Heavy Movable Structures, Inc.

SIXTH BIENNIAL SYMPOSIUM

October 30 - November 1, 1996

Doubletree Resort Surfside
Clearwater Beach, Florida

Span Lock Failure - A Case Study

by

Eric T. Kelly, P.E., HNTB Corporation

SPAN LOCK FAILURE - A CASE STUDY

Eric T. Kelly, P.E

HTNB Corporation

Introduction

The worst feeling an Engineer can have is when they receive a phone call from the construction site and are told that their design, after being in service for only two weeks, failed.

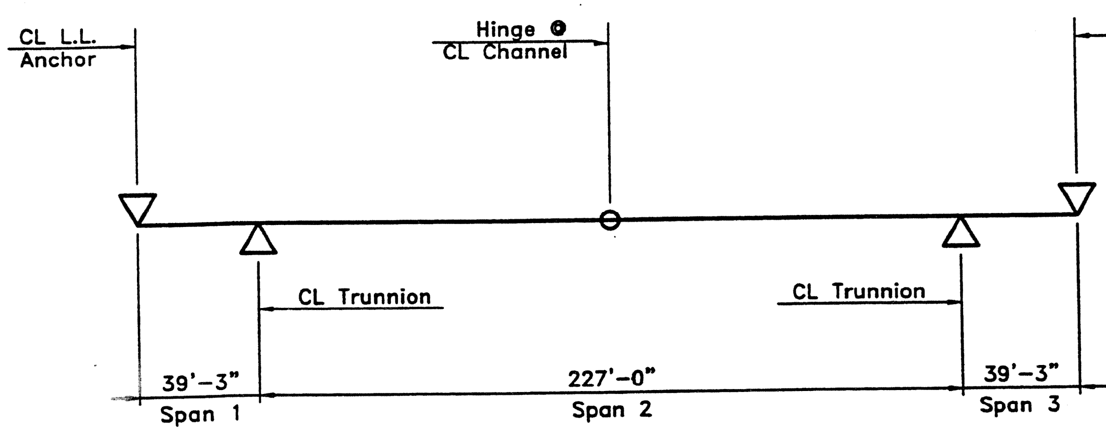
In December of 1988, two of the newly installed span (center) locks for this twin double leaf bascule failed under live load by low cycle fatigue. As the Design Engineers, HNTB Corporation became involved in assisting in the determination for the cause of failure and providing an acceptable solution to the problem.

This paper will go into a brief description of the structure's history, the center lock conditions before rehabilitation, during construction and investigations performed to resolve the failure. This paper only represents the findings and opinions of the writer as a designer having access only to limited documentation and is not meant to be a complete or thorough investigation.

Structure Background

The Woodrow Wilson Memorial Bridge spans the Potomac River between Jones Point in Alexandria, Virginia, and Rosalie Point in Prince George's County, Maryland. The total length of the structure is 5,900 ft. and was opened to traffic in 1961. The bridge carries a six lane highway whose original typical cross section consisted of two 38 ft. roadways, a 4 ft. median, two 3 ft. safetywalks, and two 1.5 ft. parapets for an overall width of 89 ft. This is the last movable bridge on the 42,500 mile interstate system (The Fuller Warren Bridge in Jacksonville, FL is also a movable bridge, but is presently being replaced). Present traffic counts on the structure exceed 167,000 vehicles a day (17,000 being trucks). The structure opens to marine traffic over 200 times a year. The allowable time for bridge openings are restricted to keep the impact on vehicular traffic to a minimum. The structure is oriented in the west to east direction with the control house being located on the south side of the west bascule pier.

The movable portion of this structure is a four leaf trunnion bascule which in the closed position provides 50 ft. minimum vertical clearance over a 175 ft. clear channel. To provide this channel clearance, the longitudinal distance between trunnions is 227 ft. Each of the four bascule leaves consist of 13 stringers supported on open truss type floorbeams which span between two girders 28.75 ft apart (See Figure 1). Two leaves make up a bascule span whose structural configuration is depicted as follows:



The two mating leaves in the closed position act like a three span continuous member with a hinge at mid-point. Spans one and three are between the rear live load anchor and the trunnion, span two is between trunnions. Span two is the longest and has a hinge at its mid-point. It is at this hinge where the center locks are located. This location is at the centerline of channel and is where the two mating bascule leaves separate to open for marine traffic (See Figure 2) Structurally the hinge (center lock) acts to transfer live load shear from one leaf to the next, but cannot transfer moment. The center locks allow the two mating leaves to deflect uniformly from the live load.

Center Locks

The center locks are located adjacent to the bascule girders and each center lock consists of an articulated jaw mechanism on the west leaves and a steel tongue or lock seat on the east leaves. Figure 3 shows the center lock assembly in the closed and open positions. To open the jaws, the rack at the rear of the lock is pulled back and this collapses the two vertical links 5 & 6 which rotates the jaws. These articulated center locks offer advantages and disadvantages to the more recognizable lock bar and socket arrangement on other double leaf bascules. Their primary advantage is allowing for a much larger leaf misalignment, which is needed for a long span bascule such as this bridge. The major disadvantage is there are more moving parts which must carry high impact, reversing loads. These pins and links which operate the jaws must also transfer these loads.

HNTB Corporation had been hired by the District of Columbia Department of Public Works (DCDPW) to develop contract plans for the general rehabilitation of the structure, which included the installation of new inspection walkways, new overhead sign structures, new bascule grating and installation of CCTV cameras on the approaches as well as the installation of a standpipe system for fire protection. As part of this rehabilitation the DCDPW requested that the span lock mechanisms be rehabilitated. HNTB Corporation was given the assignment to replace the center locks in-kind and attempt to improve the system without a detailed study into changing the type of lock mechanism.

Center Lock History

This bridge opened to vehicular traffic in December 1961. The first center lock rehabilitation occurred in 1983. The original locks provided 22 years of service. In 1988, the center locks once again required replacement after only 6 years of service. The significant increase in vehicular traffic is the primary culprit for the reduced life span of the rehabilitated locks. The biggest problem with the center lock mechanism was its failure to keep the jaws tight to the lock seat, which further compounds the situation by increasing the impact loads on the center locks. The lock seats required continued shimming to maintain a tight fit with the jaws (See Figure 4). One cause for this was due to excessive clearances developing between the links and pins. These connections are a steel on steel contact with no lubrication and the development of these clearances can be attributed to the constant load reversals and fretting corrosion along with the introduction of debris from the roadway joint above. The holes in the links were wearing in an oblong pattern, while the pins were becoming smaller in diameter at the point of contact.

Repair Approach

The first approach to the correction was to blame the existing material as being inadequate. Investigations into this venue though proved futile. The original center locks were made of alloy forged steel ASTM A237 Class G and the rehabilitated center locks were made of alloy forged steel A668 Class M. Both these materials have an ultimate strength of 140 ksi and a yield strength of 115 ksi. Both very strong materials for use on a bridge.

To give a comparison, the 1953 Standard Specifications for Movable Bridges (the design specification at the time), lists alloy forged steel to generally have an ultimate and yield strength of 90 and 55 ksi respectively. It also lists this material to have an allowable tensile stress due to bending of 24 ksi. This being 26% of ultimate strength and 44% of the yield strength. The original material selected for the center locks has strength characteristics which are 1.5 times greater than the standard material generally specified.

For the new center lock components, it would have been possible to go to the highest class of ASTM A668 which is Class N. This would have provided a strength increase in the material of 14 to 18%. It would also have been possible to investigate the use of another type of stronger forging material, but it was felt that the material's strength was not the problem. Examination of the existing design for the center locks showed the stresses to be within the acceptable range. Instead, the decision was made to use the same material and improve its resistance to wear by hardening. A668 Class M being a normalized, quenched and tempered material, after forging, generally has a brinell hardness of 285 to 341. This material has moderately hard characteristics to begin with.

The next step in the design was to make the material more resistive to local yielding and wear in the areas subject to the impact loads. This was approached by investigating the ability to further harden the material.

Three types of hardening are commonly available and are:

1. Casehardening
2. Flame Hardening
3. Local or Induction Hardening

Casehardening involves a change in chemical composition of the surface of the material by introduction of another element. This can be performed using carbon (carburizing), nitrogen (nitriding), or sodium cyanide (cyaniding). All of the treatments are performed at an elevated temperature to allow diffusion of the new element into the surface of the material and both cyaniding and carburizing require the component to be quenched.

Flame Hardening as the name suggests is the local heating of the surface portion of the material above the critical temperature (phase change) and then a quenching of the surface to produce a hardened layer. This method, rather than a material change alteration to produce hardness uses microstructure alteration by temperature change.

Induction Hardening is similar to flame hardening in that it hardens by temperature change, but it is performed by locally heating with the use of electricity. This is done by passing a high-frequency alternating current through a coil surrounding the surface to be hardened. The surface is rapidly heated due to eddy current and hysteresis. The material is then quenched as with flame hardening to produce the hardened surface.

Each of these processes can produce a very hard surface without altering the remainder of the component's characteristics. Generally hardening treatments like these only affect the top 1/16" to 1/4" of the specimen being treated.

The alteration of a material's characteristics is always a serious concern. Improvement in the material's resistance to wear can also alter it's ability to withstand the loads. Hardening of a material generally reduces its capability to absorb energy or impacts. As designers on this project, it was desired to strengthen the material by hardening, but not reduce the overall ductility of the material. This was due to the nature of the loading on the center locks which was reversing and subject to high impact as well Also, the complex shape of the members was a concern with regards to notch sensitivity.

For these reasons, the hardening of the center lock parts was isolated to specific locations on each of the components. This was specifically the areas in bearing, which take the live load impact, such as the link and jaw bores and the surfaces of the pins. These areas were to have an increased hardness of 480 brinell. The method of hardening was not specifically stated in the design plans, since the procedure for hardening was not an issue, but the resulting hardness was. All three methods were acceptable to produce the additional hardness.

To further improve the center lock's ability to resist wear, the steel on steel contact areas of the links and pins were modified for lubrication and/or restrained to prevent movement.

Lubrication was provided by putting a grease groove in the circumference of the link and jaw bores. Due to the tight constraints and the moving parts, grease fittings could not be installed on the links. Rather, each pin had a hole drilled through it center and radial grease ducts where drilled to supply the grooves in the links (See Figure 5). This provided a lubrication film to the steel on steel contact areas in the hope of eliminating the hole enlargement from fretting corrosion.

Where the pins were in fixed contact with components, keys were installed. This was also performed to prevent the possibility of relative movement between components which were meant to remain in stationary contact. Again this was to prevent the possibility of fretting corrosion at the remaining non-lubricated locations

Besides the hardening and addition of lubrication to specific points, details were added to try and prevent road debris from falling on the center locks. Since the center locks are located directly below the roadway joint, any dirt or debris that falls from the vehicles lands onto the center locks making the maintenance and operation of the locks difficult. To reduce this, covers and hoods were detailed for placement over the center lock openings. It was hoped that this would shield the moving parts from any falling debris.

Construction Events

The project was awarded and construction was proceeding according to plan. The contractor had been submitting shop drawings for the new materials being installed to ensure conformance to the design plans. When the first submission of the new center locks came in all the dimensions and materials were correct, but for the jaws, links and pins there was a note for these pieces to be hardened to a Brinell of 480. As designer, it was believed that this meant the complete piece was to have the increased hardness. This note was corrected to indicate that the jaws and links were only to be locally sufaced hardened in the necessary areas of the bores and the pins. The drawings were sent back to the contractor which were corrected and resubmitted for approval. The note had been changed and the drawings were approved. All was going according to plan.

A year went by (it is assumed for fabrication, assembly and delivery) when in December of 1988, we received a phone call, notifying us that the jaws on one of the center lock failed. Luckily, this did not turn out to be a catastrophic event. As part of the sequence of construction, the contractor installs a temporary lock bar to remove and replace the center locks, one at a time. This temporary lock bar was reinstalled as a substitute for the failed center lock, until a resolution could be developed. A few days later though, the second new center lock also failed in a similar fashion (See Figure 6, 7 and 8). An old center lock had to be re-installed to act as a substitute. At first there was a belief that the first lock failed due to material inconsistencies or imperfections, but when the second failed, questions were raised into how the design was altered from the original and could that have been the cause.

A meeting was held at the site to get all the parties involved together to try and explain the situation. This meeting consisted of the client, their resident engineers, the general contractor, their mechanical subcontractor, and the designer. The designer first went into explanation on how the original design had been modified and how that should not have greatly altered the center lock behavior. The mechanical subcontractor then went into an explanation that to the best of their knowledge, the center lock components were manufactured in strict accordance to the plans and specifications. The designer was in disagreement to this and suggested that the center lock jaws be tested. The testing was to consist of material and hardness testing, in an attempt to determine the cause of failure.

The testing would take up to six weeks to perform and new forgings would take up to fifteen weeks to fabricate and finish. To shorten the lead time, the mechanical subcontractor proposed to offer an alternate solution which was to provide a high strength steel plate, AISI 4140, in lieu of the specified forging material of A668 Class M. The client was also in favor of this to get the problem remedied as soon as possible. It appears that the installation of the new center locks occurred near the close-out of the project and all parties wanted to get the job finished.

As the designer, we wanted to be accommodating, so we told the contractor to supply shop drawings for the possible alternative material to be provided. The review of the new material was by a side by side comparison with the specified material.

	ASTM A668 Class M	AISI 4140
Ultimate Strength	140 ksi	89 ksi
Yield Strength	115 ksi	62 ksi
% Elongation	14	26
% Reduction in Area	40	58
Brinell Hardness	285 min.	187
Special Brinell	480	425

After examining the two materials, the client was notified that the material to be furnished was inferior in strength and hardness and it was not advisable to accept the substitution. The client approved of our recommendations and requested the contractor to furnish new components to the original contract specifications.

Test Results

While the recommendation to utilize an alternate material was being decided, one pair of the broken jaws was sent to an independent testing laboratory to have them tested and possibly determine the cause of failure (See Figure 9). A report which described the condition of the jaws and the tests performed with results followed. Specifics of that test report are discussed here.

First, the chemical analysis of the jaws performed by the testing laboratory matched the material's certified test report from the original forging manufacturer, which called for ASTM A668 Class M. No error in the material could be blamed.

Second, hardness readings were taken on the components and the following results were obtained. The contact areas (or bores) had the specified hardness of 480 BHN. Areas not to have the added hardness were tested and showed extremely high readings, indicating the entire jaw surface was hardened to the 480 BHN instead of just the local areas of the bores. One excerpt from the report expresses the situation. " The jaws and links were extremely difficult to cut into smaller pieces for purposes of metallurgical evaluation using tungsten carbide tipped saw. The narrow section at the fractured surface of the link was cut at a very slow rate, took several days with many saw blades being worn off and discarded. The cutting off the wider and thicker portion of the jaws was abandoned as being impractical."

This finding clearly indicats that the jaws, rather than being locally hardened, were hardened over their entire surface. This was a deviation from the design. Also, although the depth of the hardness was not determined, from the inability to cut the material, the hardening process can be assumed to have been deeper than intended. It was not determined or understood how the entire member was hardened rather than just locally, but this entire hardening surely modified the jaw's behavior to absorb impact.

An interesting finding into the cause of the failure was that the jaw forgings had their surface repaired at numerous locations by welding. One weld repair measured 11/16" deep. It turns out that the failure of one jaw initiated at a weld repair. Hardness tests of the weld area showed it to be soft (approximately 225 BHN), while the surrounding area was at the 480 BHN. This resulted in "residual stresses in the weld area which contributed to initiation of fracture." It should be noted that repair welding of forgings is not permitted by ASTM for A668 forgings.

The second jaw had heavy rough machine marks located at the initiation of the fracture and these marks can be attributed to the failure. It is believed that the jaw, due to having the high surface hardness throughout, was difficult to machine and subsequently not fully finished, allowing a stress riser to remain.

As previously mentioned, the jaws for the two fractured locks were replaced with new jaws. The two remaining new locks had been installed, but had not failed. These jaws had their hardness tested in the field and were also hardened over their entire area. For that reason, although they had not failed, they were also eventually replaced.

Conclusion

Modifying a material's characteristics, when done correctly can have a multitude of benefits. As designers, we have control over the design of a product and what procedures must be done for it to behave the way it is intended. Once the design is complete, the designer loses control and must rely on information from the contractor to ensure the proper steps are being taken.

The fabrication and installation of the design can be as complex, if not more involved than the design itself. Use the fabrication of the center lock jaws as an example. These forgings had three separate, but equally important steps performed by three different companies. One company made the initial forgings; another company performed the additional hardening and a third company did the final finishing and assembly. Anywhere in this process, it is possible for an error to arise. For the most part, quality control steps are maintained, which include material certifications and shop drawings. Sometimes though, things can go completely wrong for no apparent reason and further evaluation is needed.

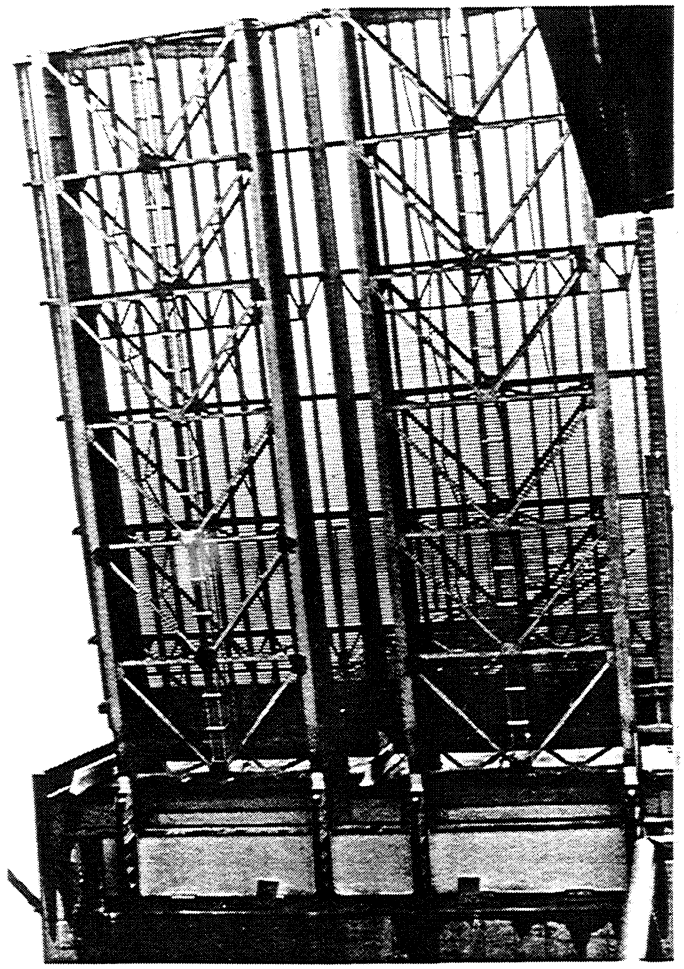


Figure 1: East Bascule Leaves in the raised position.

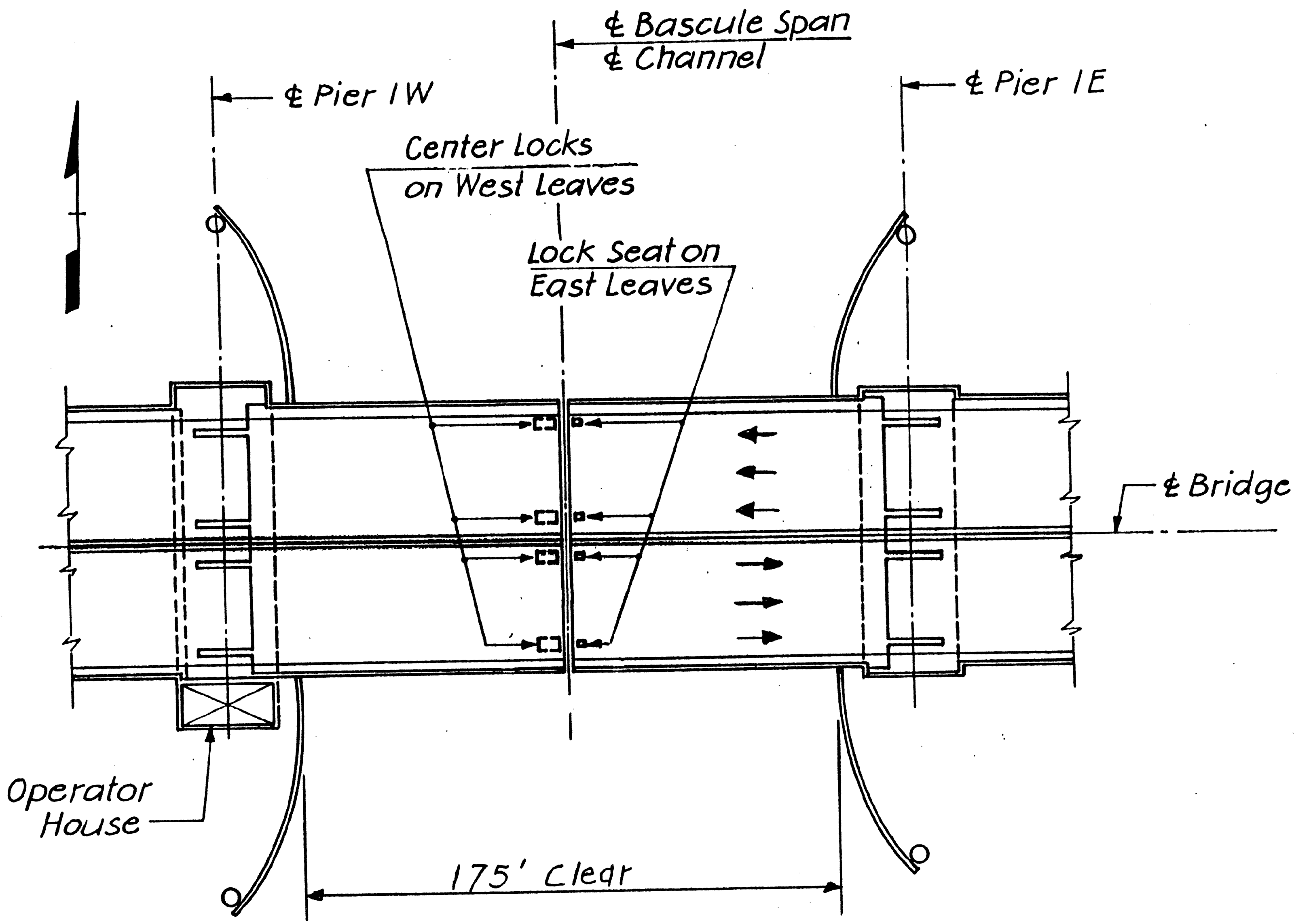


Figure 2: Plan of Bascule span showing location of center locks.

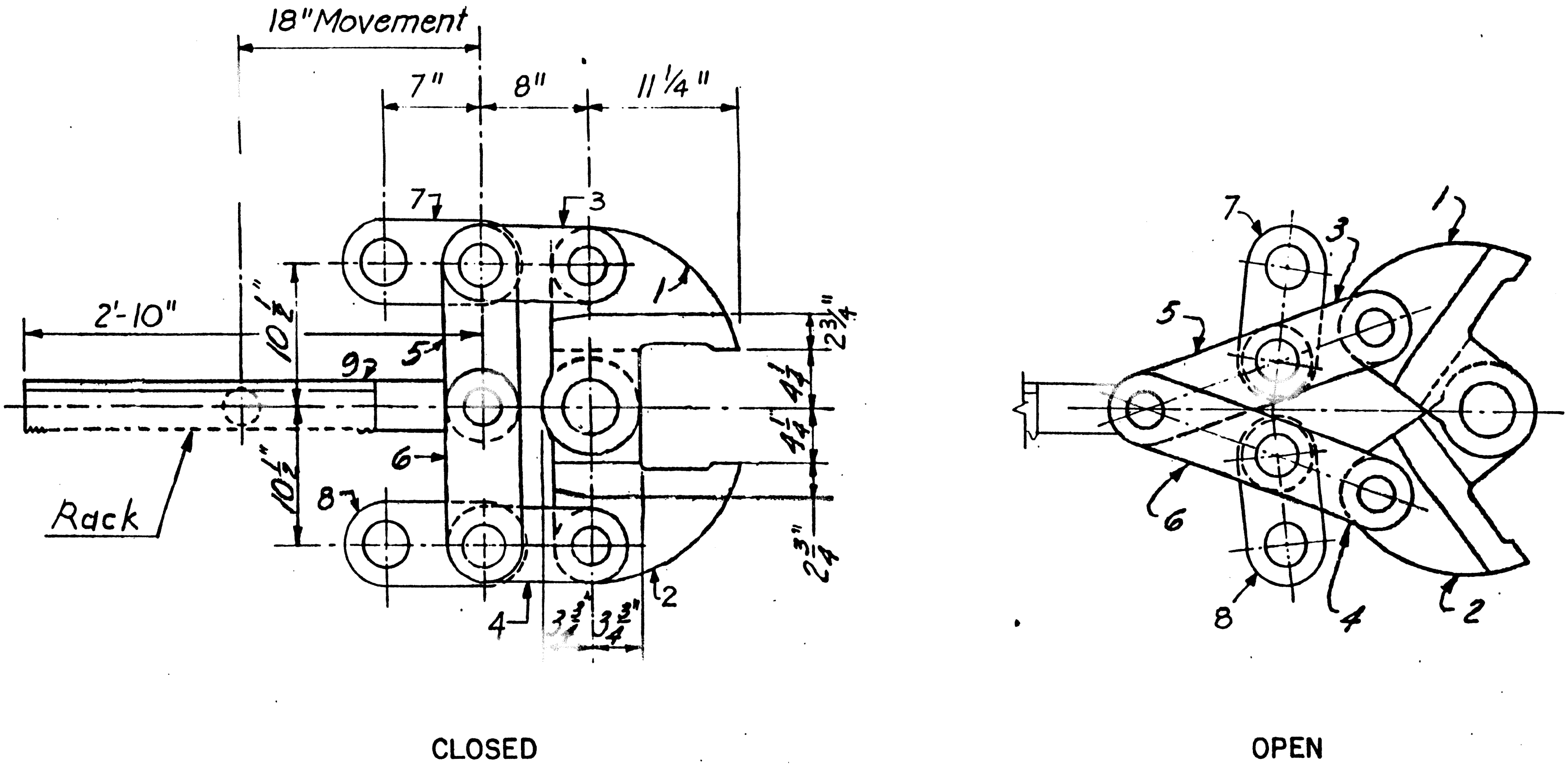


Figure 3: Center lock linkage assembly.

Figure 4: Typical view of jaws which shows extensive amount of shimming required to keep jaws tight to lock seat.

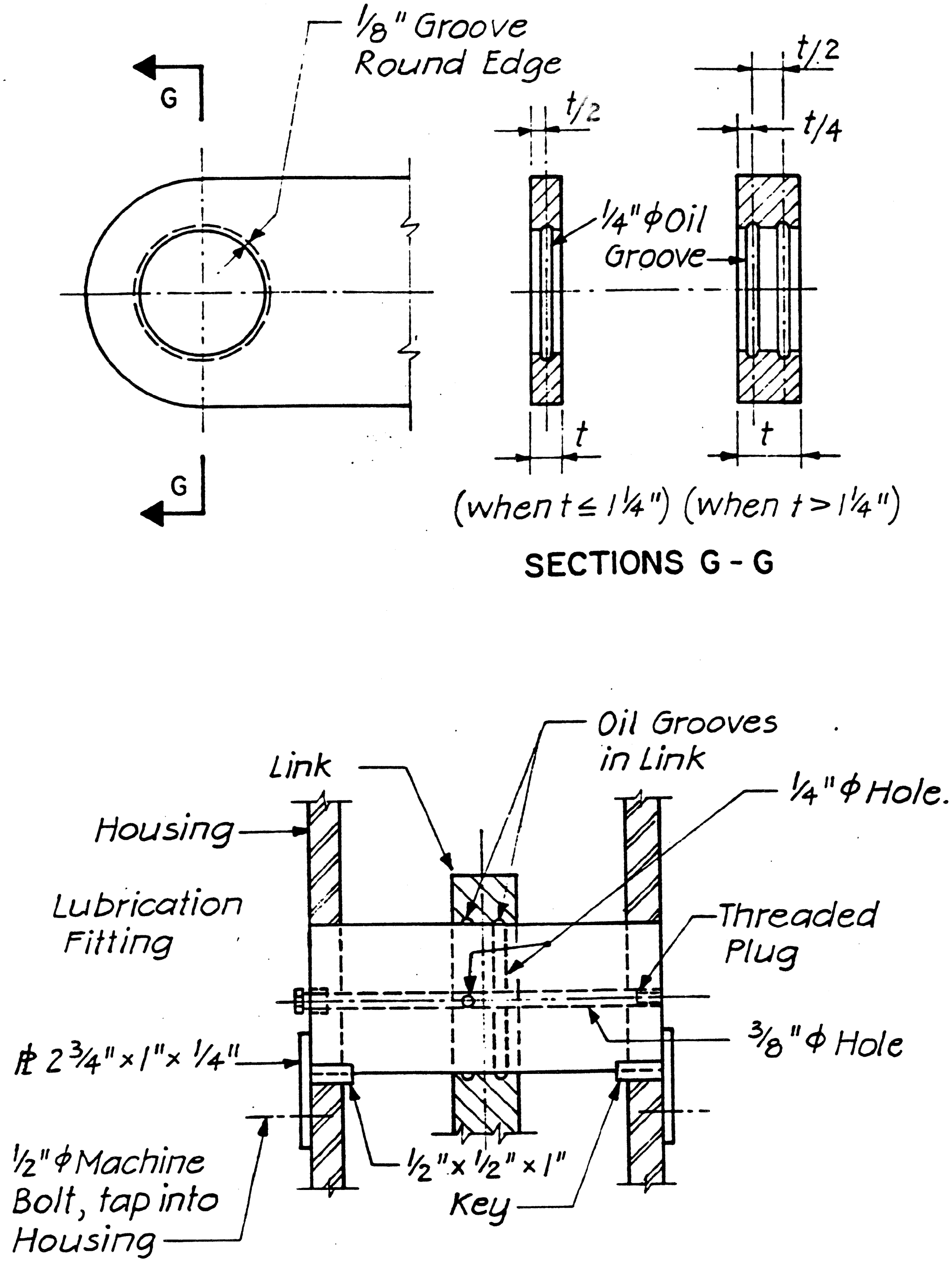


Figure 5: Modificationto links and pins to provide lubrication to surfaces.

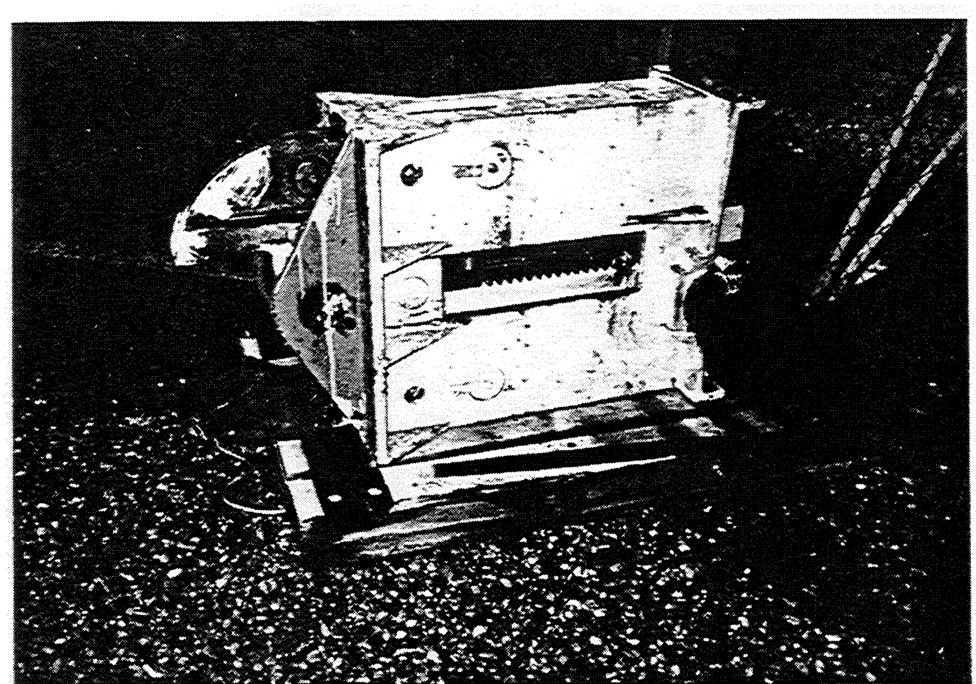
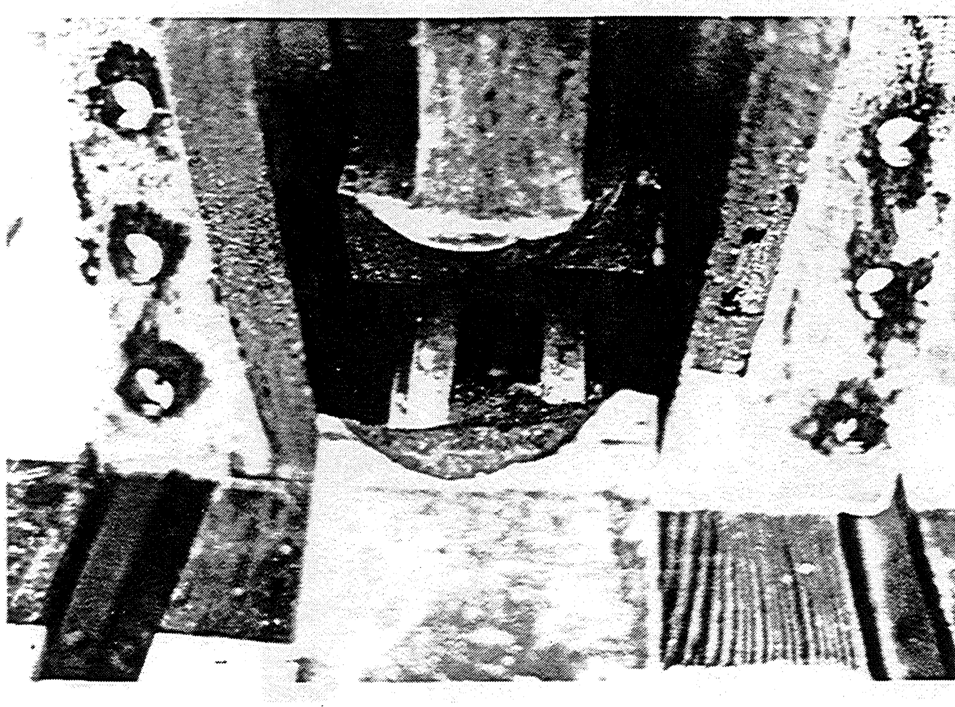


Figure 6: Center lock assembly removed from bridge due to broken jaw.



Figures 7 and 8: Close up view of jaw fracture.

Figure 9: Pair of fractured jaws out of assembly and prior to being sent for testing.