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Forensic Deformation Analysis of a Farm Clevis Using Photographs and Exemplar Tests

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Abstract

Photographic evidence can be a sufficient basis for a forensic failure analysis, especially when characteristic features of the failure mode are readily observed in photographs (e.g., deformation, fracture, etc.). In this case, the failed component (a farm clevis or round pin shackle) was part of equipment used to attempt to recover a vehicle mired in the mud at an above-ground mine site. The shackle failed, and the shackle pin became a projectile that penetrated the cab and injured the driver. The subject clevis was not available for physical inspection or testing. However, the condition of the subject clevis after the accident had been documented in photographs. Application of solid mechanics principles made it possible to determine the sequence of deformation steps that occurred during the failure. Additionally, comparing the deformation behavior documented in photographs of the subject clevis — and to tests of exemplars — allowed a determination of the strength of the subject clevis. Thus, investigators were able to use photographs to determine whether the shackle failed below its working load limit (WLL) or if a citation issued by the Mine Safety and Health Administration for using the subject clevis over its WLL was merited.

Keywords

Metal deformation, towing, extraction, heavy equipment, mining, photographs, shackle, clevis, projectile, tow rope, forensic engineering

Introduction and Background

A piece of heavy equipment (18,000 pounds) became mired in the mud at an above-ground mine. The operator of the mired equipment requested that a bulldozer attempt to recover the mired equipment. The driver of the mired equipment connected the bulldozer to the mired equipment using a braided nylon recovery rope (rated at 130,000 pounds-force) that was connected to the bulldozer and mired equipment by a clevis on each end. Recovery ropes are designed to stretch to reduce the peak impulse when using the extracting vehicle in a jerking action. However, stretching of the rope can also store energy in the rope.

When the bulldozer pulled on the recovery rope in an attempt to recover the mired equipment, the clevis connected to the mired equipment failed and was launched by the elastic energy stored in the stretched tow rope toward the bulldozer. The clevis pin traveled toward the bulldozer cab, penetrated the steel grate on the rear window, penetrated the window, broke the headrest off the operator station, struck the operator with a glancing blow to the back of his head, and then fractured a front side window. The clevis bow also traveled toward the bulldozer, but did not strike it — and was found on the ground some distance beyond the bulldozer. The recovery rope remained in one piece with no visible damage after use.

The Mine Safety and Health Administration (MSHA) concluded that the accident resulted both from using an under-strength (25,000 pounds-force) clevis and from using the clevis in a side-loaded configuration. The MSHA issued a citation to the mine operator, citing eCFR Title 30 Chapter I Subchapter K Part 56 Subpart M Safety Practices and Operational Procedures:

> ***§ 56.14205 Machinery, equipment, and tools.*** *Machinery, equipment, and tools shall not be used beyond the design capacity intended by the manufacturer where such use may create a hazard to persons.*

The contractor and mine operator disputed this citation, claiming that the clevis failed below its rated working load limit and that it was not side-loaded. Additionally, the injured worker initiated a lawsuit against multiple parties, including the manufacturer and vendor of the failed clevis,

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alleging that it failed below its rating. This prompted investigation by the involved parties as well as the MSHA.

The MSHA citation had included photographs of the mired equipment, bulldozer, tow rope, and clevises (**Figures 1** through **4**). An overview of the scene is shown in **Figure 5**. Damage to the bulldozer is shown in **Figure 6**.

Figure 1
The MSHA citation included photographs of the mired equipment.

Figure 2
The MSHA citation included photographs of the hitch where the clevis was connected to the mired equipment (top) and the rope used to attempt to recover the mired equipment (bottom).

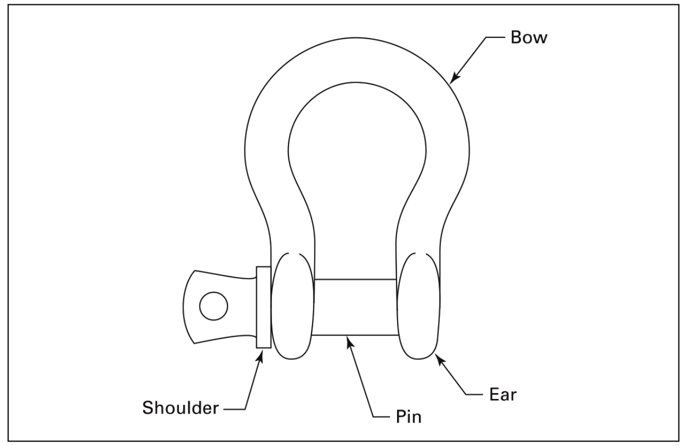


Figure 3
Terms for parts of a farm clevis, also known as a round pin shackle.

Figure 4
The MSHA citation included a photograph of the clevis and pin that were connected to the mired equipment (left) and the clevis that was connected to the bulldozer (right).

Figure 5
Photograph of the accident scene included in the contractor incident report. The mired equipment is mired in the mud on the right, and the CAT D8T bulldozer is positioned on the left of the image with a side-by-side UTV positioned in the foreground between the bulldozer and the mired equipment.

The locations where the clevis bow and clevis pin were found are shown in **Figure 7**. Although the exact distance that the clevis bow traveled is unknown, photographs of where it was recovered showed it embedded in soil that exhibited an impression from the bulldozer track.

Most likely, when the clevis failed and departed from the mired equipment, the clevis bow traveled past the bulldozer, landed on the ground in front of the bulldozer, and was then run over when the bulldozer continued to roll forward — after the operator was incapacitated by the head injury from the clevis pin. The clevis appeared to have sunk into the mud under the track, and did not exhibit any deformation or damage from being run over.

The MSHA responded to the claims that the subject clevis failed beneath its rating by testing similar exemplar clevises in tension (**Figures 8** through **10**). The MSHA tests used polymer webbing to load the exemplar clevises, attempting to simulate the vehicle recovery operation. The clevises that were tested in-line (no side-loading) or with slight side-loading all withstood 60,000 pounds-force or more. The side-loaded clevises failed at 22,500 pounds-force or less. The failure mode of the subject clevis resembled the failure mode of the exemplars tested in-line, but

Figure 6
Photographs of the bulldozer cab included in the contractor incident report showing damage to a steel guard and the rear window (left) and fractured left front cab window (right).

Figure 7
Failed clevis found some distance beyond the bulldozer (left) and clevis pin found inside the bulldozer (right) from photographs included in the contractor incident report.

Figure 8
Exemplar clevises that were tested in-line (no side-loading).

Figure 9
Exemplar clevises that were tested slightly off-axis (slight side-loading).

Figure 10
Exemplar clevises that were tested with severe side-loading.

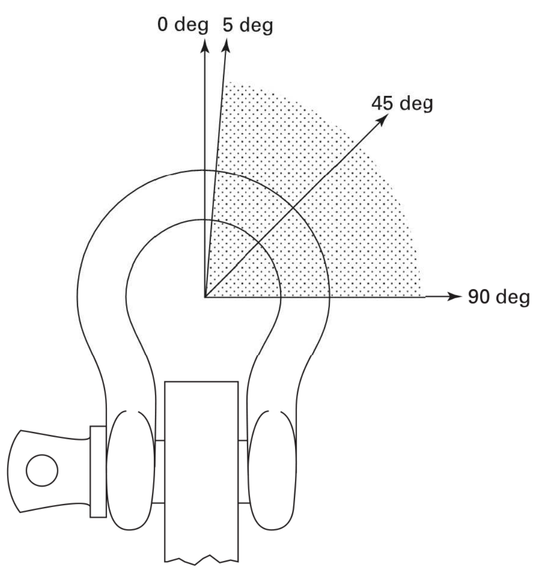
did not resemble the failure mode of exemplars tested in side-loading. Based on these test results, the MSHA maintained its position that the subject clevis was used over its load rating, and withdrew the claim that the subject clevis was side-loaded. **Figure 11** demonstrates the standard terminology for applied loads on a clevis.

Deformation Failure Analysis of Clevis

The photographs of both the subject clevis (**Figure 7**) and exemplars tested by the MSHA (**Figure 8** through **Figure 10**) can be evaluated using the principles of deformation mechanics to understand and determine how the clevis deformed and failed during the accident and the forces reached during the failure. Terms for parts of a clevis are defined in **Figure 3**.

The subject clevis was documented with multiple photographs, but the polymer recovery strap was not. Only the photographs were available for examination and analysis, and the clevis was not available for inspection and testing.

Fig. 26-1.9.4-2 Side Loading



Side Loading Angle, deg	% Rate Load Reduction
In-line (0) to 5	None
6 to 45	30%
46 to 90	50%
Over 90	Not recommended to load in this condition. Consult manufacturer or qualified person.

Figure 11
ASME B30.26-2015 provides Fig. 26-1.9.4-2, which describes side loading and corresponding WLL reduction.

However, the photographs documented the deformation and damage to the clevis, which was sufficient to identify the location and orientation of forces and moments applied to the clevis during the failure process.

The failed component was what is referred to as a "farm clevis" or a "round pin anchor shackle" that had a non-threaded pin held in place by only a cotter pin — in this case, an R-clip. This is in contrast to shackles with screw pins or bolts, where the pin is restrained by a threaded connection. Prior studies of bolt-type[1,2] and screw-pin[3,4] shackles involved failure by fracture, by fatigue, and/or embrittlement, including a failure due to a manufacturing defect[1]. The subject farm clevis exhibited extensive deformation, and did not fracture.

Because of the limited ability of the cotter pin to keep the pin in place, farm clevises have less ability to resist side loading and are generally not used for lifting, as noted in ASME B30.26-2015 - Rigging Hardware, which explicitly excludes round pin shackles/farm clevises from its scope for this reason. In this analysis, the authors treated the resistance offered by the cotter pin as negligible relative to the forces required to induce plastic deformation in the bow and pin. All of the clevises discussed in this paper exhibited R-clip cotter pins that were sheared through, but none exhibited plastic damage or deformation around the ears indicative of significant load transfer from contact between the cotter pin and clevis.

For failure analysis of the subject clevis, the team applied balance of forces, balance of moments, and yield criteria: Permanent (i.e., plastic) deformation (shape change) of a metallic part indicates that it experienced a stress exceeding its yield strength, the minimum stress necessary to drive dislocation motion, causing plastic deformation. Therefore, any plastic (permanent) deformation of the clevis must have been the result of an equally balanced action/reaction force pair. The overall loading condition of the shackle was always tension between the attachment points of the tow rope and the mired equipment. The material that deformed must have been located between these attachment points such that it transmitted force from the recovery rope to the mired equipment. The absence of deformation in that portion of the clevis indicates that any load transfer through that material was beneath the yield strength of the material. Since the clevis was loaded in simple tension between the tow rope and mired equipment, the net force on the clevis will always be in tension, though the shape of the clevis (i.e., any offset between the line between the attachment points and the material participating in the load transfer) can cause localized bending moments and shear stresses in addition to tension.

The side-loaded exemplar clevises — where the clevis ears were oriented transverse (90º) to the applied tensile force as shown in **Figure 11** — are straightforward to interpret. The tensile forces would be parallel or near-parallel to the pin in extreme side loading, which would result in minimal load transfer through the pin, limited to the shear strength of the cotter pin and friction between the pin and clevis ears. The pin in the side-loaded clevises exhibited no deformation because in side-loading, the pin never experienced a bending stress in excess of its yield strength. The bow of the clevis would transmit the majority of the force exerted by the tow rope and mired equipment. Thus, the bow was the part that exhibited deformation in the extreme side-loading case. The lateral offset between the loading axis and the load-bearing clevis bow would produce a bending moment (**Figure 12**) that would cause the bow to open up when it deformed, which is what the authors observed in testing the exemplar, side-loaded clevises.

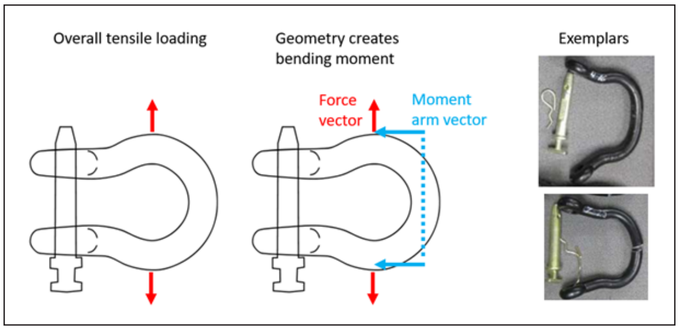


Figure 12
In transverse tensile loading, 90º (side loading), the overall loading condition is tensile (left). Because load transfer is primarily through the clevis bow, which is offset from the tensile axis, the bow is in bending (center). Thus, the exemplars tested in side loading exhibited bending of the bow and the ears spread apart (right).

The in-line and slightly side-loaded cases, where the clevis ears were oriented longitudinal (at or nearly parallel) to the applied tensile force, followed a more complex series of deformation steps. To understand the deformation sequence, the authors identified locations where deformation was present or not present in the subject farm clevis (**Figure 13**). Notable features included: 1) The pin was bent; 2) The right side of the bow retained much of its original shape, but localized deformation appeared on the inside edge of the hole on that side; and 3) The left side of the bow was significantly deformed, and no deformation appeared in the hole on that side.

The authors anticipated that a clevis loaded in-line would be symmetrical, with load transfer through both sides of the bow and through both ears. However, the condition of the clevis after failure indicated asymmetrical loading, and more extensive deformation of the left side of the clevis.

The photographically documented deformation of the subject shackle provided the forensic team with the necessary information to determine the sequence of events involved in the shackle failure. Before the pin bent, there would be no force to cause the shackle ears to spread and the shackle bow to bend, as observed in the subject clevis.

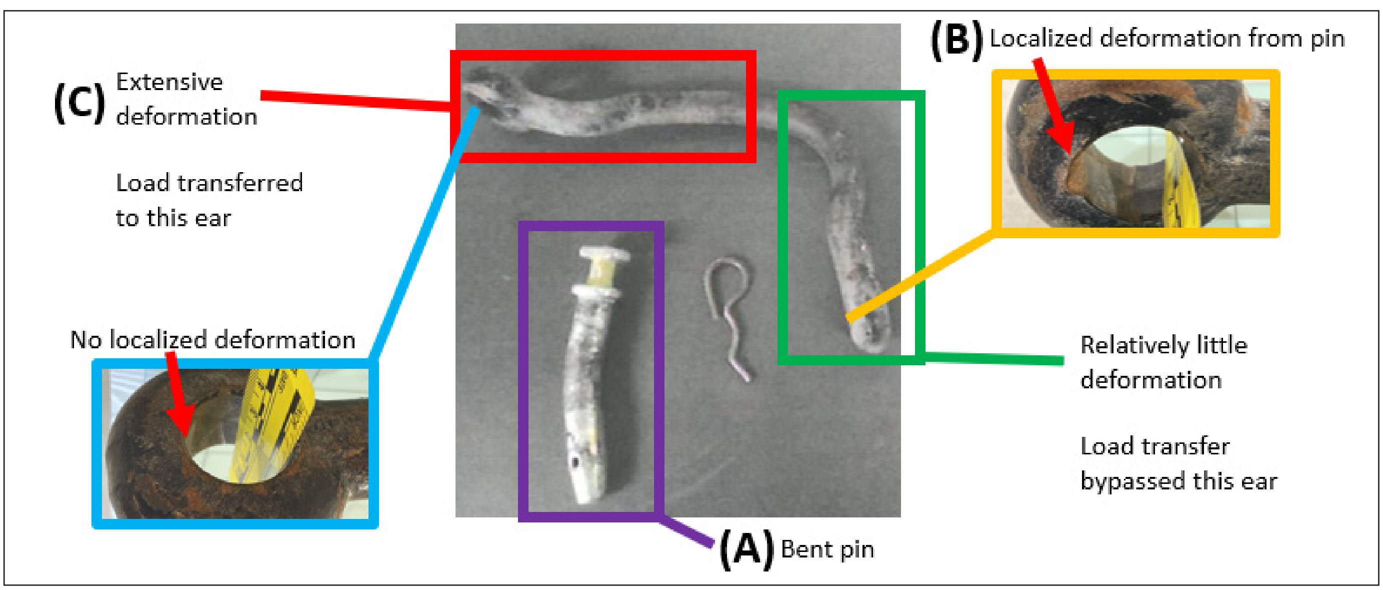


Figure 13
Notable areas of deformation or absence of deformation in the subject clevis.

After the pin bent, the angle of the bend would create a lateral force component that would tend to make the ears of the shackle spread apart. The bend in the pin indicated a three-point bending loading condition, which would exist while the pin was in contact with both ears, but would not exist after the pin disengaged from one or both ears. Bending of the pin after it disengaged from one ear would be a cantilever bending condition, with maximum stress in the pin at the base of the cantilever where the pin passed through one ear.

Deformation at that location was not apparent in the available photographs. Therefore, the bend in the pin occurred before the ears began to spread. Bending of the pin was the first step in the failure (**Figure 13A**). Before the pin bent, force between the pin and the clevis ears would have been parallel to the overall tensile forces. After the pin bent, the angle of the bend would have resulted in a horizontal component of forces between the clevis ears and pin, and the horizontal component would have caused the clevis ears to spread apart (**Figure 14**). Bending of the pin would also have exerted a bending moment on the ears, which would also have caused the ears to spread apart.

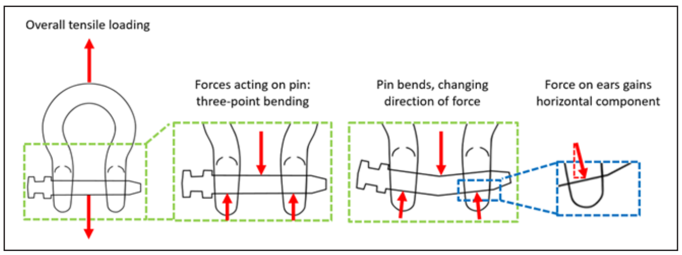


Figure 14
Longitudinal tensile loading on the clevis resulted in three-point bending of the pin. Bending deformation of the pin resulted in a horizontal force spreading the ears of the clevis apart.

Once the pin bent, there would be a driving force to make the ears of the shackle move apart. As the ears spread apart, the distance between the points of contact with the pin would increase, which would also increase the length of the moment arms of the pin in three-point bending, further increasing the driving force for bending the pin. Eventually, the ears would spread far enough so that first the cotter pin would shear, then the tip of the pin would slide out of one ear, disengaging the pin from the shackle body.

From photographs, it appeared that shearing of the cotter pin did not induce enough stress on the ear to cause visible deformation. The tip of the pin sliding out of the eye created the contact damage present on the inside of one ear (**Figure 13B**). Before the pin disengaged, both sides of the clevis bow and both ears would be under load — and, to the extent they deformed, would be symmetrical. After the pin disengaged, only the side of the shackle that retained the pin would be under load, and deformation would no longer be symmetrical (**Figure 15**).

Once the pin disengaged from one ear of the shackle, that ear would no longer participate in load transfer and would no longer deform (**Figure 16**). This is why the relatively undeformed side of the shackle was on the same

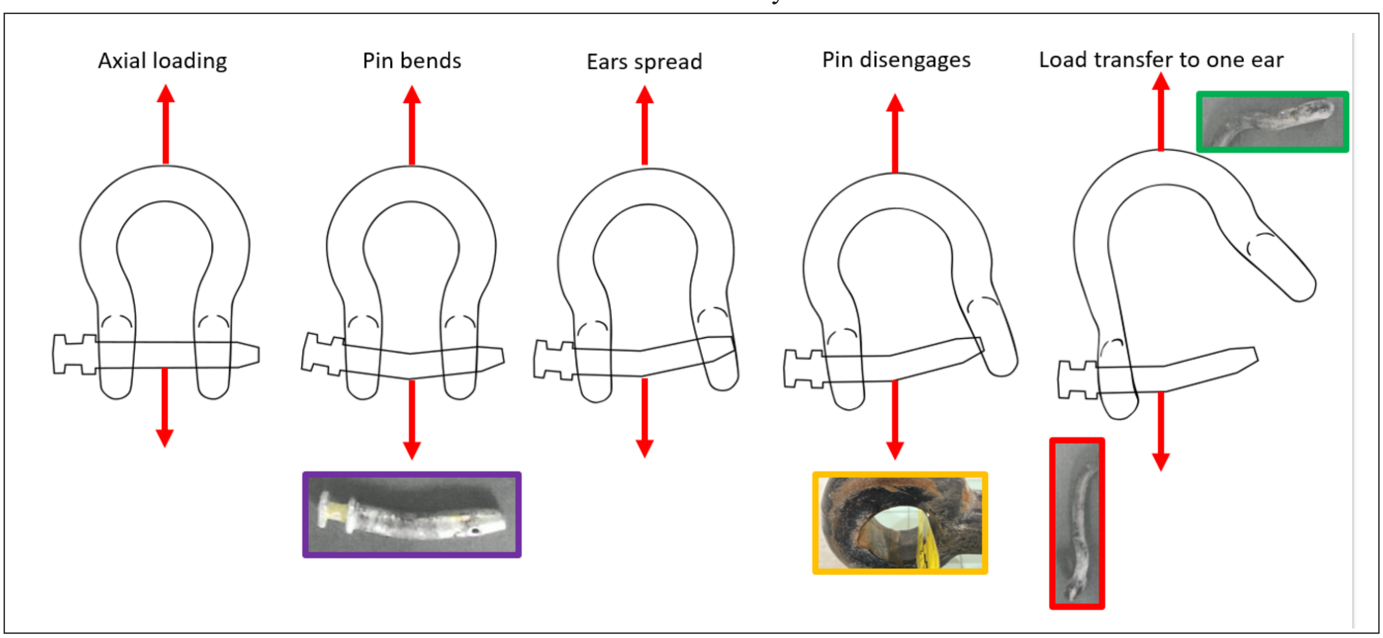


Figure 15
The shackle deformed until the pin disengaged from one ear, creating localized deformation inside the ear.

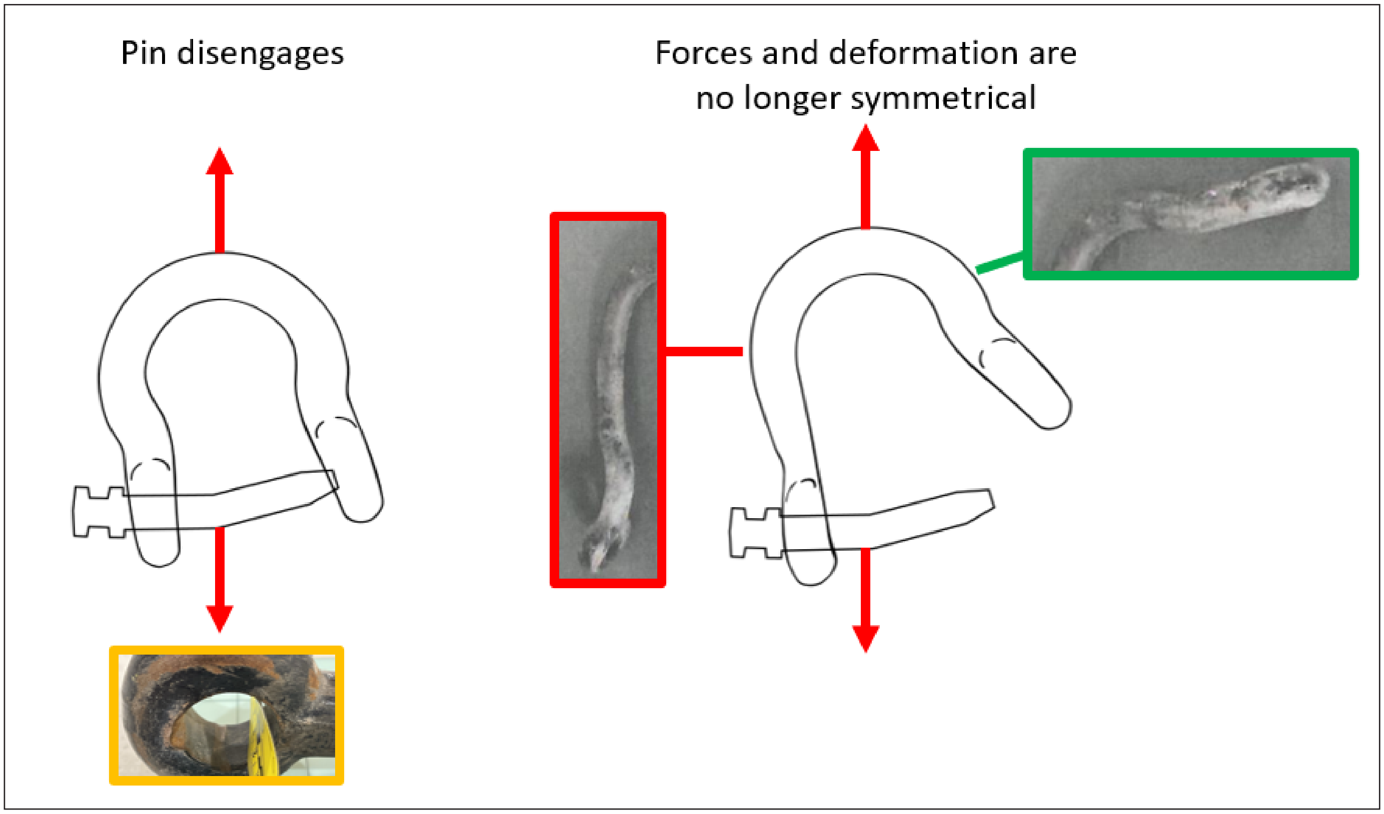


Figure 16
Once the pin disengaged from one ear, deformation would no longer be symmetrical. Thus, the left side of the shackle, which remained connected to the pin, deformed significantly more than the right side, which disengaged from the pin first.

side as the ear with the contact damage — because that ear disconnected from the pin first. All load transfer would be through the other ear, which would continue to deform (**Figure 13C**). Deformation would continue to change the angle of the pin relative to the tensile direction, up until the point where the pin was able to slide out of its connection point to the mired equipment (**Figure 17**). This is why the other leg was more severely deformed, and went from its original curved shape to nearly straight. Deformation of the left side of the shackle bow continued until the shackle slid off of its connection point to the mired vehicle (**Figure 17**).

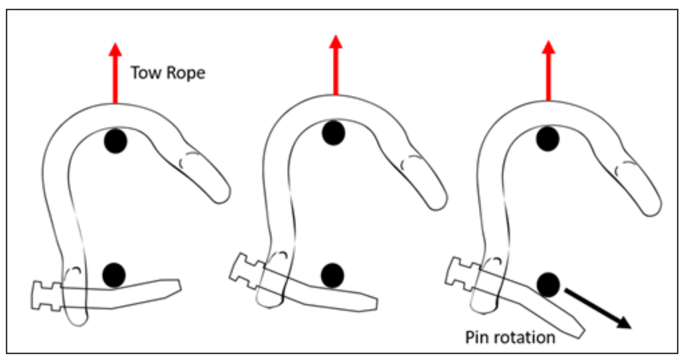


Figure 17
Deformation would continue until the angle of the pin allowed it to slide off of its connection point to the mired equipment.

The MSHA-tested shackles that were in-line or only slightly side-loaded (longitudinal loading) all had bent pins (**Figure 8** and **Figure 9**), and failed at more than twice the shackle's load rating. Bending of the pins indicates a three-point loading condition that existed before the pin disengaged from the clevis ears. Most likely, the maximum force during the test was at the yield point of the pin, which was loaded in three-point bending with relatively short moment arms.

The MSHA test was a quasi-static test with very low strain rate. The strain rate experience by the subject clevis is unknown. However, yield strength and work-hardening of steel generally increase with strain rate[5], so dynamic loading of the subject clevis, if it had an effect, would tend to increase the failure forces. Since the subject clevis did not fracture, the strain rate effects on impact or fracture toughness did not play a part in the failure. From that point onward, the moment arms would increase (as the ears spread apart), or the amount of material available to transfer load would dramatically decrease (when the pin disengaged from one ear).

The subject clevis also had a bent pin, and the ear that retained the pin was significantly more deformed than the other ear (**Figure 7** and **Figure 13**). Similarities between post-failure conditions of the subject clevis and one of the exemplars (**Figure 18**) indicated that they followed a similar series of deformation steps. Thus, the subject clevis failed by the same sequence of deformation and load transfer as the exemplars — and with similar forces in excess of the clevis' rating. The MSHA was correct to cite the mine operator for using the clevis above its rating.

As a matter of practice when recovering mired equipment, it is generally not advisable to select recovery straps, shackles, etc., based on the weight of the mired equipment or an estimate of the force needed to recover it. The risk of an error in such an estimate is high (consider fluid dynamics, soil properties, unknown buried obstructions, etc.), and risks failure of the tow strap or shackles if the estimate is incorrect. Best practice is to select recovery straps, shackles, etc., based on the towing equipment — in this case, the bulldozer that was attempting to recover the mired vehicle.

The subject bulldozer, like most similar equipment, had instructions to this effect in its manual. The bulldozer's manual recommended choosing recovery straps, shackles, etc., rated for at least 150% the weight of the towing vehicle. The best practice in this case would have been to use the 85,000 pounds-weight of the bulldozer to select a tow strap and shackles rated for at least 127,500 pounds-force. This way, if the force to recover the mired vehicle was higher than expected, the bulldozer would be more likely to spin its treads than break the towing equipment. Using the subject shackle (with its 25,000 pounds-force working load limit) went against the bulldozer manual's instructions and would foreseeably result in overloading and breaking the shackle.

The MSHA was also correct to withdraw its conclusion regarding suspected side-loading of the clevis — or at least severe side-loading (transverse tension). In severe side-loading, the pin would carry little to no load because the applied force would tend to make the ears spread apart, moving parallel to the pin. In this case, most of the load would be borne by the bow of the clevis with a bending moment roughly equal to the radius of the bow.

The authors would expect the side-loaded clevis to be much weaker than in-line loading. Rather than distributing the stress across both ears, only the bow would carry the load. Rather than bending the pin with a very short moment arm, the bow would be bent using a longer moment arm. Thus, the MSHA's report that the exemplars tested in extreme side-loading (**Figure 10**) failed at a force beneath the clevis' rating was predictable. Since there was no deformation of the pin in severe side loading (but there was deformation of the pin in the subject shackle), the logical finding is that the subject shackle was not severely side-loaded.

The most significant difference between the exemplar and subject clevises (**Figure 18**) was that the exemplars fractured. This fracture may be due to the testing equipment used with the exemplars. The quasi-static test conducted by MSHA involved less dynamic loading, and therefore less likelihood that the clevis could disconnect from the load frame in the manner that the subject clevis disconnected from the mired vehicle. Thus, the MSHA exemplar continued to be loaded until final fracture, while the subject clevis disconnected from the mired vehicle before it could fracture.

Differences among the deformations exhibited by different clevises were most likely due to the distribution of external forces acting upon the clevises. There were two clevises in use at the time of the accident — one connected to the bulldozer and one connected to the mired vehicle (**Figure 4**). Even though the clevises were identical to one another and were subjected to the same total amount of force, the clevis connected to the bulldozer exhibited only slight spreading of its ears; it was significantly less deformed than the clevis connected to the mired vehicle.

The difference in deformation is due to the difference in how those forces were applied. The more extensively deformed clevis was connected with its pin passing through a ring-shaped hitch on the mired vehicle (**Figure 2**), while

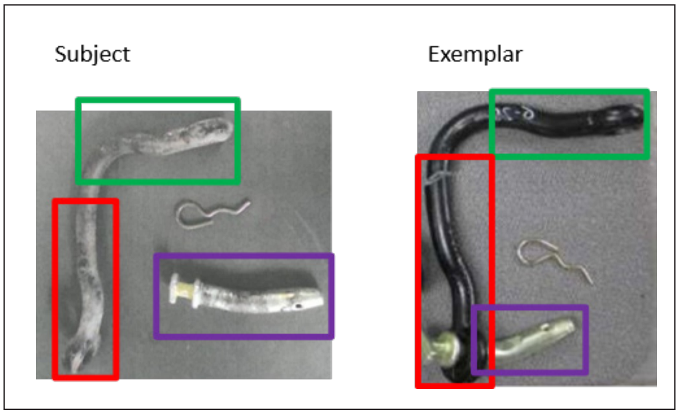


Figure 18
Similarities between the subject clevis and exemplar clevis indicate that they followed a similar sequence of deformation steps and that the subject clevis failed at a similar force to the exemplar clevis.

the less deformed clevis was connected with its pin passing through a bracket on the bulldozer. The ring on the mired vehicle (with its round shape) would tend to concentrate stress at the center of the pin, inducing a three-point bending condition. The bracket on the bulldozer would distribute the stress more evenly across its pin. Nevertheless, the presence of some permanent deformation (however slight) on this other clevis indicates that it had also exceeded its elastic limit. The failed clevis was essentially loaded in three-point bending while the clevis connected to the bulldozer was in double-shear loading. Thus, even though both clevises were subjected to the same force, the clevis with a more concentrated force acting on its pin exhibited more extensive deformation and failed first.

Summary

Analysis of artifacts present in photographs as well as the testing performed by the MSHA was used to determine the failure mode and the applied forces to the clevis that caused it to fail. The locations on the shackle where deformation was present (or not present) provided the evidence necessary to infer the sequence of deformation steps leading up to failure. The photographs also provided enough documentation of the failure mode to rule out a manufacturing defect as a cause of failure. The cause of failure were longitudinal (not side-loaded) tensile forces in excess of the clevis's working load limit and elastic limit.

Conclusion

Basic principles of solid mechanics, such as balance of forces (Newton's Third Law) and yield criteria, can be used to analyze deformation of a failed component and determine how the failure initiated and evolved. This, combined with testing that replicates similar deformation, can also be used to determine the failure strength of the component.

In this case, investigators determined that a clevis failed by longitudinal tension (in-line or mild side-loading) and that the failure occurred in a sequence of steps: 1) pin bending; 2) clevis ears spreading; 3) pin disengagement from one ear; 4) continued deformation of the other ear; and 5) pin desengagement from the mired vehicle, releasing the clevis such that both the pin and clevis became projectiles moving toward the bulldozer cab. By comparison to exemplars, investigators determined that the failure occurred at a force greater than the working load limit of the clevis.

References

1. D. P. Couture, "Forensic Engineering Investigation of a High-Voltage Transmission Line Anchor Shackle Failure," *Journal of the National Academy of Forensic Engineers*, vol. 39, no. 1, pp. 35-46, 2022. Online]. Available: https://doi.org/10.51501/jotnafe.v39i1.65.

2. S. Lee, I. Jeon, and D.-C. Baek, "Deviation based fault detection method for shackles under variable loading," *Journal of Mechanical Science and Technology*, vol. 32, no. 2, pp. 753–760, 2018. Online]. Available: https://doi.org/10.1007/s12206-018-0124-2.

3. S. Weller, P. Thies, T. Gordelier, and L. Johanning, "Reducing Reliability Uncertainties for Marine Renewable Energy," *Journal of Marine Science and Engineering*, vol. 3, pp. 1349-1361, 2015. Online]. Available: https://doi.org/10.3390/jmse3041349.

4. R. R. Gaji and M. T. Telsang, "FEA Based Analysis of Shackle For Offshore Application," *International Journal of Mechanical and Industrial Engineering*, vol. 3, no. 3, Article 2, 2014. Online]. Available: https://doi.org/10.47893/IJMIE.2014.1146.

5. B. L. Boyce, T. B. Crenshaw, and M. F. Dilmore, "The Strain-Rate Sensitivity of High-Strength High-Toughness Steels," Sandia Report, SAND2007-0036, 2007.