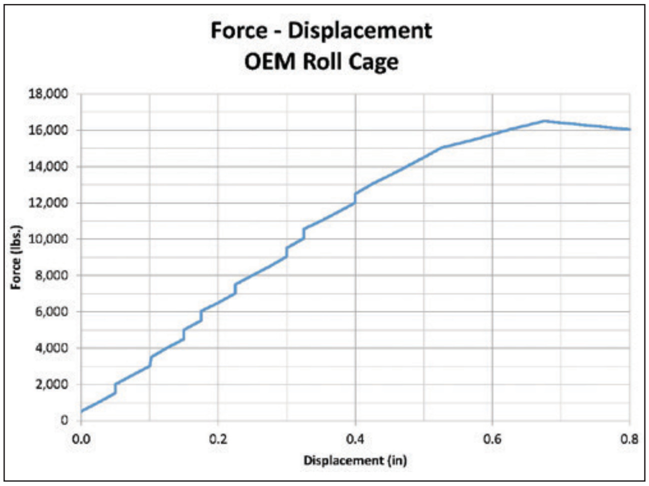

Figure 19
Load/displacement data from test shown in Figure 18.
Peak force was 16,510 pounds.

Engineering Analysis – B-pillar Column Buckling

Engineering analysis shows that replacing the Z-shaped B-pillars with straight columns would have significantly increased the strength of the roll cage. The following simple modifications would have increased the buckling strength of the B-pillars as follows:

B-pillar design	Tube Diameter (inches)	Wall Thickness (inches)	Buckling Load (pounds)	Increase
Subject, Z-shaped tube	2.00	0.131	16,510	Baseline
Straight, original tube (see Figure 23)	2.00	0.131	88,600	540%
Straight, larger diameter tube	2.25	0.131	105,400	640%
Straight, thicker wall tube	2.00	0.250	155,000	940%
Straight, larger/thicker tube	2.25	0.250	187,800	1,140%

This data demonstrates that simple modifications to the roll cage design would have significantly increased the strength of the roll cage. It should be noted that in the test, the B-pillars were loaded evenly, and the load was purely vertical. This represents an ideal loading condition to be used as a baseline for further analysis and does not represent the actual loads applied to the roll cages during the subject pitchover events. Fundamental engineering design principles should have been incorporated into the entire UTV design from the conceptual stage.

Finite Element Analysis of Additional Reasonable Alternative Designs

Additional reasonable alternate roll cage designs were evaluated with finite element analysis (FEA). The physical testing described above was used to validate a finite element model of the roll cage.

The FEA analysis was performed with LS-Dyna version 971 software. A Lagrangian mesh formulation was used to simulate the deflection of the roll cage under quasi-static loading. The roll cage was loaded in the vertical direction at a rate of 100 mm/s through a simulated platen at the top of the B-pillar. Automatic surface-to-surface contact was enforced at the platen-to-roll-cage contact and bolt-to-bolt-hole interaction. Static and dynamic coefficients of friction used were 0.1 and 0.07, respectively. Runs were made with a symmetric half-section with the center point of the front and rear header fixed to prevent Z-axis (lateral) motion, X-axis rotation and Y-axis rotation. This was done to promote computational efficiency. The force results of the half-model were doubled to give the total force resistance of the full FEA model.

A graphical output from the FEA model is shown in **Figure 20**. The FEA model predicted a failure load of 17,200 pounds with a deflection of 0.5 inches compared to the laboratory test results of 16,500 pounds with a deflection of 0.675 inches. The FEA model had a somewhat stiffer initial response as shown by the steeper curve. Peak loading was about 4% greater than the measured physical peak cage load, and peak deformation of the model occurred with ~0.2 inch less deformation compared to the physically tested roll cage. The general shape and resulting peak load are very similar. **Figure 21** shows the data from the physical test and the output of the FEA model. Overall, the testing provided a reasonable validation of the FEA model.

The validated FEA model was then used to analyze various roll cage alternative designs. The FEA analysis shows that replacing one of the Z-shaped B-pillars on each side with a straight column would change the failure mode of the roll cage. With a vertical column, the B-pillar does not buckle. In this design, the B-pillar rotates rearward about its base, and the angle at the A-pillar opens up. Three additional conceptual alternatives are discussed below.

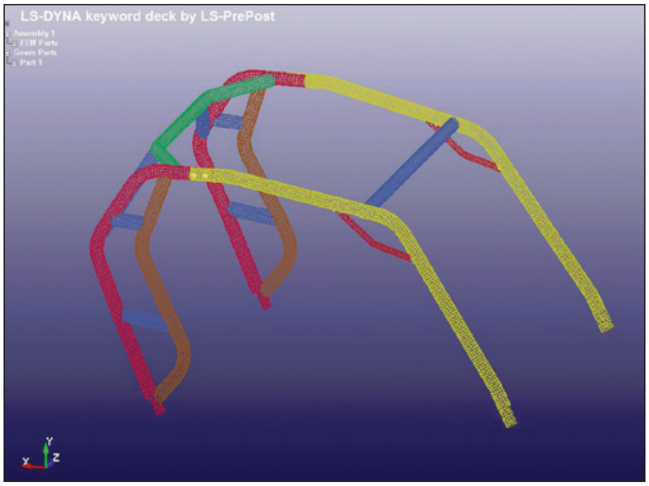

Figure 20
LS-DYNA graphical output of roll cage model.

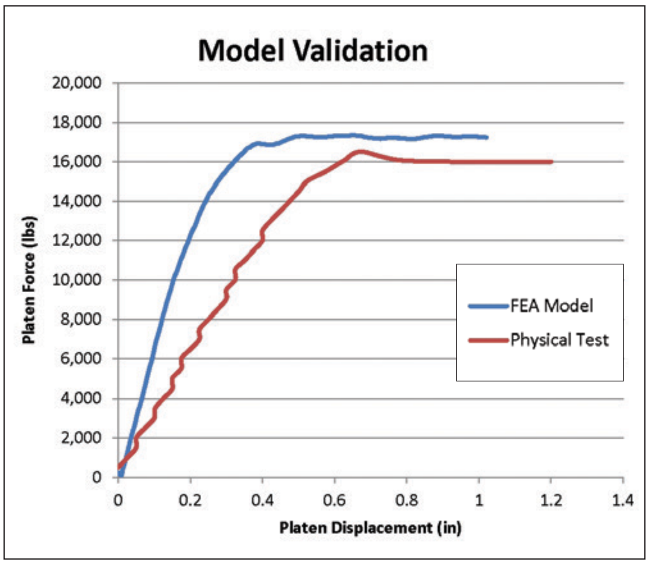

Figure 21
Validation of FEA model vs. laboratory test.

Conceptual Alternative 1

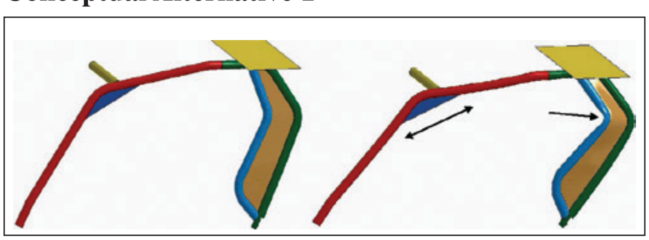

Figure 22
Graphic of conceptual alternative 1. Conceptual design shown in left panel. Resulting deformation shown in right panel.

Figure 22 shows the first alternative concept, which uses a 0.090-inch (2.3 mm)-thick steel web to fill in the area between the two B-pillar uprights in order to transfer shear loading between the uprights. As such, this concept deletes the two horizontal connecting tubes. The rear-most cage to chassis attachment points are identical to the baseline model. The model is shown in the unloaded and heavily loaded states with 4 inches of deformation. Note the maximum distortion at the top bend of the rear cage forward upright. Also, note the straightening of the A-pillar / roof rail segment and minor rotation about the rear mount. The peak load of conceptual Alternative 1 measures 21,600 pounds at 0.5 inches of platen movement.

Conceptual Alternative 2

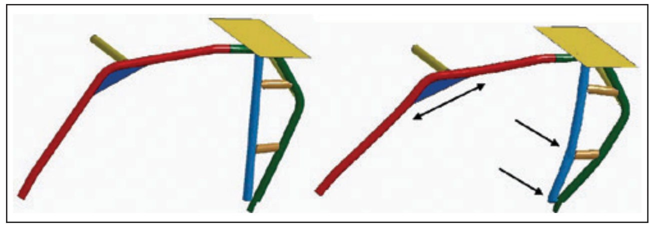

Figure 23
Graphic of conceptual alternative 2. Conceptual design shown in left panel. Resulting deformation shown in right panel. Z-shaped tube has been replaced by a straight vertical tube (see blue member).

Figure 23 shows the second alternative concept that uses a vertical tubular member in place of the original Z-shaped tube, eliminating the bends in the column. The bottom of the tube has been modeled as a fixed connection to the chassis. Thus, the fixation of the rear cage to the vehicle chassis has been strengthened by replacing the two fixed rear chassis connections with four fixed connections. This design concept is shown below in the unloaded and heavily loaded states with 4 inches of vertical deformation. The rear upright is not grossly distorted; the B-pillars rotated rearward about the mount with plastic deformation. The A-pillar / roof rail intersection straightened. The peak load of conceptual Alternative 2 measures 37,900 pounds at 2.0 inches of platen movement.

Conceptual Alternative 3

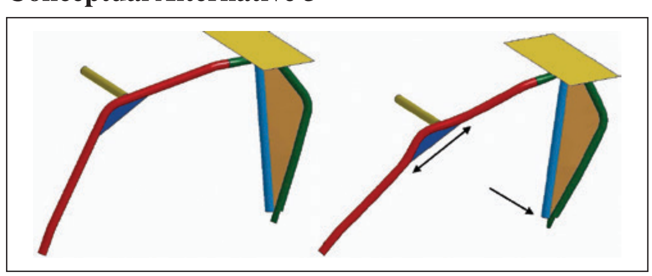

Figure 24
Graphic of conceptual alternative 3. Conceptual design shown in left panel. Resulting deformation shown in right panel.

Figure 24 shows the third alternative concept, which is a combination of concepts 1 and 2. The design is shown in the unloaded and heavily loaded states with 4 inches of vertical deformation. Since the vertical upright is attached to the rear upright with the web, the bottom of the forward vertical tube is not fixed to the mount and can rotate with deformation. This is identical to the frame attachment of the baseline model. When this model is loaded, the rear uprights do not buckle. Instead, they rotate rearward about the rear cage mounts, and the A-pillar / roof rail segment straightens. The peak load of conceptual Alternative 3 measures 47,500 pounds at 3.0 inches of platen movement.

Summary of FEA Analysis of Conceptual Alternative Designs:

Conceptual Design	Buckling Load (pounds)	Increase
Subject	17,200	Baseline
Conceptual Alternative 1	21,600	126%
Conceptual Alternative 2	37,900	216%
Conceptual Alternative 3	47,500	276%

Vehicle Dynamics: Dynamic Testing of Pitchover Tendencies

Exemplar UTVs from various manufacturers were tested in an off-road environment to evaluate dynamic performance. Testing was conducted in an OHV riding area with both man-made and natural terrain features. The exemplar vehicles were driven over a variety of terrain and obstacles to gain an understanding of performance and handling characteristics. On certain obstacles, the subject UTV had a tendency to kick the rear of the vehicle up, resulting in a nose-down pitch instability after the vehicle became airborne. The obstacle that produced the rear kick-up tendency was a step-up style jump, approximately 12-18 inches tall, with a short approach ramp that was negotiated at a speed of approximately 34 mph.

Operating a competitor's UTV on the same feature and at the same speed as the subject UTV confirmed that the both vehicles had the rear kick-up tendency. Both UTVs had adjustable springs and shock absorbers. Utilizing the full range of compression and rebound damping adjustments, along with the spring preload adjustments, resulted in no appreciable improvement in the rear kick-up tendency or in the pitch instability. The only improvement noted was when the front and rear springs were swapped on the subject UTV (installing the stiffer rear springs in the front and the softer front springs in the rear). In this configuration, the rear kick-up tendency was decreased but was still present.

The rear kick-up tendency was likely due to the geometry of the vehicles and is a characteristic that is likely inherent in most, if not all, UTVs. As such, it is readily foreseeable that a rear kick-up event could be encountered during typical operation of the subject UTV. Considering the high-performance capability of the UTV, it is foreseeable that an unintentional rear kick-up event with pitch instability could occur during normal use at speeds either higher than the tested 34 mph, or on a bump feature that caused more severe pitching, even at lower speeds. It is foreseeable that a UTV operated at reasonable speeds could experience a rear kick-up event severe enough to cause the vehicle to unexpectedly pitch nose-down, resulting in an end-over-end tumble during normal operation.

The UTV is intended to be operated off-road over uneven terrain. The UTV has the capability to operate over such terrain at high speeds, which makes overturn events such as the subject cases foreseeable to a design engineer. For these reasons, the UTV design is unsafe without a robust roll cage that can withstand the kind of over-turn events that could foreseeably occur. In contrast, it may not be foreseeable to a typical consumer that the UTV may pitch over forward in "normal" use, and it is not foreseeable that the roll cage is likely to fail in even a low-speed rollover or pitchover event.

UTV Design and Roll Cage Requirements

The subject UTV is an off-road vehicle with a short wheel base, a narrow track width and a high center of gravity. The low yaw, pitch and roll moments of inertia indicate that a UTV is much more prone to instability, pitchovers, and rollovers than a highway passenger vehicle. A UTV is intended for off road use exclusively where it is foreseeable that bumps and uneven surfaces will be encountered.

Testing shows that due to the dynamic characteristics of the UTV and its intended off-road use, it is or should be foreseeable to the designer that the UTV will roll over or pitch over, potentially at high speed. Dynamic testing shows that after running over certain bumps, it is foreseeable that the UTV may pitch nose down and land with the front end down.

When a hazard such as the propensity to roll over or pitch over exists in a vehicle design, the best design choice is to modify the design to remove the hazard. If this is not feasible, a secondary method to protect occupants is to provide a guard to prevent or reduce the probability of injury. The least effective approach is to utilize warnings and operator training.

Given that it may not be possible to prevent pitchovers and rollovers, the UTV roll cage should have been designed for the foreseeable use of the product. The roll cage should have been designed and tested to withstand the foreseeable rollovers and pitchovers of the UTV. A properly designed roll cage would have guarded against the danger resulting from the inherent propensity to pitch over and roll over. Fundamental engineering design principles should have been incorporated into the entire UTV design from the conceptual stage.

The roll cage is an important component of the overall occupant protection system. From a consumer's perspective, the UTV appears to be technologically sophisticated and robust. The roll cage conveys the impression of strength and safety. The cost of the subject UTV, which is similar to an automobile, suggests a level of sophistication and safety to the consumer. Although the roll cage conveys the impression of strength and safety to the consumer, it does not share the level of engineering and technical sophistication of the rest of the vehicle.

As mentioned, it may not be foreseeable to a typical consumer that the UTV may pitch over forward in "normal" use, and it is not foreseeable that the roll cage is likely to fail in even a low-speed rollover or pitchover event.

Standards

The manufacturer of the subject roll cage referred to portions of various automotive and agricultural standards, which, upon inspection, were not applicable to the subject UTV.

Agricultural and Automotive Standards

Standards are published for agricultural ROPS and automotive roof strength. These standards are not adequate for the intended and foreseeable use of UTVs.

The UTV is not an agricultural tractor. Tractors typically roll over at low speed and often experience only ¼ roll onto the side or rear. The agricultural standards require very low forces, on the order of 1.5 times the vehicle weight.

The UTV is not an automobile. Automobile rollovers are relatively rare events when compared to UTVs. Automobile pitchovers are even more unusual. The automotive standards involve relatively low forces, on the order of 1.5 to 3 times the vehicle weight.

It is likely that a foreseeable rollover or pitchover incident will expose the vehicle to forces well in excess of those expected in the minimal agricultural and automotive standards available. Standards are a minimum requirement. Designing the UTV roll cage to meet only the minimal requirements of agricultural and automotive standards was a defect in the design of the subject roll cage. Proper engineering design requires a roll cage strength that is adequate for the foreseeable uses of the UTV, including foreseeable misuse.

Roll Cage Standards for Off-Road Vehicles and Racing Applications

Numerous standards and recommended practices exist for the proper design of a roll cage. Typical roll cage design standards include requirements for two vertical hoops and diagonal bracing, both longitudinally and laterally. The subject UTV roll cage does not comply with these standards. Modifications to comply with these standards and practices could have been easily included with minimal cost. The roll cage standards describe proper methods for joining tubes where a joint is necessary, without improperly loading bolts in shear.

Review of the design concept and performance characteristics of the subject UTV suggest that it is more closely akin to a high-performance off-road go-cart or an off-road racing vehicle. Traditionally, vehicles with the power, speed, and terrain capability of the UTV were built for competition in off-road racing events and were required to employ a structurally sound roll cage. As such, the roll cage requirements from racing organizations would likely have been the most reasonable design guide for the UTV designers to follow. Basic features of conventional roll cage designs include straight vertical support structures, cross-bracing (triangular trusses), and six attachment points (three on each side) to the vehicle chassis. The purpose of these design features is to ensure adequate strength and stability of the safety structure for foreseeable crash events.

The design of the subject roll cage does not include the basic features of a conventional roll cage. The vertical support structures consist of bent columns, there is no lateral cross bracing, and there are only four attachment points of the cage to the chassis. The lack of basic roll cage features results in a structure that is easily deformable in low to moderate speed rollovers and offers inadequate protection for the performance capabilities of the vehicle.

It was technologically and economically feasible for a UTV in this market to be equipped with a properly designed roll cage in accordance with roll cage standards and sound engineering design practices.

Conclusions

- In both Case A and Case B, the subject UTVs were traveling at relatively low speed (29 to 34 mph and 43 mph or less, respectively).

- As each UTV traversed a relatively benign rise in terrain, the rear end of the UTV unexpectedly kicked up into the air, and the vehicle landed in a nose-down pitchover orientation.

- During the pitchover, the roof came into contact with the ground, and the roll cage collapsed.

- The roll cage collapsed during the initial roof contact, and it did not provide any useful occupant protection during the final rollover.

- During the pitchover, in both Case A and Case B, the driver's head contacted the ground due to the failure of the roll cage, resulting in injury. In Case B, the driver's hand was also injured due to crushing between the ground and the steering wheel.

- The roll cage was defective and unreasonably dangerous. Fundamental engineering concepts were ignored in the design of the roll cage, resulting in the roll cage failing during foreseeable pitchover and rollover events.

- It was technologically and economically feasible to design a roll cage that would have remained sufficiently intact to protect the occupants. Fundamental engineering design principles should have been incorporated into the entire UTV design from the conceptual stage.

- A properly designed roll cage would not have failed in the subject accidents. A properly designed roll cage would have prevented the driver's head contact with the roof and ground during the pitchover. In Case B, a properly designed roll cage would have also prevented the driver's hand injury.

APPENDIX A

Bolted Joint Stress Analysis

Bolt Geometry

Per Shigley SAE grade 8.8 bolt $S_{ybolt} := 660\ \text{MPa} = 95.7\ \text{ksi}$

Per Machinery Handbook, 3/8 inch blt minor diameter $\phi_{minor} := 8.344\ \text{mm} = 0.329\ \text{in}$

Cross sectional area $A_{shear} := \frac{\pi}{4}\ {\phi_{minor}}^2 = 0.085\ \text{in}^2$

Beam Geometry

Length of beam from front to rear supports $l := 37\ \text{in}$

Tubing Outer Diameter $D := 2.025\ \text{in}$

Tubing Wall Thickness $t_{wall} := \frac{1}{8}\ \text{in} = 0.125\ \text{in}$

Tubing Inner Diameter $d := D - 2\ t_{wall} = 1.775\ \text{in}$

Second Moment of Area about Bending Axis (Shigley) $I := \frac{\pi}{64}\left(D^4 - d^4\right) = 0.338\ \text{in}^4$

Distance from Load to Forward Support $b := 28\ \text{in}$

Distance from Load to Rear Support $a := l - b = 9.0\ \text{in}$

Spacing of bolts (from UTV inspection) $s := 1.0\ \text{in}$

Failure load - tubing wihtout a bolted connection (Beam Bending)

Yield strength of tubing steel $S_y := 71.121\ \text{ksi}$

Second Moment of Area about Bending Axis (Shigley) $I = 0.338\ \text{in}^4$

Tubing Outer Diameter $D = 2.025\ \text{in}$

Distance to Neutral Bending Axis $c := \frac{D}{2} = 1.013\ \text{in}$

Length of the Beam $l = 37.0\ \text{in}$

Distance from Load to Forward Support $b = 28.0\ \text{in}$

Distance from Load to Rear Support $a = 9.0\ \text{in}$

Bending Stress $\sigma = \frac{M \cdot c}{I}$

Moment required to produce failure $M_{tube} := \frac{S_y \cdot I}{c} = 23752.5\ \text{in} \cdot \text{lbf}$

Classical Bending Diagram (Shigley) $M = \frac{F \cdot b \cdot x}{l}$

Force Required to Yield the Tubing $F_{tubing} := \frac{M_{tube} \cdot l}{b \cdot a} = 3487.5\ \text{lbf}$

APPENDIX A (continued)

Bolted Joint Stress Analysis

Failure load at bolted connection - **moment** applied at center of the bolt pattern (Single Shear of 2 Bolts)

Yield Strength	$S_{ybolt} = 95.7 \text{ ksi}$
Area over which bolt shearing would act	$A_{shear} = 0.085 \text{ in}^2$
Force required to shear a single bolt	$F_{shear\_bolt} := \langle S_{ybolt} \rangle \langle A_{shear} \rangle = 8113.3 \text{ lbf}$
Couple Distance between bolt heads	$s = 1.0 \text{ in}$
Moment Required to Shear Bolt Heads	$M_{bolts} := \langle F_{shear\_bolt} \rangle \ s = 8113.3 \text{ in} \cdot \text{lbf}$
Length of the Beam	$l = 37.0 \text{ in}$
Distance from Loading to Forward Support	$b = 28.0 \text{ in}$
Distance from Loading to Rear Support	$a = 9.0 \text{ in}$
Force Required to Shear Bolts due to Bending	$F_{bolt} := \dfrac{M_{bolts} \cdot l}{b \cdot a} = 1191.2 \text{ lbf}$

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