# Investigation of the May 4, 2014 incident at the Ringling Bros. and Barnum & Bailey performance in Providence, RI

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U.S. Department of Labor
Occupational Safety and Health Administration
Directorate of Construction


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## Introduction

On May 4, 2014, an incident occurred at the Dunkin' Donut Center in Providence, Rhode Island during the 11:00 a.m. performance of "Ringling Bros. and Barnum & Bailey Presents Legends". At the time of the incident, the "Hang Hair Act" was being enacted. The "Hang Hair Act" involved eight performers in an aerial act where the performers, aka hairialists, were suspended from their hair alone with their hands and feet free to perform swinging and spinning motions in a choreographed acrobatic manner. Suddenly, during the act, the metal apparatus supporting the performers plummeted in excess of 20 feet to the floor below along with the performers injuring all eight performers to varying degrees. Two of the performers sustained critical injuries. A dancer on the floor was also caught in the mishap, and was also injured. In total, there were injuries to nine employees. Rescue workers and police immediately responded to the call, and the injured performers were taken to the nearby hospital.

Ringling Bros. and Barnum & Bailey is a subsidiary of Feld Entertainment, Inc., (Feld) which has its headquarters on the gulf coast of Florida. Besides Ringling Bros. and Barnum & Bailey, Feld has many other subsidiaries, e.g., Disney on Ice, Disney Live, Feld Motor Sports, etc.

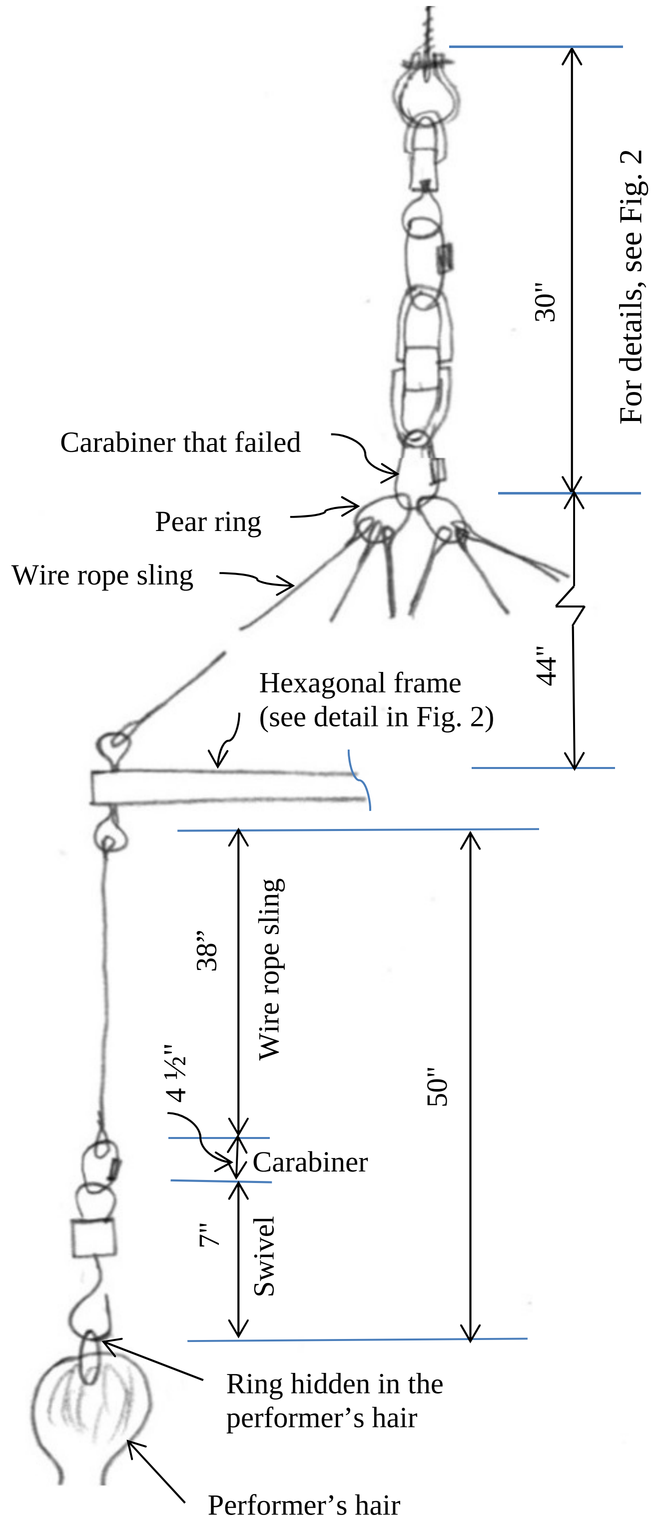
The Directorate of Construction (DOC) of the Occupational Safety and Health Administration's (OSHA's) National Office, in Washington, DC, was asked by OSHA's Region I to provide engineering assistance to OSHA's Providence Area Office to determine the cause of the collapse. Personnel from the Area Office went to the incident site to observe the failure, and to discuss the incident with company officials. It was soon discovered that a metal carabiner near the top rigging of the apparatus had failed; this became a prime suspect for the cause of the incident. OSHA's Providence Area Office took possession of the failed carabiner for metallurgical examination. Feld took possession of all other parts of the apparatus including the metal frame, wire rope slings, swivels, other carabiners, etc., and stored them in a secured storage facility at 2100 US highway 301, Palmetto, Florida for later examination by interested parties. A structural engineer from DOC visited Palmetto on July 21, 2014 to examine the retrieved pieces and to take measurements and photographs.

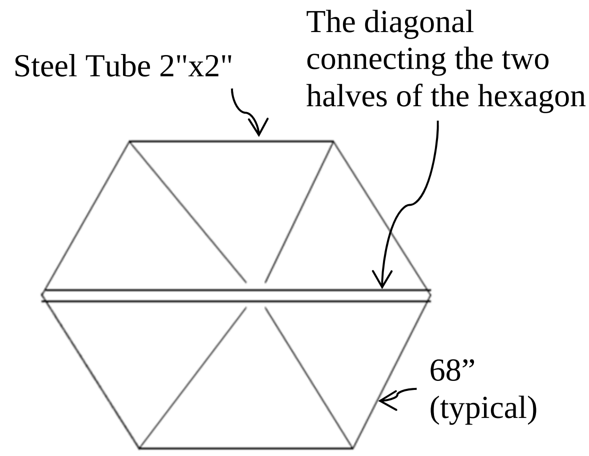
## Hair Hang Act

The hair hang act is advertised as a spectacular and thrilling act to perform and watch, see photo on the report cover. Six performers are hung from their hair from an overhead hexagonal steel framed apparatus, see Fig. 1 and 2, with wire rope slings, carabiners, swivels with hooks. The hook engages to a steel ring concealed in the hairdos of the performers, see Fig. 1.The swivels have an almost frictionless rotational capability of 360 degrees. The swivel allows the performers to spin their bodies full circle about the vertical axis. The entire apparatus which they are hung from could also rotate clockwise or counter-clockwise due to the motion generated by the performers. The apparatus' movement is possible due to a swivel located near the very top of the rigging, see Fig. 2. In addition to the six performers hung at each corner of the hexagonal apparatus, there are two additional performers who engage in acrobatic dancing while lowering or raising themselves at the center of the apparatus. The two performers at the center are supported by fabric "lanyards" decoratively woven and wrapped, see photo on the report cover. The upper center performer is hung upside down by the lanyards fastened to the horizontal center diagonal member of the apparatus where the two halves of the apparatus are connected. The lower center performer is hung by wire rope slings connected between the hairdos of the top and bottom center performers.

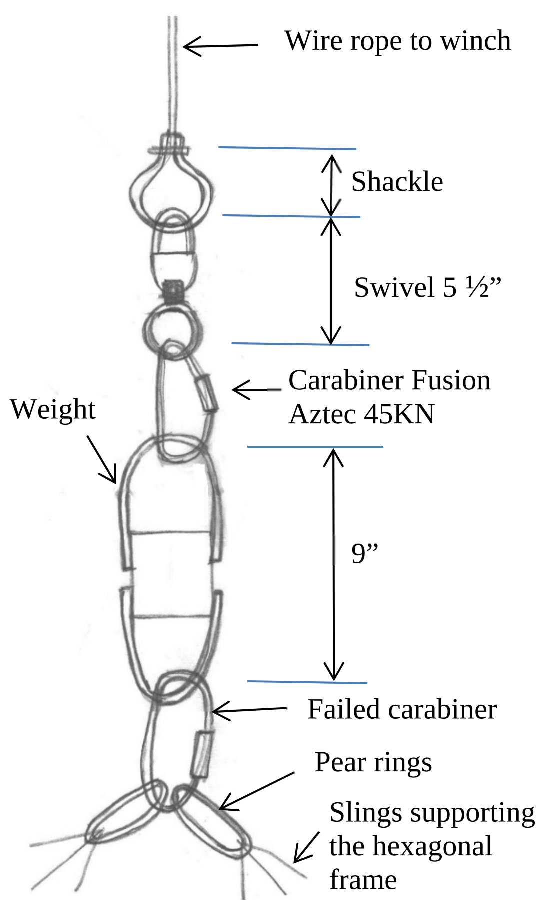
## The apparatus and its rigging

The hexagonal apparatus and its rigging were organized in a manner which employed several wire rope slings, swivels, carabiners, shackles, pear rings, weight, etc. One of the carabiners near the top, identified as failed carabiner in Fig. 2, was subjected to tri-axial loading, and failed, discussed in detail later in the report. The failed carabiner contained two pear rings supporting the apparatus which was the primary structural frame. Each pear ring held three slings connected to the three corners of the apparatus. All other carabiners and other parts remained intact after the incident.




Hexagonal Steel Frame Plan




Note: Fig. 1 & 2 are hand-drawn; Not to scale; Dimensions shown are approximate

Fig. 1 – Schematic of rigging

Fig. 2 – Top assembly of rigging parts

The primary structural framing of the apparatus was a hexagonal welded steel frame with each side equal to approximately 68 inches, see Fig. 2 and 3. The hexagonal frame consisting of 2”x2” steel tube was fabricated in two halves joined together with four connecting plates and fasteners, see Fig.s 4 thru 7. Each corner of the frame included two eyelets, one above and the other below the frame, see Fig.s 3, 8 and 9. The bottom eyelet supported the vertical slings, 38 inches long, to support a performer, see Fig. 1. One performer was supported at each corner of the hexagon. The wire rope slings were equipped with thimbles at each end. The upper end of the sling was attached to the bottom eyelet of the apparatus, and the lower end of the sling was attached to a carabiner which was fastened to a swivel with a hook meant to engage the ring hidden in the hairdo of the performer, see Fig.s 1, 10 thru 12. A close-up picture of a carabiner and swivel is shown in Fig.s 13, 14, 15 and 16.

Fig. 3 – Hexagonal frame placed on a table after the incident

Fig. 4 - Hexagonal framing in plan

Fig. 5 - Hexagonal framing in plan view

Fig. 6 – Hexagonal framing in plan view

Fig. 7 - Separation of two halves of hexagonal frame

Fig. 8 - Sling attachment to framing at each corner of the hexagonal framing

Fig. 9 - Part of the hexagonal tubing framing

Fig. 10 - Swivel hook with socket, carabiner

Fig. 11 – Sling, carabiner and swivel to support a performer

Fig. 12 – Sling, carabiner and swivel to support a performer

Fig. 13 - Close up picture of swivel and carabiner to support a performer

Fig. 14 - Close up picture of swivel to support a performer

Fig. 15 - Close up view of sling, carabiner and swivel to support a performer

Fig. 16 – Another view of the assembly to support a performer

The diagonal where the two halves of the hexagon were connected had four eyelets to connect a performer, upside down, at the center of the apparatus, see photo on the report cover. At the time of the incident, only the two farthest eyelets were used to connect the performer. The upside down performer at the center was then connected below to another performer by wire rope sling, carabiners and swivels. The swivels were engaged to the hidden rings of the hairdos of the two performers. The top performer was connected with fancy fabric slings to the eyelets connected to the center diagonal member of the apparatus, see

photo on the report cover and Fig.s 17 thru 20.

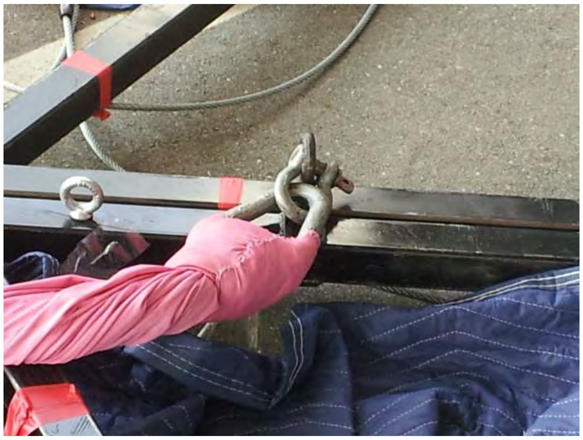


Fig. 17 – Rigging for the center performer

Fig. 18 – Rigging for the center performer

Fig. 19 - Rigging for the center performer

Fig. 20 - Rigging for the center performer

As described above, one eyelet was provided above each of the six corners of the hexagon to fasten to a wire rope sling to support the hexagonal apparatus at six corners. The hexagonal frame was supported by six diagonal wire rope slings, one at each corner. The diagonal slings were approximately 81 inches long. Three of the slings were grouped together and connected to a pear ring, see Fig.s 21 thru 23. There was, therefore, one set of two pear rings supporting the six sloping slings. The two pear rings were then fastened to a carabiner at the top. The pear rings were approximately 44 inches above the apparatus frame. The carabiner was then attached to another carabiner, one over the top of the other. The topmost carabiner was fastened to a weight approximately 9 inches long. The weight was then fastened to yet another carabiner which was attached to a swivel, approximately 5 ½” long. Finally the swivel was attached to a shackle which was hooked to wire rope and to a winch, see Fig.s 24 thru 30.

Fig. 21 - Pear rings to support the frame

Fig. 22 - Pear ring with three slings attachment

Fig. 23 - Pear ring with three slings attachment

Fig. 24 – Top rigging (also see Fig. 2)

Fig. 25 - Top rigging (also see Fig. 2)

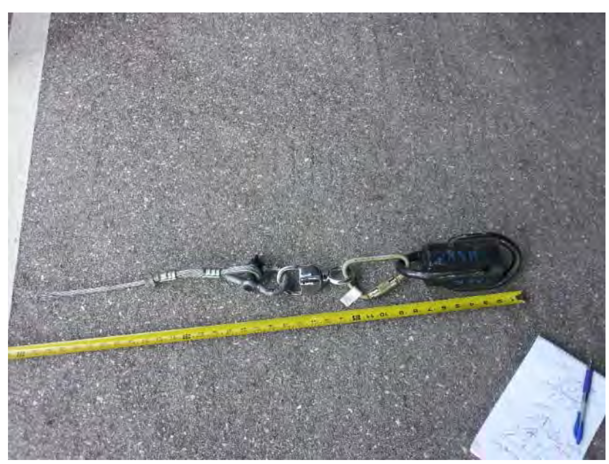


Fig. 26 - Top rigging (also see Fig. 2)

Fig. 27 - Top Rigging

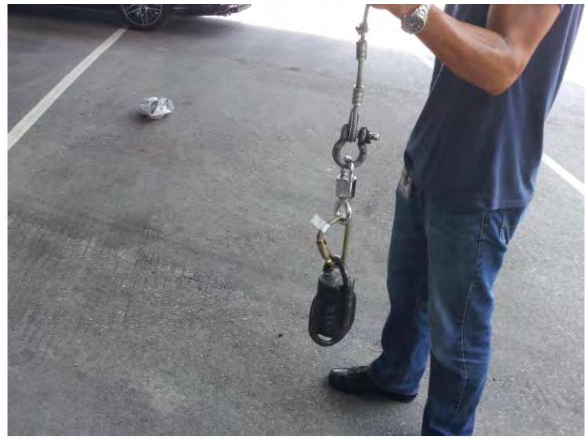


Fig. 28 - View of weight, carabiner, swivel and shackle

Fig. 29 - Close up of weight and carabiner at top rigging

Fig. 30 - Another view of top-most shackle and swivel

**Laboratory Examination**

The failed carabiner, see Fig.s 31, 32 and 33, was sent to Massachusetts Material Research, Inc. (MMR) of West Boylston, MA for non-destructive testing following usual chain of custody procedures. The general purpose was to examine the fractured surfaces of the carabiner to determine the type, origin and nature of failure. The first six pages of the narrative of the MMR report of September 18 is attached to this report, see appendix A.

Fig. 31 - Fractured pieces of carabiner and non-failed similar carabiner

Fig. 32 – Fractured pieces of failed carabiner

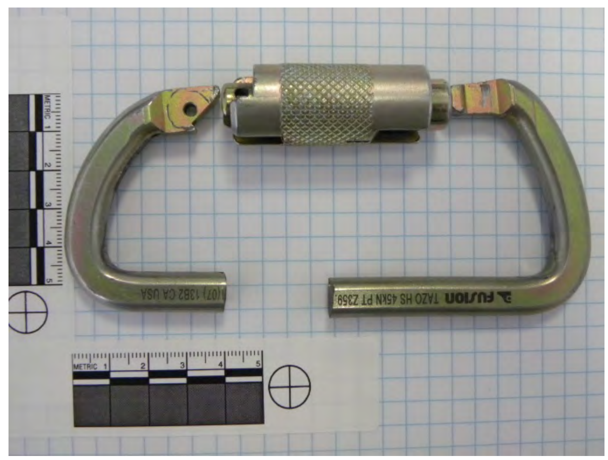


Fig. 33 – Fractured pieces of failed carabiner

MMR conducted a visual examination followed by scanning electronic microscope and energy dispersive x-ray spectroscopy examinations.  Dimensions of the failed carabiner at critical locations were taken and tabulated in the report.

The lab determined that the fracture essentially was a result of an overload, with origins at the retainer pin hole. A summary of the findings of the laboratory is reproduced below:

*SUMMARY OF FINDINGS OF THE LABORATORY*

*"The failed carabiner appeared to be in overall satisfactory condition from a physical viewpoint. The failed carabiner did not reveal any corrosion, significant surface anomalies, excessive wear, etc., which could have contributed to the failure. The fracture was identified to be due to an overload condition. A significant amount of intergranular fracture was noted together with ductile dimple features. No significant anomalies were detected at the fracture origins. The*

*fracture occurred through approximately the mid-diameter of a retainer pin hole present at the ID surface of the straight arm of the carabiner loop.*
*The carabiner was made, most likely, from an alloy steel. The carabiner was zinc plated with a chromate surface finish."*

**Evaluation by OSHA's Salt Lake Technical Center**:

The Salt Lake Technical Center (SLTC), Materials Investigation Team, examined a similar carabiner, and reviewed the MMR report including photographs of the failed carabiner taken by MMR.   SLTC conducted study on the physical attributes of the carabiner and the fractured surface as described and photographed by MMR.  SLTC's report is attached in appendix B.

## Analysis and Discussion

The carabiner that failed was Fusion TAZO, see Figs. 32 and 33 above.  A similar unfailed carabiner is shown in Fig. 34. It was made of alloy steel believed to have an average ultimate tensile strength of 80,000 to 120,000 pound per square inch (psi).  The ultimate strength is the maximum stress a material can sustain before breaking due to tensile failure.  As discussed earlier, the carabiner is imprinted with a breaking strength of 45 KN (10,000 pounds). Based on the accurate measurement of the net area of the spine taken by OSHA's Salt Lake Testing laboratory, to be 0.1076 square inches, the ultimate tensile strength is determined to be 93,000 psi which is within the range mentioned above.


Fig. 34 –  A carabiner similar to the failed carabiner

Carabiners, aluminum or steel, are manufactured for the specific purpose of supporting a load in the major axis of the spine of the carabiner. The major axis is along the long spine of the carabiner. The capacity of the carabiners in the minor axis with or without the closed gate is significantly reduced. For example, the carabiner in question had a major axis load carrying capacity of 45 KN (45KN x 224.8= 10,116 pounds) but had a capacity of only 16 KN (3,596 pounds) in the minor axis. The load test confirmed the load capacity of the carabiner along the major axis. It must be noted here that these capacities are not to be considered concurrent. In other words, one can rely on these capacities singularly, but not when simultaneously loaded in both axes. Further, these loads are based on static loading without any impact due to the dynamics of the load being applied. In this instance, the carabiner was subjected to significant impact loads due to twisting, revolving, swinging and acrobatic dancing of the performers while being supported by the carabiner, see Fig. 35.

Fig. 35 – Acrobatic movements subjecting the rigging to significant impact load (File photo; not taken on the day of the incident)

The carabiner was loaded with an approximate vertical load of 1,500 pounds, well below the breaking strength of 10,000 pounds, and still the carabiner failed.

The industry has long recognized that carabiners should not be loaded in a manner that could subject them to what is known as tri-axial loading. It is believed that there is not a single manufacturer that permits the users to load the carabiner in a tri-axial manner. Tri-axial loading subjects the carabiner to forces in its major and minor axes simultaneously, see Fig.36 and 37. This becomes additionally critical because the bottom part of the carabiner is not flat but curved, which shifts the pear rings to different elevations. The different elevations of the pear rings subject the carabiner to additional rotation until equilibrium of forces is achieved. Each pear ring supports three inclined wire ropes connected to three locations on the apparatus frame. This produces inclined force on the carabiner which can be resolved in vertical and horizontal directions. Since there were two rings, at different elevations, the carabiner had to adjust and rotate until all the forces created by the two rings were in a state of equilibrium. The carabiner is constantly undergoing rotations and adjustments due to the dynamic nature of the load.


Fig. 36 – A similar carabiner subjected to tri-axial Loading by similar pear rings (wrong way)
(Courtsey: OSHA's Salt Lake Technical Center)

Fig. 37 – A similar carabiner loading in major axis (correct way)

There is another complexity in the design of the carabiner which arises from the fact that the gate of the carabiner is not in physical contact with the upper body of the carabiner until some deformation takes place. At the nose of the carabiner, there is a $^1/_8$” – $^1/_4$” separation in the horizontal and vertical direction between the gate and the body of the carabiner. That is due to the nature of the gate which permits the gate to open and close. Therefore, initially the carabiner acts like an open-ended section with the bottom portion acting like a cantilever. The carabiner will adjust itself in a manner based on the principle of least energy such that the two vertical and horizontal components of the forces are in equilibrium, and this does not result in any twisting at the point where the carabiner is supported.

Calculations indicate that each pear ring, when placed in the narrower part of the carabiner, will exert a horizontal force of approximately 770 pounds, and vertical force of approximately 750 pounds on the carabiner. Based on the concept presented above, a number of calculations were done to determine the final resting position of the carabiner where all forces balance each other. Fig.s 38 and 39 indicate the two extreme positions of non-equilibrium at the angles of 0 and 20 degrees. Fig. 40 indicates that at an approximate angle of 10½ degrees to the vertical, the carabiner will have negligible moment at the top support, see Fig. 40. At this position, the spine of the carabiner where the pin hole for the gate-keeper is located, the weakest point of the carabiner, will be subjected to a moment of 1,100 inch pounds. Adding an impact factor of 25%, the resulting moment is calculated to be 1,360 inch pounds. The section modulus of the spine was calculated to be 0.0075 inch cube taking into account the reduction due to the pin hole in the spine, see Fig. 41 and 42. Elastic section modulus was used instead of the plastic section modulus due to non-symmetrical shape of the spine. The non-symmetrical shape was created by the presence of a pin hole. The stresses were computed to be 183,000 psi, well above the ultimate strength, and this caused the failure. The section modulus was computed based on the accurate measurements taken by Massachusetts Materials Research, Inc. The magnitude of the loads computed above is of an order which will not result in any appreciable deformation of the carabiner, maintaining the original space between the gate and the body of the carabiner.

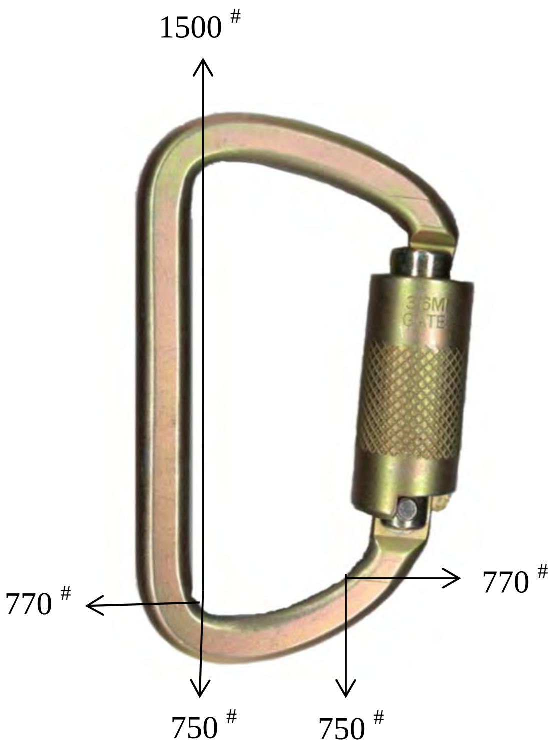



Fig. 38 – Initial stage- state of unequilibrium

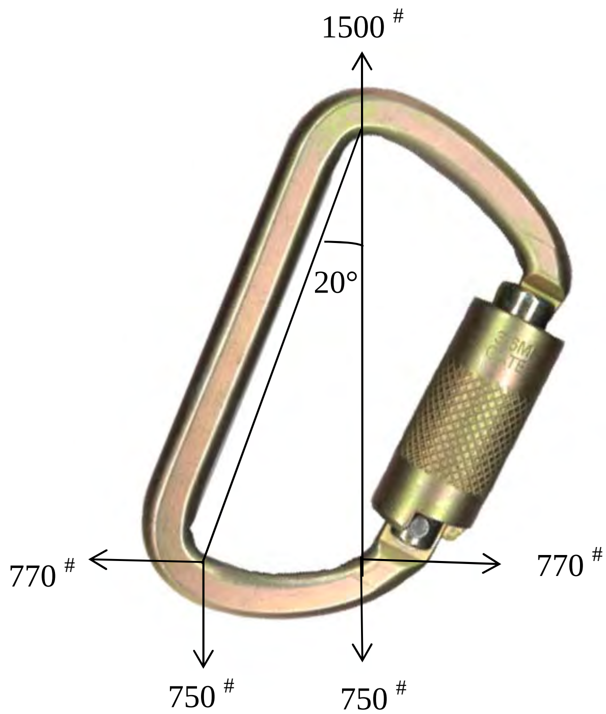



Fig. 39 – Another stage- 20 degrees

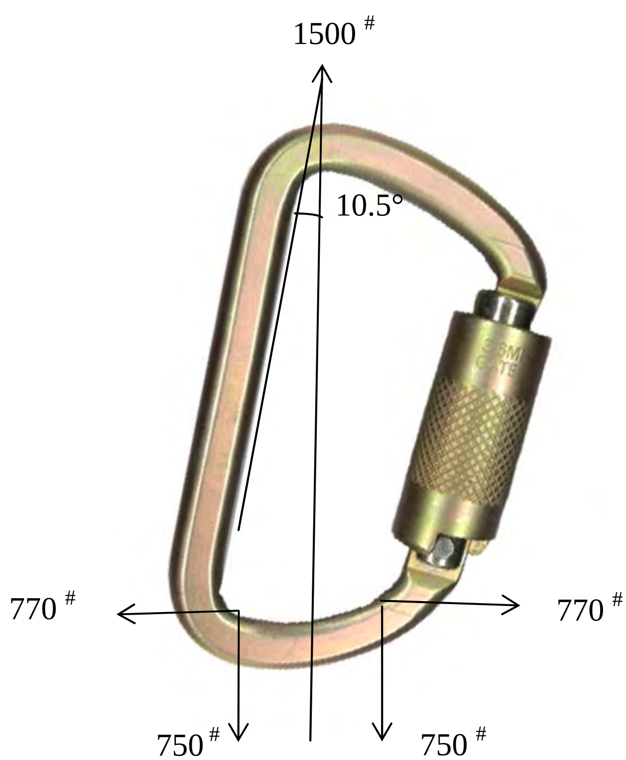



Fig. 40 – Final state at 10.5 degrees – State of equilibrium (rings placed in the narrower part of the carabiner)

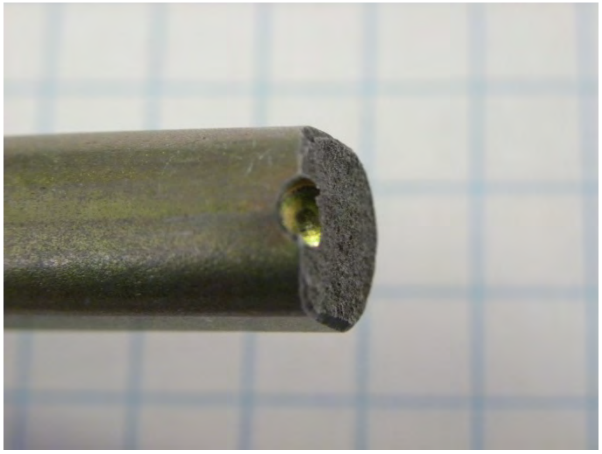


Fig. 41 – Location of the pin hole

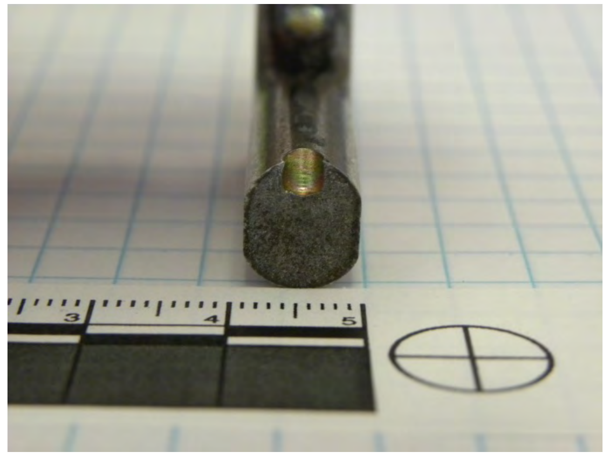


Fig. 42 – Another view of the location of the pin hole

Calculations were also performed to determine the stresses in the carabiner if the pear rings were placed in the wider part of the carabiner instead of the narrower part, as shown in Figs. 43 thru 45. The carabiner became balanced at an angle of 11.5 degrees. The resulting flexural moment was determined to be 780 inch pounds. Adding an impact factor of 25%, the resulting moment was 975 inch pounds with flexural stresses of 130,000 psi, well above the ultimate strength of the material. It is, therefore, determined that failure of the carabiner would occur regardless of where the pear rings were placed either in the narrower or the wider part of the carabiner.

The 1/8” diameter rivet pin connecting the gate to the carabiner’s lower body is generally made of alloy steel but of a lower strength compared to the high-strength steel of the carabiner because the pin generally is not subjected to any load.

The question of why the carabiner did not fail in earlier performances could have several explanations. First, the impact load on the carabiner at the time of the incident could have suddenly surged due to the dynamics of the performance, significantly increasing the load on the carabiner, see Fig. 35. Second, the alloy steel could have a yield strength greater than the assumed value as the yield strength is known to vary between batches. Third, all the six slings supporting the apparatus might not have equal tension, subjecting the carabiner to asymmetrical loading. Regardless, the root cause of the failure was the tri-axial loading of the carabiner in violation of the industry practice and the instructions of the manufacturer.

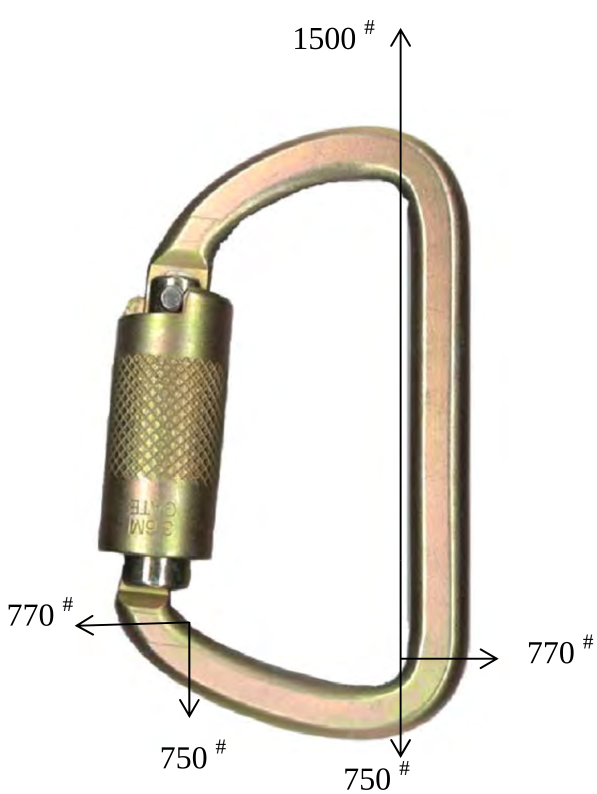



Fig. 43 – Initial stage- state of unequilibrium

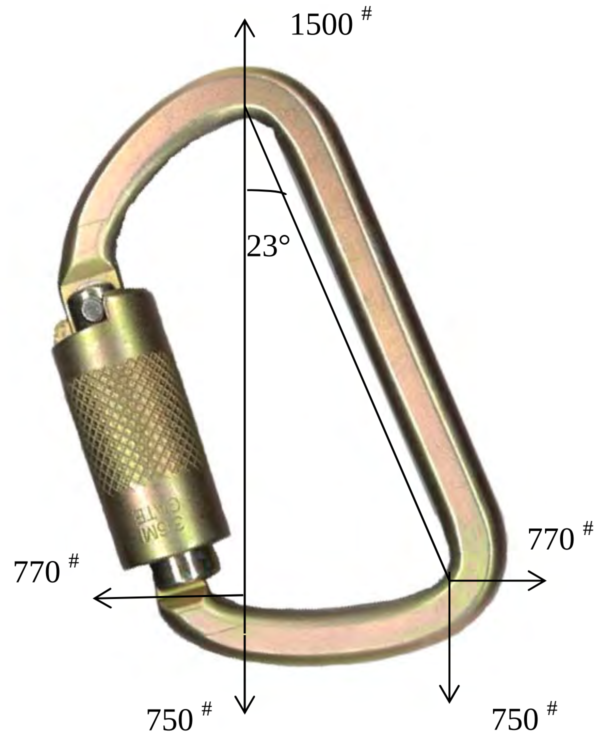



Fig. 44– Another stage- 23 degrees

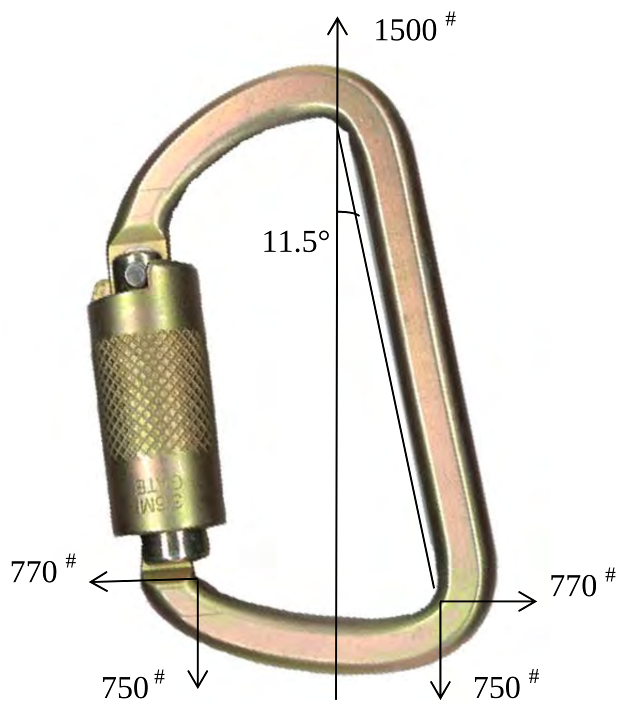



Fig. 45 – Final stage at 11.5 degrees – State of equilibrium (rings placed in the wider part of carabiner)

## Conclusions

1. The cause of the failure of the carabiner was the manner in which it was loaded, subjecting the carabiner to tri-axial loading in violation of industry practice and the instructions of the manufacturer. The carabiners are designed to be loaded in their major axes along the spine.
2. Feld Entertainment, Inc./Ringling Bros. and Barnum & Bailey acted in an imprudent manner to rig the entire metal frame supporting eight performers on two pear rings attached to a carabiner. As there was no redundancy in the system, when the carabiner failed due to tri-axial loading, the entire frame with the performers attached fell to the ground.
3. There is no document available to indicate that the rigging supporting several performers was ever reviewed and checked by a professional engineer for its structural adequacy and performance. This was a serious flaw that led to the incident.
4. One of the means of abatement was to place the two pear rings in a shackle instead of a carabiner.

# APPENDIX A

(Narrative of the MMR report of September 18)

## 1. BACKGROUND

Massachusetts Materials Research, Inc. (MMR) performed an investigation on a failed carabiner from OSHA. A similar functioning carabiner was also examined for comparison with the failed one. Reportedly the failed carabiner is from the Ringling Brothers Circus May 4, 2014 incident. The functioning carabiner is also from the same group as the failed one.

It was a witnessed investigation in the presence of other interested parties. The list of the parties present during the investigation is presented in Appendix A.

The credentials of MMR personnel performing the analysis and operation of analytical tools, as well as documentation of MMR laboratory credentials and certifications, failure analysis protocol, and the calibration records for the analytical tools are also presented in Appendix A.

This was a nondestructive investigation.

## 2. INVESTIGATION

Overall visual examination was performed on the fractured components from the failed carabiner as well as the new one with photographic documentation. The pieces arrived in a packaged box which was opened and each individual piece from each evidence/property package was removed with photographic documentation at every step. The pieces were examined visually and documented photographically. Dimensional measurements were performed using a micrometer.

In-detail stereomicroscope examination was performed on the components of the failed carabiner at up to a magnification of 50X. The fracture surfaces and all the surface areas of the failed components were examined in detail and documented. Relevant areas of the functioning non-failed carabiner were also examined as necessary.

Scanning electron microscope (SEM) examination was performed on one of the mating fracture surfaces of the carabiner and on the gate/connector. Note that this examination is performed at relatively high magnifications to determine the fine features associated with the fracture and in the crack initiation areas. The crack initiation areas are called “origins.” This examination would identify any anomalies at the crack origin areas and on the fracture. If there is post fracture damage, sometimes, the actual conditions at the origin areas may not be determined.

Energy dispersive x-ray spectroscopy (EDS) was performed on the fracture surface and on the outer diameter (OD) surface of the failed carabiner. EDS is a semi-quantitative microchemical analysis technique performed using equipment attached to the scanning electron microscope (SEM). This is an elemental analysis technique. The analyses were performed both in the standard and in the “Light Element" (LE) modes. Note that the LE mode is more sensitive to the elements with lower atomic weights (e.g. carbon, oxygen). The graphs obtained from the EDS analysis are called “spectrograms”. The peak heights of each element on the graph indicate the relative amounts of the elements present in the particular area analyzed. The elements are reported qualitatively as major, minor and trace amounts.

EDS analysis would identify semi-quantitatively any foreign contaminants, plating, corrosion deposit, inclusions, etc. in the areas of interest.

## 3. RESULTS

### 3.1 Visual Examination

An overall view of the evidence/property packages with three components of the failed carabiner is shown in Figure 1. The three individual broken pieces of the failed carabiner are displayed in Figures 2-4. After the documentation the pieces were taken out from the evidence packages. An overall view of the functioning carabiner is shown in Figure 5. Figure 6 shows the failed carabiner. The arrow in Figure 6 points to the crack area of the carabiner. Note that the gate/connector was separated from the carabiner. The different pieces from the failed carabiner were marked 1a, 1b and 1c for identification purposes. Views of the functioning and the failed carabiners placed side-by-side for comparison purposes are displayed in Figures 7 and 8. In Figure 8 the dotted black line shows the two holes which were present on the inner diameter (ID) surface of the carabiner which are intended for a retainer pin. Note that the fracture of the failed carabiner occurred through one of these holes which was present on the longer straight arm of the carabiner.

The gate/connector of the carabiner works in a keychain type locking mechanism. One end of the gate, left hand side in Figure 8, is connected to the carabiner loop with a rivet. The opposite end on the right-hand side is the locking/opening slot. The gate can be rotated to line up the slot of the gate with the caribiner end which can be slid out from the gate. The gate can be pushed inward for unlocking. The gate swivels around the rivet at the riveted end.

Close up views of the fractured section 1a, longer piece, from the opposite surfaces are shown in Figures 9 and 10. An overall view of the identification markings is shown in Figure 11. Figures 9 and 11 show the numbered locations where the diameters were measured for pieces 1a and 1b. The fracture surface from the overall ID for piece 1b, the shorter piece, is shown in Figure 12.

An overall view of the gate from the failed carabiner is shown in Figure 13. On the top is the gate of the functioning carabiner. On the left hand side is the riveted end of the gates. Note a longitudinal crack pointed by the arrows in the failed carabiner in Figure 13. Later higher magnification examination indicated that the crack propagated for about half of the length of the gate.

Figures 14 and 15 show the locking mechanism of the carabiner. Figure 14 shows the locked position. Note the slot at the lower end of the gate towards the ID of the loop. Figure 15 shows the position where the gate is rotated counterclockwise and the slot is now lined up with the carabiner loop end and the gate can be pushed downward to be in an open position.

In-detail overall examination of the failed and the good carabiner revealed that there were no significant surface anomalies on the failed carabiner. Some shallow scratches/markings were noted which can be typically expected from being in service for a few years. The overall surface revealed a yellowish gold color which is typical of a zinc plated and chromated surface. The connecting rivet of the gate end carabiner loop was missing and was not found after the incident..

### 3.2 Dimensional Measurements

The overall diameters of the failed carabiner were measured for both sections 1a and 1b. The measurements are shown in Table I below. The long and short diameter values are consistent without any significant variations.

**Table I**
**Failed Carabiner: Dimensions**

| Piece/Location | Diameter (inches) | |
|---|---|---|
| **Piece 1a (Fig. 9)** | | |
| **Location** | **Long** | **Short** |
| 1 | 0.414 | 0.346 |
| 2 | 0.411 | 0.347 |
| 3 | 0.411 | 0.346 |
| 4 | 0.413 | 0.346 |
| 5 | 0.408 | 0.344 |
| 6 | 0.406 | 0.345 |
| 7 | 0.386 | 0.346 |
| 8 | 0.413 | 0.346 |
| 9 | 0.413 | 0.346 |
| 10 | 0.379 | 0.370 |
| | | |
| **Piece 1b (Fig. 11)** | | |
| **Location** | **Long** | **Short** |
| 1 | 0.413 | 0.346 |
| 2 | 0.410 | 0.346 |
| 3 | 0.410 | 0.346 |
| 4 | 0.386 | 0.346 |
| 5 | 0.405 | 0.346 |
| 6 | 0.411 | 0.346 |
| 7 | 0.410 | 0.347 |
| 8 | 0.403 | 0.351 |
| 9 | | |

### 3.3 Stereomicroscope Examination

Both fractured pieces 1a and 1b were examined in detail in the stereomicroscope including the fracture surfaces, OD surfaces and the ends of the carabiner loops. In-detail examination was also performed on the gate/connector of the failed carabiner.

Piece 1a: An overall view of the fracture surface is shown in Figure 16 with a rotated view in Figure 17. The arrows in Figure 18 point to the approximate origin areas of the fracture. The origins are at the two corners of the retainer pin hole. The view shows that the fracture occurred almost through the mid-diameter of the hole. No macro crack arrest markings or any evidence of progressive type fracture features were noted on the fracture surface. The fracture appeared to be an overload failure. In Figure 17 a shear lip is noted around the fracture. Later higher magnification SEM examination was performed on the fracture. A tilted view of the fracture origin at the hole diameter is shown in Figure 19. Examination was performed on the overall ID surface of the carabiner loop for evidence of any fine cracks and none were noted.

Representative views of the OD surface of the sample are displayed in Figures 20-22. Some shallow markings were noted in some locations but they did not appear to be related to the fracture. These markings appeared to be more from service/handling over the years. An overall view of the open/close end of the carabiner loop is shown in Figure 23. The markings are from service. The representative views of the overall ID surface of the carabiner loop are displayed in Figures 24-30. Again, all the markings appear to be superficial and related to normal service conditions. Representative views from the flat surface of the carabiner loop are shown in Figures 31 and 32.

Gate: Overall views of the gate at the open/close end are displayed in Figures 33 and 34. The fixed or riveted end of the gate revealed a crack which was shown in the overall view in Figure 13. Close up stereomicroscopic views of this crack are presented in Figures 35-40. This crack initiated at one of the radii and propagated in the lengthwise direction of the gate. The crack length was about half of the length of the gate. Note that the exact tip of the crack could not be determined as it was significantly fine. During the SEM examination the approximate crack tip area was determined but it could not be unequivocally confirmed whether the fine cracks were on the plated layer or in the base metal. The radius opposite to the cracked one is shown in Figure 41. No crack was noted at this radius. Overall views of the rivet holes on the gate are displayed in Figures 42-45. No significant differences were noted between the rivet hole near the cracked radius and the one at the opposite location.

Piece 1b: Overall views of the fracture are displayed in Figures 46 and 47 with a tilted view in Figure 48. This mating fracture surface also clearly indicates that the crack initiated at the mid-diameter of the hole and no progressive type of features were noted. Representative views of the OD surface of the piece are shown in Figures 49 and 50. The connector end is presented in Figure 51. Representative views of the overall ID surface of the carabiner loop are displayed in Figures 52-56. All the surface features noted on this piece can be typically expected from service and no significant anomalies were noted.

### 3.4 EDS Analysis

Limited EDS analysis was performed for semiquantitative compositional information of the carabiner. Figure 57 shows the EDS spectrogram obtained from the mid-fracture of fracture surface (FS) 1a. The semiquantitative compositional results indicate that there is about 1wt.% chromium (Cr) and about 1wt.% manganese (Mn) with the balance being iron (Fe). This semiquantitative composition indicates an alloy steel.

A representative spectrogram from the fractured edge for piece 1a is shown in Figure 58 which indicated different contaminant elements in trace amounts, e.g., chlorine (Cl), potassium (K), calcium (Ca), oxygen (O) and zinc (Zn). All these elements are foreign contamination resulting from the surface being on the ground or from handling.

The analysis performed on the plating on the OD surface of the carabiner identified a major amount of zinc with a minor amount of chromium. The representative EDS spectrogram is presented in Figure 59. This analysis indicates that indeed there was a zinc plating present on the carabiner and, most likely, with a chromate surface finish.

### 3.5 SEM Examination

In-detail SEM examination was performed on the **fracture surface 1a**. For SEM photographs the operating voltage, magnification and comments are shown at the lower left hand side corner. The working distance used for the photographs was around 24mm.

An overall view of the fracture at the hole is shown in Figure 60. The radial marks identified the origin which are identified at the two corners or at the opposite ends of the diameter of the hole. The two corners were identified as areas x and y. The arrows point to the crack origin areas and the overall crack propagation directions. Both areas x and y were examined at higher magnifications and representative photographs are included in the report. All the areas examined at higher magnifications were identified with numbers and the examination was performed on the entire fracture surface.

A higher magnification view of area x in Figure 60 is shown in Figure 61. The fracture at the edge, Figure 62, of area x indicate a post fracture rub type damage. This may happen during the separation of the piece. Area 1 in Figure 61 is shown at a higher magnification in Figure 63. The fine fracture features indicate predominantly an intergranular type of fracture. Note the piece was not cleaned and there were many superficial debris on the fracture surface. Higher magnification views of the overall fracture around the hole traveling in a clockwise fashion are displayed in Figures 64-66. A higher magnification view of area 5 in Figure 61 is shown in Figure 67. The views predominantly revealed intergranular fracture with slight evidence of dimples in some locations. A higher magnification view of area 7 is presented in Figure 68. This view also shows intergranular fracture with some ductile overload features. The views from areas 9 and 10, about mid area of the fracture are displayed in Figures 69-71. These areas revealed more ductile separation with a lesser amount of intergranular fracture. The upper half of the fracture is shown in Figure 72. The areas identified were examined at higher magnifications and the representative views are presented in Figure 73-76. Note that these areas of the fracture revealed predominantly a ductile separation with an intergranular tendency.

A tilted view of the fracture showing the edge around the hole are displayed in Figures 77-79. No significant anomalies were noted at the crack origin locations.

An overall view of the **gate** at the crack location is shown in Figure 80 with a higher magnification view in Figure 81. Note that the crack ran in the lengthwise direction of the gate.

Near the radius the crack was slightly open as shown in Figure 81. The fracture surface at this location, area z, could be examined and is displayed in Figures 82 and 83. The fracture features indicate a ductile overload separation and the overall look of the fracture being woody along the lengthwise direction of the gate. An overall view of the radius where the crack was present is shown in Figure 84. No significant anomalies were noted.

The crack on the OD surface of the gate is shown in Figures 85-89. The entire length of the crack was documented and only representative views are displayed here. Towards the crack tip the crack became finer and appeared to be numerous and branched. We could not determine unequivocally whether these cracks were only in the plating and were not in the base metal.

## 4. SUMMARY OF FINDINGS

The failed carabiner appeared to be in overall satisfactory condition from a physical viewpoint. The failed carabiner did not reveal any corrosion, significant surface anomalies, excessive wear, etc., which could have contributed to the failure. The fracture was identified to be due to an overload condition. A significant amount of intergranular fracture was noted together with ductile dimple features. No significant anomalies were detected at the fracture origins. The fracture occurred through approximately the mid-diameter of a retainer pin hole present at the ID surface of the straight arm of the carabiner loop.

The carabiner was made, most likely, from an alloy steel. The carabiner was zinc plated with a chromate surface finish.

# APPENDIX B

Report from OSHA Salt Lake Technical Center
dated 9 October 2014

**Report Date:** 9 October 2014
**Company:** Feld Entertainment
**Inspection number:** 975518
**Compliance Officer:** Robert Sestito
**Area Office:** Rhode Island
**Region:** 1
**SLTC Staff**: Daniel T. Crane

**Feld Entertainment at Ringling Bros. and Barnum and Bailey Circus – Failure of a Carabiner Used in Rigging.**

A carabiner failed on 4 May 2014 during a performance, causing an aerial apparatus to fall to the ground, injuring nine workers. Eight performers were hanging from their hair and performing the "Hair Hang Chandelier Performance" on an apparatus designed for the act. A ninth performer was below the apparatus and was injured when the apparatus and other performers fell on him.


**Photo 1:** Hair Hang Chandelier Performance. Six performers are on the outer ring. At the time of the incident, one performer was at the center and one was underneath on the ground. AP Photo Frank Caprio

The Salt Lake Technical Center, Materials Investigations Team provided information and material to the OSHA Directorate of Construction (DOC) and is providing investigative information in this report.

Laboratory analysis was performed by Massachusetts Materials Research, Inc, (MMR). Imaging by scanning electron microscopy (SEM), digital imaging (DM) and Keyence microscopy were performed along with chemical analysis on each of the three pieces of the carabiner.

Fusion provided an exemplar carabiner and SLTC locally procured two Crosby™-type ½" pear rings similar to those used on the apparatus. The pear



rings were used to connect six wire ropes from the corners of the hexagon to the carabiner at the center. The carabiner and pear rings were sent to DOC for their use.

Photo 1 is representative of the apparatus configuration during use.

**Description of the carabiner**

The carabiner was identified as a Fusion, TAZO, FP-9103GPK-HS steel alloy with a minimum breaking strength of 45kN (10,000lbs)[1]. The markings on the carabiner are: FUSION TAZO HS 45kN PT Z359.1 (07) 13B2 CA USA. It has a key nose and is a modified D design.

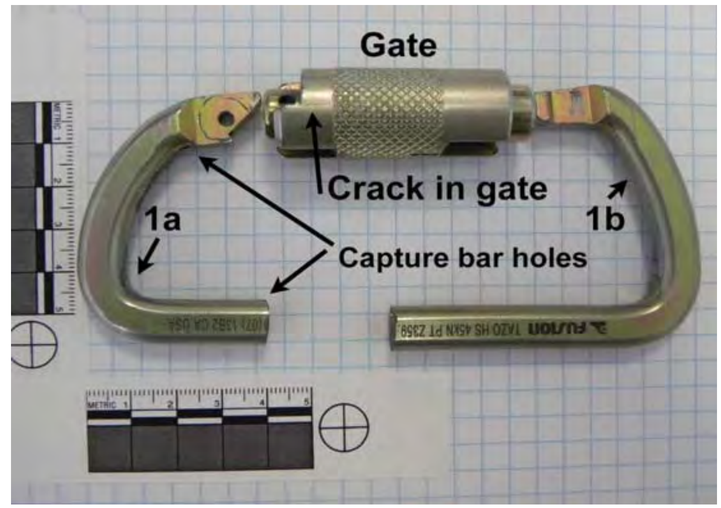



**Photo 2:** Failed carabiner. This image shows the identification of the parts, the location of the capture bar holes, the location of the crack in the gate and the main fracture in the long side or back of the carabiner.

The dimensions of the carabiner from the specification sheet provided by Fusion are in Figure 1. The published overall length is 4.37", the width is 2.47", the diameter of the body is 0.42" and the gate size is 0.86". The figure lists the strength as 45kN and the gate strength as 3600lbs.[2]

[1] Part identified by Fusion Product Specialist, Frank Hsu, Personal communication, 17 May 2014
[2] Information provided by Fusion Product Specialist, Frank Hsu, Personal communication, 19 August 2014

Only the body major and minor chord diameter measurements were provided by MMR. They were provided in Table 1 of their report. (Reproduced here as Table 1). For the purposes of this report, only the values at position 1 of parts 1a and 1b are used for area calculations. The body cross section is not round. It is flattened in one dimension as can be seen in both photos 3 and 4 which are digital images of the fracture surfaces of 1 a and 1b.

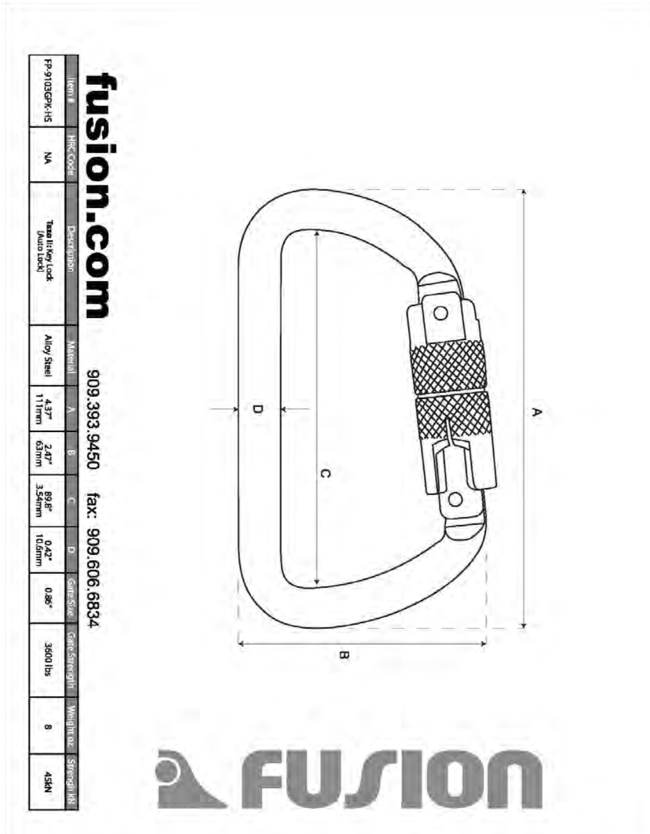



**Figure 1:** Nominal dimensions of the failed carabiner provided by Fusion.



**Table 1: Failed Carabiner Dimensions of body**[3]

| Piece/Location | Diameter (inches) | |
|---|---|---|
| **Piece 1a (Fig. 9)** | | |
| **Location** | **Long** | **Short** |
| 1 | 0.414 | 0.346 |
| 2 | 0.411 | 0.347 |
| 3 | 0.411 | 0.346 |
| 4 | 0.413 | 0.346 |
| 5 | 0.408 | 0.344 |
| 6 | 0.406 | 0.345 |
| 7 | 0.386 | 0.346 |
| 8 | 0.413 | 0.346 |
| 9 | 0.413 | 0.346 |
| 10 | 0.379 | 0.370 |
| | | |
| **Piece 1b (Fig. 11)** | | |
| **Location** | **Long** | **Short** |
| 1 | 0.413 | 0.346 |
| 2 | 0.410 | 0.346 |
| 3 | 0.410 | 0.346 |
| 4 | 0.386 | 0.346 |
| 5 | 0.405 | 0.346 |
| 6 | 0.411 | 0.346 |
| 7 | 0.410 | 0.347 |
| 8 | 0.403 | 0.351 |
| 9 | | |

The material for the carabiner was JIS SCM435 cold forged alloy steel[4].
The theoretical materials properties for this steel are[5]:

| | |
|---|---|
| Tensile Strength | 980MPa (142,000 psi) |
| Yield Strength | 735MPa (107,000 psi) |
| Elongation | 12% |
| Reduction in Area | 50% |
| Impact | 71 |
| Hardness | ≤229HRB |

| **Table 2** | Composition | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| C | Si | Mn | Cr | Mo | P | S | Cu | Ni |
| 0.32-0.40 | 0.17-0.37 | 0.40-0.70 | 0.80-1.10 | 0.15-0.25 | ≤0.035 | ≤0.035 | ≤0.30 | ≤ 0.30 |

[3] Carabiner Testing, Massachusetts Materials Research, Project No. 102147, Table 1, page 3, September 18, 2014
[4] Information provided by Fusion Product Specialist, Frank Hsu, Personal communication, 10 October 2014
[5] For example: http://sclftg.en.alibaba.com/product/1181339106-0/ANSI_4135_JIS_SCM435_structural_alloy_steel.html (accessed 07 October 2014)

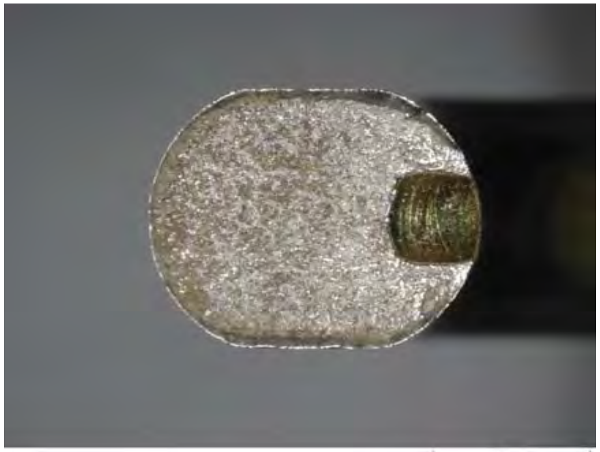


**Photo 3:** The cross section of the carabiner body, part 1a at the fracture. The dimensions given by MMR are 0.414" by 0.346". Note the hole for the capture bar at the right. Using Photoshop area function, the area of this piece was determined to be 0.119377 $in^2$. The area of the hole is 0.012423$in^2$.

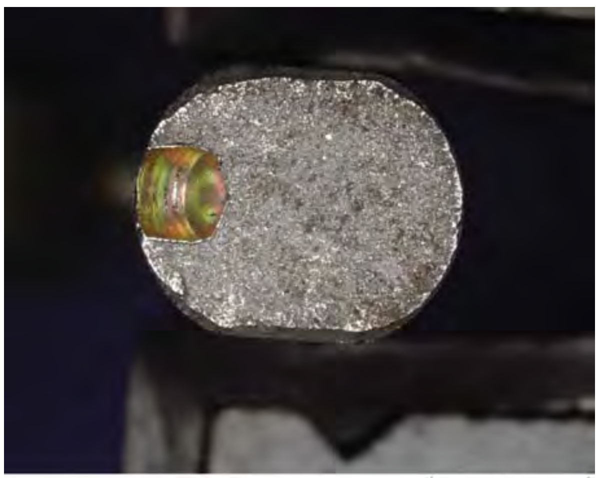


**Photo 4:** The cross section of the carabiner body, part 1b at the fracture. The dimensions given by MMR are 0.413" by 0.346". Note the hole for the capture bar at the right. Using Photoshop area function, the area of this piece was determined to be 0.120658$in^2$. The area of the hole is 0.012459$in^2$.



**Area Measurements**

The area of the carabiner back was determined using the area measurement of Photoshop™ applied to the raw images provided by Massachusetts Materials Research, Inc. (MMR) The area was determined as the average measured from image 1409A00129 (carabiner part 1a) and image 1409A00062 (carabiner part 1b). The images were calibrated to the major and minor chord measurements made and reported by MMR. (At locations 1 on pieces 1a and 1b.)

The average area of the carabiner back is: 0.12002 $in^2$
The average area of the hole for the capture bar is 0.01242 $in^2$
The net area is 0.12002 – 0.01242 = 0.1076 $in^2$

**Discussion**

The ANSI standard that applies to this carabiner is ANSI Z359.1 (07) 3.2.1.4. This requirement is that the carabiner, when tested according to ANSI Z359.1 (07) 4.3.1.1.1 shall be capable of withstanding a 5,000-pound (22.2kN) tensile load without breaking or distortion sufficient to release the gate. When tested according to ANSI Z359.1(07) 4.3.1.1.2, the gate of a carabiner shall be capable of withstanding a minimum load of 3,600 pounds (16kN) without the gate separating from the nose of the carabiner body by more than 0.125 inches (3.1 mm). When tested in accordance with ANSI Z359.1 (07) 4.3.1.1.3, the gate of the carabiner shall be capable of withstanding a minimum side load of 3,600 pounds (16kN) applied to a point midway between the nose and gate hinge without breaking, permanent deformation greater than 0.125 inches (3.1 mm), or separating from the nose of the carabiner body by more than 0.125 inches (3.1 mm)[6].

Using the area determined as 0.1076 $in^2$ and the tensile strength as 142,000 psi, the theoretical breaking strength of the carabiner is 15,300 lbs. However, this value is derived from standard tensile coupons cut from bulk stock for the particular grade of steel. The actual tensile strength depends upon the delivered size, shape, any surface defects or body heat treatment or cold work.

The value obtained for a tensile test of the material is obtained from a straight, longitudinal pull along the axis of an axially uniform test coupon. The stress on the carabiner is more complex, having a bending moment on the elements of the carabiner because the sides of the carabiner are offset to the center of the pull. In addition, the capture bar hole constitutes a surface flaw, or stress multiplier, on the side of the carabiner back which is in tension. This will cause the carabiner to fail below the ultimate tensile strength of the alloy steel.

Fusion indicated that the alloy steel used for this carabiner was cold forged[7], which will introduce internal stress to the finished carabiner. Fusion provided two test certificates for the

[6] ANSI Z359.1-2007 Safety Requirements for Personal Fall Arrest Systems, Subsystems and Components
[7] Information provided by Fusion Product Specialist, Frank Hsu, Personal communication, 10 October 2014

FP-9103GK-HS carabiner. One was dated October 13, 2009[8] and the second was dated May 12, 2014[9]. These are provided in the Appendix to this report.

Note that neither certificate shows a gate load test required for ANSI Z359.1 (07). They only list the tensile test specified in ANSI Z359.1 (07) 4.3.1.1.1.

Certificate 0062083-1 indicates that the carabiner was pulled to 5000 pounds, held for 1 minute, and then pulled to destruction at 10,000 pounds. It indicates that the carabiner passed.

Certificate 0081656-2 indicates that the carabiner was pulled according to ANSI Z359.1(07) 4.3.1.1.1. The carabiner deformed, but did not break. The carabiner was then pulled to destruction at 11,430 pounds.

The following table compares the two certificate failures to the theoretical failure:

**Table 3:** Comparison of Theoretical to actual breaking strength

| | Breaking Force (lbs) | Tensile strength (psi) |
|---|---|---|
| Theoretical | 15,300 | 142,000 |
| Certificate 0062083-1 | 10,000 | 93,000 |
| Certificate 0081656-2 | 11,430 | 106,000 |

The carabiner was axially tested to the ANSI standard of 5,000 pounds (22.2kN). The marking on the body is indicative of the failure strength 45kN (10,000).

A Fusion representative indicated that in their experience, the carabiner would deform at about 7 kN (1600 lbs)[10] if the gate were not engaged.

The analysis here considers only the static stress components. The "Hair Hang Chandelier" performance placed dynamic loads on all components of the apparatus. These dynamic loads increased the actual loads on each of the components including the carabiner that failed.

The carabiner was in use as shown in Photo 5.

The pear rings are at the approximate angle they would have been when connected to the apparatus. The angles from horizontal are noted in the photograph as 37º and 40º. The pear ring on the right is in contact with the gate. The carabiner was not axially loaded. It was tri-axially loaded imposing moment loads for which it was not designed or tested. The ANSI standard only requires testing for axial loads.[11]

The carabiner was not tested for a tri-axial orientation. They are only designed and tested for a two point load along the major axis.

The Fusion representative confirmed that the carabiner had not been tested for a tri-axial load[12].

[8] Received by SLTC from compliance officer 14 May 2014 Certificate Number 0062083-1
[9] Received by SLTC from Fusion, 19 August 2014 Certificate Number 0081656-2
[10] Personal Communication, Fusion, Frank Hsu, Product Manager, 19 August 2014
[11] ANSI Z359.1 (07) 4.3.1.1.1
[12] Personal Communication, Fusion, Frank Hsu, Product Manager, 19 August 2014



**Discussion of Microscopy Examination**

The microphotography performed by MMR shows morphology consistent with tensile stress. No surface flaws were noted. No compositional anomalies such as inclusions were noted. The edges of parts 1a and 1b have the typical "cup and cone" morphology of tensile failure. Photo 3 shows 1a with a "cup" edge while photo 4 shows 1b with a "cone" edge.

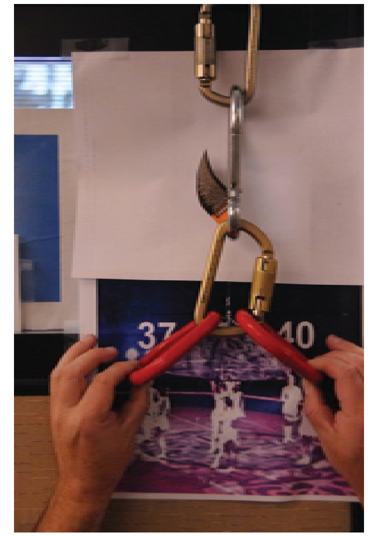



**Photo 5:** Carabiner with pear rings at the angles noted in the photo in the background. This is a tri-axial orientation.

Examination of the fracture surface by SEM reveals that the fracture has a mixed, ductile, intergranular appearance consistent with tensile overload.

Photo 7 is from the MMR report[13] and shows the direction of the failure as it progressed from the initiation point at the mouth of the capture bar hole. The fracture radiated inward rapidly until failure occurred. The points of initiation are shown at the bottom of the photo in red. The direction of travel of the failure is shown with blue arrows radiating up and away from the hole.

Close examination of the photographs provided by MMR, show that the fracture surface near the initiation site appears more intergranular.[14] As the fracture moved away from the initiation point, more ductile failure was observed. There was no evidence of micro or macro fatigue in the images provided.

**Photo 6:** Keyence photograph of the crack in the gate. The crack initiated at an inside corner which is a stress multiplier.

The crack observed on the gate was likely caused when the back of the carabiner broke, forcing the gate outward against the fixed restraint where it was riveted. Examination of the crack shows that it initiated at an inside corner, which is a stress multiplier, and progressed along the length of the gate. The location of the crack is consistent with the gate being forced outward from the carabiner, in the plane of the carabiner, while it was connected to the upper tang.

[13] MMR report, Page 4 and Figure 18
[14] MMR report, Page 5 and Figure 63.

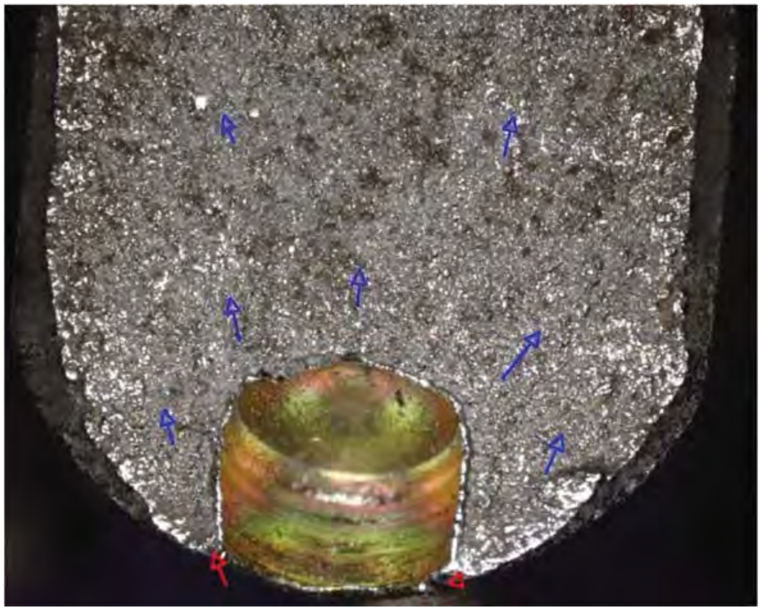


**Photo 7:** Figure 18 from the MMR report showing the initiation and progression of the failure of the carabiner back.

## Conclusion

The carabiner had no defects or anomalies revealed by the laboratory analysis.  No fatigue or cyclic load failure was detected. The carabiner was loaded in a tri-axial load configuration which placed it in an overload condition such that it failed.



APPENDIX

Accredited
By
U.S. Department of Labor
O.S.H.A.
D.I.S. Approval No. A-6

Certificate No.: 0062083-1
Date: October 13, 2009

**John A. Batchelor Co., Inc.**
**Certificate of Test and/or Examination**

This is to certify that the John A. Batchelor Co., Inc., has subjected the following to inspection or test as quoted herein.

**Customer:** Ace Metal Products
**Customer Order No.** Verbal Frank
**Sling (s) Serial No.:** N/A
**No. of Sling (s):** 1 Each

**Description:** Customer's – FP-9103Gkhs Carabiner per ANSI-Z359.1-2007. Pulled to: 5,000Lbs. Held for 1 Minute. Pulled to Destruction – Broke @: 10,000Lbs Passed

**Proof Test Load (Lbs)** xxxxxxxxxxxxxxxxxxxxxxx **Working Load Limit (Lbs)** xxxxxxxxxxx **At** °

**Certification**

The above described items have been inspected/-tested/fabricated per applicable regulations and/or industry standards.
The result of said inspection/test is indicated above.
All applicable ratings are listed above.
Proof loads, where applicable, were performed without deformation.
The undersigned hereby attests that the above has been tested/examined by a designated competent person in the manner set forth in this certificate.

**John A. Batchelor Co., Inc.**
5922 TRIUMPH STREET, COMMERCE, CA 90040
Ph. (323) 262-4125

By Inspector
Service Center: JABCO Los Angeles

**Photo 7:** Certificate 13 October 2009

Accredited
By
U.S. Department of Labor
O.S.H.A.
D.I.S. Approval No. A-6

Certificate No.: 0081656-2
Date: May 12, 2014

John A. Batchelor Co., Inc.
Certificate of Test and/or Examination

This is to certify that the John A. Batchelor Co., Inc., has subjected the following to inspection or test as quoted herein.

**Customer:** Ace Metal Products, Inc.
**Customer Order No.** Verbal Frank
**Part (s) Serial No.:** N/A
**No. of Part (s):** 1 Each

**Description:** Test Sample #2 – FP-9103 GPK-HS (Taxo II Carabiner) According to ANSI Z359.1-2007 Section 4.3.1.1.1. The Carabiner configured with (1) 3/8" Couplings On One End of the Carabiner, 3/8" Coupling on the Other End. The Carabiner Body was deformed but did not Break. Pulled to Destruction – Broke @: 11,450Lbs.

**Proof Test Load (Lbs)** xxxxxxxxxxxxxxxxxxxxxxxxxxx **Work Load Limit (Lbs)** xxxxxxxxxxxxxx **At** Degrees

Certification

The above-described items have been inspected/-tested/fabricated per applicable regulations and/or industry standards.
The result of said inspection/test is indicated above.
All applicable ratings are listed above.
Proof loads, where applicable, were performed without deformation.
The undersigned hereby attests that the above has been tested/examined by a designated competent person in the manner set forth in this certificate.

John A. Batchelor Co., Inc.
Wire Rope & Rigging Supplies
5922 Triumph Street, Commerce, Ca 90040
Ph. (323) 262-4125

By Inspector

**Photo 8: Certificate 12 May 2014**