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"Bolted Connections For Machinery;
A Case Study", R. Mayeaux,
Mayeaux Engr'g, Inc. Baton Rouge, La.

INTRODUCTION

When the industrial revolution began, the primary structural materials were wood and stone. These materials were replaced by wrought iron and then, steel, as engineering technology became more sophisticated. Part of this sophistication was connection techniques. Mortise and tenon were replaced by riveted and bolted connections. Riveting was primarily for structural steel construction while the bolted joints were for wood and steel construction and machinery. Surprisingly, the bolted connections were not standardized. They were custom made. Thread forms and pitch were made to the fabricators liking and often were not interchangeable. This practice continued until the end of the 1800's when industry and engineering associations standardized thread forms. The primary driving force for bolted connections was the steam engine. The need for increased power and mobility applied greater demands on fastener connections. Bolted connections for machinery differs from traditional structural connections in the rigidity required in the joint and service.

Bolted connections in machinery should allow for location within tolerances, adjustment, rigidity, transfer of loads and disassembly. Components are designed, fabricated and assembled relative to some reference. Because of inequities in fabrication and erection, tolerances are required for proper assembly. This tolerance may be clearance between mating parts or, in some situations, an interference may be appropriate.

Relative movement between machinery components inevitably produces wear. To compensate for wear, the bolted connection should provide a means for adjustment. This could be by a shim pack or by adjustment screws. One characteristic that differentiates machinery connections from structural connections is rigidity. Deflections between machine components less than 0.010 inches or one quarter of a degree of arc are common. Rigidity also manifests by keeping the bolted machine parts secure. The need to seal in steam pressures at high temperatures puts a heavy demand on holding preload on the fasteners. Keeping the preload on a threaded fastener can be obtained by locknut, lockbolt, anaerobic adhesive, lockwasher or jam nuts. These five methods are used most often.

Regardless of the locking method, a thorough understanding of the load rate, magnitude and direction enables one with the means to providing an efficient and properly executed bolted connection. Any bolted connection may be made to hold loads for the short term. However, properly designed and executed transfer of loads can provide for a maintenance free connection for the long haul.

One of the selling points for a bolted connection is that the parts may be disassembled. Ask someone that has had to pay for removing rivets or have had to cut a shrink fit in a lathe to remove a shaft. Downtime and labor costs multiply fast; exponentially, if you are the one paying for it to be done. However, disassembly is a subtle trait often taken for granted. Frequency of disassembly should be kept in mind when designing or in maintaining threaded fasteners. Most people have experienced a time when installing a new bolt would have kept the lawn mower together or the water pump on your car. Being able to unscrew a fastener may be as important as being able to tighten it.

Specifications provide an avenue of judgement from which to design. Analysis and research provide the direction the design takes. Experience determines the quality of the ride.

SUMMARY

This paper examines six case studies of bolted connections for bridge machinery. While all the cases are critiqued, not all the examples created problems. The bolting systems performed many different functions. These case studies are from existing movable bridges. However, similar designs exist in other industries such as sugar mills, paper mills, chemical plants, dams and locks. Regardless of the industry, all machinery require bolted connections.

CASE STUDY NO. 1

This first study is directed to the center locks on a double bascule bridge. This rolling leaf bridge consist of two 57'-9" spans with oil hydraulic power systems for the span, end and center lock drives. Located in an industrial area, this facility carries a large amount of eighteen wheel truck traffic. Additionally, it is suspected by bridge maintenance personnel that many of these trucks are overweight though, no measurements have been made. Vehicular speed is posted for 35 mph but, is optimistic. At 35 mph, a truck takes 2.3 seconds to cross the movable spans. Unofficial timing produces times well under 2.0 seconds. Operations for marine traffic for the past five years averages 550 openings per month. Peak traffic is usually about 795 openings. In other words, this bridge gets quite a workout. Loads on the center lock loosened bolt assemblies, elongated bolt holes and bent structural plates.

The center locks on a double bascule provide shear transfer for wind, ice and vehicular loads between the movable spans. Particular to this design is the vibration and impact generated by vehicular loads. As traffic travels the bridge, particularly overweight trucks, the bascule leaf deflects under the live load. The center locks attempt to keep the opposite leaf at the same relative elevation by a shear force of variable magnitude.

Problems develop from the rate of shear loading on the opposite leaf. The variable shear load combines with the inertia of the opposite leaf and clearances in mating components to cause this vibration and resulting impact loads. These forces are defined as impact because they have a large magnitude, short duration and oscillating direction. One has only to stand on these bridges as a truck passes to appreciate the forces involved. Loosening of the bolts on the center locks accentuated the impact loads because of the increase in relative movement, or slop, between the movable spans. The bridge maintenance people revealed they periodically had to snug up these bolts when the bridge operator complained of the noise of the clanging machinery.

The effects on the structure about the center locks were bent structural plates, loosened structural bolt assemblies, elongated bolt holes, broken welds on the grid flooring, skewed lock alignment and increased operating pressures to drive and withdraw the locks. See Plate 1A. The plates supporting the locks over the middle of the waterway were bent. This bending, resembling the "oil canning" of sheet metal, required heat straightening and shimming to put the center locks into alignment. Plating was added to reinforce the existing members as well as distributing the forces over a larger area. Elongated bolt holes were filled by plug welding, inspected for cracks, ground flush and redrilled at the proper location. The bolt assemblies were of adequate strength in regards to size. This conclusion was deduced by reviewing the original design and reinforced because of no shear failures of the original bolts. The new structural bolts installed were equipped with prevailing torque nuts of sufficient strength in accordance with ASTM A 325.

In the past two years since these repairs, there have been no indications of loose bolts or erratic operation of the center locks. Lock operation pressures have been lowered as a result of an accurate alignment and calls for lock maintenance was reduced. Though both vehicular and marine traffic remain heavy, the locknuts have solved this bolting problem.

CASE STUDY NO. 2

A fastener failure is the subject of this next case study. The failure occurred on the span drive of the bridge in the previous case study. Horizontally mounted hydraulic cylinders provide the motive power to move the rolling bascule leaves. On one occasion, the rod end separated from the cylinder rod. The components were inspected to determine the failure mode. The threads in the rod end and on the cylinder rod were undamaged except for the first five of the 4"-12UN external threads on the rod. These had been stripped but, were repairable. Damage to the rod end threads was negligible and held the remains of the stripped threads from the rod. Further examination resulted in no other features on the rod or the rod end; no set screws, locknuts or any adhesive on the threads. The rod simply unscrewed itself.

Repairs began almost immediately. First, the rod end was cleaned with a degreaser and dried. The threads were picked to remove the stripped cylinder rod threads and the threads chased to dress the profile. The rod ends internal threads, lastly, were wire brushed lightly to remove grit and filings and rinsed with the degreaser solution again, leaving clean, usable threads.

Next, attention was turned upon the cylinder rod and its threads. A procedure similar to the one used on the rod end was used on the rod except for not having to remove stripped threads.

Options for preventing a recurrence of this failure were discussed. Various aspects discarded were set screws and anaerobic adhesive. Set screws were attractive as simple, inexpensive and available. However, their use would distort the cylinder rod threads rendering span adjustment difficult, if not impossible. Past experience has also resulted in set screws working loose when not checked periodically. Discarded was the use of an anaerobic adhesive for lack of a positive method to determine unscrewing of the cylinder rod and insufficient information on an adhesive in high stress reversal situations. The configuration settled on was a locknut safetied to the rod end. See Plate 2A.

The safetied locknut performed three tasks. The locknut afforded infinite adjustment of the rod end and acted as a jam nut to keep the cylinder rod from rotating. Use of safety wire provided a visual indication of the locknut integrity. Holes were drilled through the thickness of the nut near the hex corners and a steel block welded on the rod end. The rod end was adjusted to its proper location and the locknut drawn tightly against the rod end. Safety wire was threaded through the holes and the wire ends twisted together so the wire would pull the nut in the direction to tighten it against the rod end. This method thus provides a secure means to prevent twisting of the cylinder rod.

Since its installation three years ago, performance has been excellent. Span operations have been practically flawless. No rod twisting has occurred nor, has there been any indications of twisting. This fastener solution appears capable of providing many years of service.

CASE STUDY NO. 3

An example of excellent machine and bolting design practice is showcased in this case study. Constructed in 1928, this trunnion mounted double bascule is driven by open gears. Electric motor modulation is by resistance banks and drum switch. Span drive is by a moving pinion engaging a rack anchored to the bridge pier. The characteristic that attracts one's attention is the unitized frame housing the gear train. This cast iron device exemplifies strength, stability and rigidity. These attributes could not be obtained by accident. Careful analysis, inspection of load vectors, experience with shop practice and ease of maintenance are in this design. Attributes from this example may be applied to current designs.

One notices immediately that the gear drive appears as a monolith. See Plate 3A. This is because of the density of the gear sets and the fact they rest in a single frame. This substantial cast iron frame provides for a precise and rigid mounting for the gears. Though this is 1920's technology, a frame of equal moment and torsional rigidity may be accomplished with welded members for current gear drives. The single frame allows the machining of the frame to be accomplished with a minimal amount of fixturing thus, reducing misalignment of bearing and gear surfaces. Note the number and location of the anchor bolt connections. The $1^9/_{16}$" diameter drilled holes were fitted for $1^{35}/_{64}$" ($1^9/_{16}$"$-^1/_{64}$") turned bolts. The tight fitting bolts fixes the frame location to less than 0.050" between ideal and actual orientation. Also noticeable are the numerous anchor bolts at the more heavily loaded bearings. This results in a most equitable distribution of forces into the substructure. The monoframe concept reduces working loads and increases accuracy when it is bedded into place. Leveling relative points on the frame is easier which, reduces construction cost.

Let us shift our attention to the details of the frame. The bearing caps are finished in all of the orthogonal directions. With the frame in the horizontal plane, the primary loads from the gearing are in the vertical plane. This loads the gear shaft toward the frame or against the bearing cap. Loading in this direction on the frame is in the direction of maximum rigidity. Loads on the gearing cap bolts consist of preload and up loads from the gears. Since the cap is held by four $2^1/_4$" diameter high strength bolts, equivalent to ASTM A 325 bolts, the tension loads from the gears will be less than the preload or 70% yield strength. These bolts transfer this uplift into the frame in the direction of maximum rigidity. Horizontal loads in the cap are transferred directly into the frame because of the close fit between the cap and frame. This close fit should be in the order of an LC1 fit. Proper fitting constrains assembled parts, such as the cap, into its mating aperture allowing the running gears to turn straight and true. A feature often neglected, this allows the cap direct bearing on shims and consequently, the frame. This is another illustration of how to maintain high rigidity.

On bascule and vertical lift bridges employing pinion drives, some parallels may be drawn from this example. For instance, on pinion drives on bascule bridges a current practice is to straddle the pinion between pillow blocks. Pillow blocks have slotted holes which may allow movement should the gears encounter any shock or impact loads. Therefore, the pillow block should be constrained to prevent any loss of alignment thereby, assuring the accuracy of the mating gears.

Concluding this case study, we have examined an approach for bolting an open gear drive that is easy to fabricate and install, accurate in operation and reliable as a system. Though open gear systems are becoming rare, the purpose of this study is to illustrate simple and effective methods available to the designer to fasten heavily loaded machines.

CASE STUDY NO. 4

An equal arm mechanical swing span was built in 1930 near the Gulf of Mexico. The movable span is a 250 foot long steel truss, has a 20 foot wide roadway, rotates 90 degrees and is powered by wound rotor motors. This motive force is driven through two pinions to a rack bedded to the circular concrete pivot pier. Problems had developed in the pinion drive.

The pinion is the last open gear reduction set of the bridge span drive. One of the vertical gear sets consist of a bull gear on top driving a 6 inch diameter forged steel shaft to the rack pinion on the bottom. Supported by bronze bushings, this shaft assembly turns in a cast iron bearing assembly. The bearing assembly consists of the housing, bronze bushings and bearing caps. See Plate 4A. This gearset-bearing assembly was shimmed and bolted to a built up machinery beam to transfer the rotating forces into the movable span thus, moving the bridge. Problems in this pinion drive assembly had been developing in the form of broken bearing cap studs and loose structural bolts connecting the bearing assembly to the bridge structure. Noticeable movement between the bearing assembly and machinery beam brought these problems to the attention of maintenance personnel.

To affix repairs, a decision was made to design, fabricate and install a new gearset and bearing assembly. This decision was made as the result of other bridge repairs as repairs to the existing bearing assembly were deemed too expensive. The main objective was to prevent bearing cap stud failure and increase rigidity in the bearing assembly-machinery beam connection.

The existing bearing cap studs were breaking at the rate of twice weekly. These studs were made from ASTM A 193, Grade B7 alloy steel bars. This is a ductile chrome-moly steel. The alloy has a minimum ultimate tensile strength of 125 kpsi, a minimum yield strength of 105 kpsi and a 2 inch gage elongation of 16 per cent. The steel was turned to the required body dimensions with cut threads and a 125 finish. Nuts used with the studs were either ASTM A 194, Grade 2H or A 563, Grade DH. All fractures of these studs were tensile failures occurring at the reentrant corner of the chamfer.

The fracture plane exhibited 80 per cent to 85 per cent brittle fracture with the remaining fracture area exhibiting ductile shear lips on the periphery. This brittle fracture was the result of the stud geometry. The sharp angles of the necked transition and rough finish produced a high stress concentration factor. When a large load is applied to the stud, an area near the surface would be stressed well beyond the yield strength even though the core of the stud is lightly stressed. Increasing this load stresses this peripheral area to the ultimate strength and the beginning of fracture. This start of fracture is exhibited by the shear lips. Rapid propagation of the break results in the brittle type of fracture in the core of the stud.

Indications from this fracture are that three characteristics of the stud can be changed to prevent failure. They are material, geometry and finish. See Plate 4B. The material selected was ASTM F 593, Group 7 heat treated in accordance to ASTM A 564, Type 630, in the H1025 heat treated condition. Otherwise known as 17-4PH stainless steel, this alloy is readily available, equivalent in cost as ASTM A 193, Grade B7, exhibits slightly better impact and machining properties, superior strength and longitudinal toughness and has corrosion properties similar to austenitic, type 18-8, stainless steel. The second change was to use generous fillets at any section changes thus, reducing the stress concentration factor and stress gradient. Low stress concentration was assured by a 32 finish on the stressed areas on the stud by the prevention of tool marks of significant size.

Rigidity in the bearing assembly to machinery beam connection was achieved by two fronts. First, the bolted connection loads were distributed over a larger area. Second, gussets were added to key areas of the assembly along primary load paths.

The new bearing assembly provided a larger bolting area. A 3'-9" wide connection was used in lieu of the original 1'-9". This added 80 per cent to the original bolting strength capacity and over 176 per cent to connection stiffness. Additional bolt spacing allows the use of larger bolts should repairs be required at a later time. Gussets were added near the bronze bushings along primary load paths to increase rigidity and reduce internal bending stresses. The combination of a larger bolting area and stiffening gussets restricts relative displacements between the bearings while they are being machined and while they are under working loads.

The original bearing assembly had bolted connections at the top and bottom of the housing. When these repairs got under way, the top and bottom had $1^1/_4$" diameter high strength bolts, up in size from the original $^7/_8$" diameter bolts in the original construction. Lack of net section between the existing bolts, precluded the use of any larger fasteners. Additionally, it was determined most of the bolt holes in the machinery beam structure were oblong, elongated or were cut by a torch. This explained the movement of machinery and added another parameter to the bearing assembly-machinery beam connection.

The existing beam was replaced so the new bearing assembly would have firm, solid metal to bolt onto. New flange angles and web plate replaced the "swiss cheese" steel that previously existed. New metal allowed the use of $^{3}/_{4}$" diameter high strength structural and turned bolts, more than adequate for the job. The new bearing assembly was aligned, shimmed and bolt holes drilled and reamed to size in the field. The new high strength structural bolt holes were reamed $^{1}/_{32}$" larger than the $^{3}/_{4}$" nominal bolt diameter. Running the bolts up to design preload completed the attachment of the bearing assembly to the structure. The final sequence was to install the new gear shaft assembly, bearing caps and torque the locknuts on the new studs.

Since the installation of the new components four years ago, no bolts have worked loose and no studs have broken. The increase in machinery stiffness assures gear operations within AGMA gear quality requirements. Maintenance on the gear drive has been reduced to periodic lubrication of the gears and bushings.

CASE STUDY NO. 5

On the previously discussed bridge, anchor bolts and structural bolts fasten the sectional rack to the pivot pier of this swing span bridge. Sixty years of service in an exposed marine environment had taken its toll on the steel fasteners. Rust over $^1/_4$" thick on bolts, nuts and rebars gradually loosened these bonds. Before long, rack sections began to move. Concrete spalling started as tiny flecks then, almost overnight, grew to slabs the size of shoe boxes. Exposed by this spalling, anchor bolts and resteel corrosion accelerated, further aggravating the problem. Bolted connections between the cast iron rack sections stretched, elongating bolt holes and loosening nuts under the increased impact and strain. Examination of the existing condition and design drawings determined that the concrete pier should be rehabilitated to provide a solid foundation for the rack and new anchor bolts set for a rigid, solid load path into the pier. Prevailing torque locknuts were required to prevent loss of preload on the anchor and structural bolts.

Executing concrete repairs required the removal of all loose, cracked and broken concrete. Reinforcing steel was cleaned for reuse, spliced or new holes drilled for insertion of new rebars into epoxy. Existing anchor bolts were cut flush with the concrete and new anchor bolt holes drilled midway between them. Accuracy for the new anchor bolt holes were tight in order to maintain a AGMA Gear Quality 6. After the epoxy had set on the new anchor bolts and the leveling nut installed, the rack sections were roughed in. Finally, the rebars were installed, the pier formed up and the rack leveled and set in its final position. The epoxy cement was mixed, pours made and allowed to set. A typical repair section is illustrated in Plate 5A.

Provisions were being made for the final operation as the epoxy cement was hardening. The anchor bolt holes in the rack are $^{1}/_{4}$" larger than the nominal anchor bolt diameter, in this case $1^{3}/_{4}$" diameter. The annulus was to be filled with molten lead to prevent the rack from shifting out of position. Lead is poured sequentially around each anchor bolt. A locknut is removed with its flat washer, the lead poured to just below the rim and the washer and locknut run down and retorqued. This sequence was repeated for the next anchor bolt until all sixty were done. Even though the molten lead has a relatively high pouring temperature, about 630°F, the small volume constituted little thermoelastic effects. Point of fact, the only effect was a warming adjacent to the bolt connection. Since the bolt holes were near the centriod of the rack section, no bending effects were expected or measured thus, the rebedding of the bridge rack was completed.

Since the rebedding of the rack and the installation of the new bolts and locknuts four years ago, no movement in the rack or effects of movement have been detected. The prevailing torque locknuts have provided cheap insurance to assure adequate bolt preload. Their modest additional cost had no perceivable effect on the contract bid price. It is surprising this available and affordable technology is not used more effectively.

CASE STUDY NO. 6

An investigation was made to resolve the poor operation of a vertical lift bridge. Constructed in 1936, this small narrow two lane bridge had a 45 foot steel "I" beam movable span topped with steel grid flooring. Needing paint, the riveted overhead trussed superstructure, arched like a canopy, showed the years. The tidal stream moved as slow as the traffic. This sleepy south Louisiana bridge gives a false impression of the marine activity through this bridge. Averaging 230 openings a month and peaking at 560 per month during the shrimp season, the wear and tear begins to take a toll on the machinery. Problems began manifesting first as broken couplings then, as abnormal gear teeth wear.

While lowering the span, the operator noticed a corner of the span stop. Raising the span and then lowering it again failed to free the stuck corner. Maintenance personnel were called and inspected the errant bridge. The cause of the problem was immediately apparent. A flexible coupling connecting the low speed shaft to the pinion shaft had shattered the cast aluminum cover and had forced out the flexible steel grids. The cast cover was shattered around the periphery at the middle of the coupling. The break left penny sized pieces of cover on the machinery floor and a ragged edge on the remaining bolted cover halves.

The maintenance crews began disassembly of the shafts to replace the coupling. A pinion gear drives a bull gear on a common shaft with the counterweight rope sheave. The rotating sheave moves the lift span up and down. Maintenance workers had noticed the gear lubricant extruded from the gear teeth, leaving the top outer quarter of the teeth clean of lube. This pattern was mirrored on the other side of all the gear teeth, indicating one or both of the gears were moving relative to each other under load. Plate 6A illustrates the machinery layout.

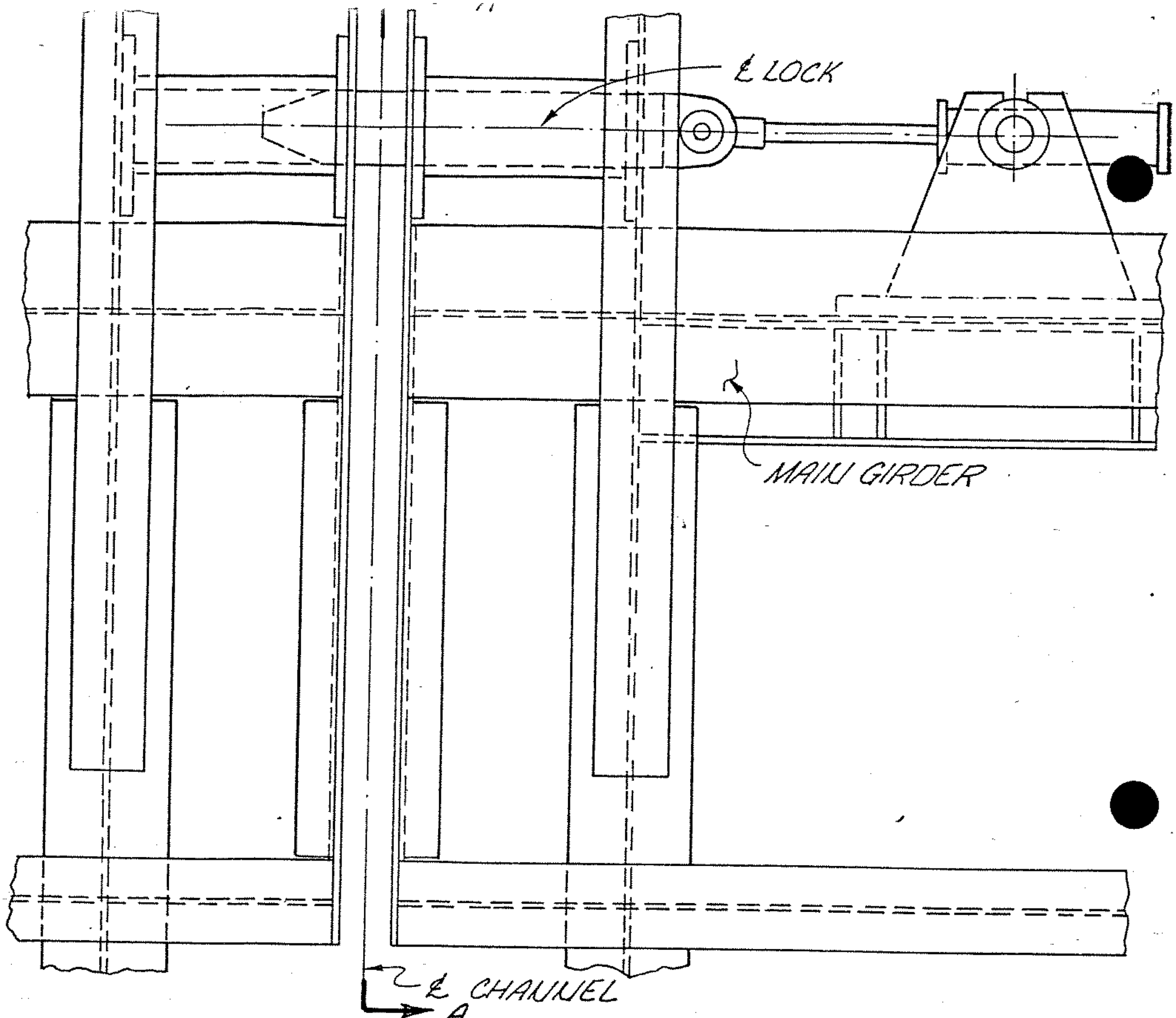
Misalignment and length of time over which this occurred sharpened the tooth profile in this area. One end of this pinion shaft is supported by a flange pillow block. The four A 325 bolts on this pillow block were found to be loose. Upon removal of the pinion shaft and pillow block, it was apparent that bridge operation had elongated the holes. The original pinion shaft and bearings were put back into position and the bolts installed to approximately their original tightness. Loading the shaft at the flanged pillow block end deflected that end of the shaft a total of $^1/_2$"; roughly $\pm ^1/_4$" from the design centerline. This movement was 450 per cent above the maximum operating deflection angle recommended by the manufacturer. What began as loose bolts deteriorated to a shaft slamming to and fro against its supports. The impact must have been tremendous to elongate the holes in the $^3/_4$" web.

This excessive movement explained both phenomenon, the rupture of the cast cover and sharpened gear teeth. The cast coupling cover was ruptured when the excessive deflection caused the shaft to bind inside the coupling thus, inducing a moment into the coupling cover. It was this moment that eventually ruptured the coupling cover. The sharpened pinion gear teeth were not only a result of this deflection but, also indicated the long period of time of this occurrence.

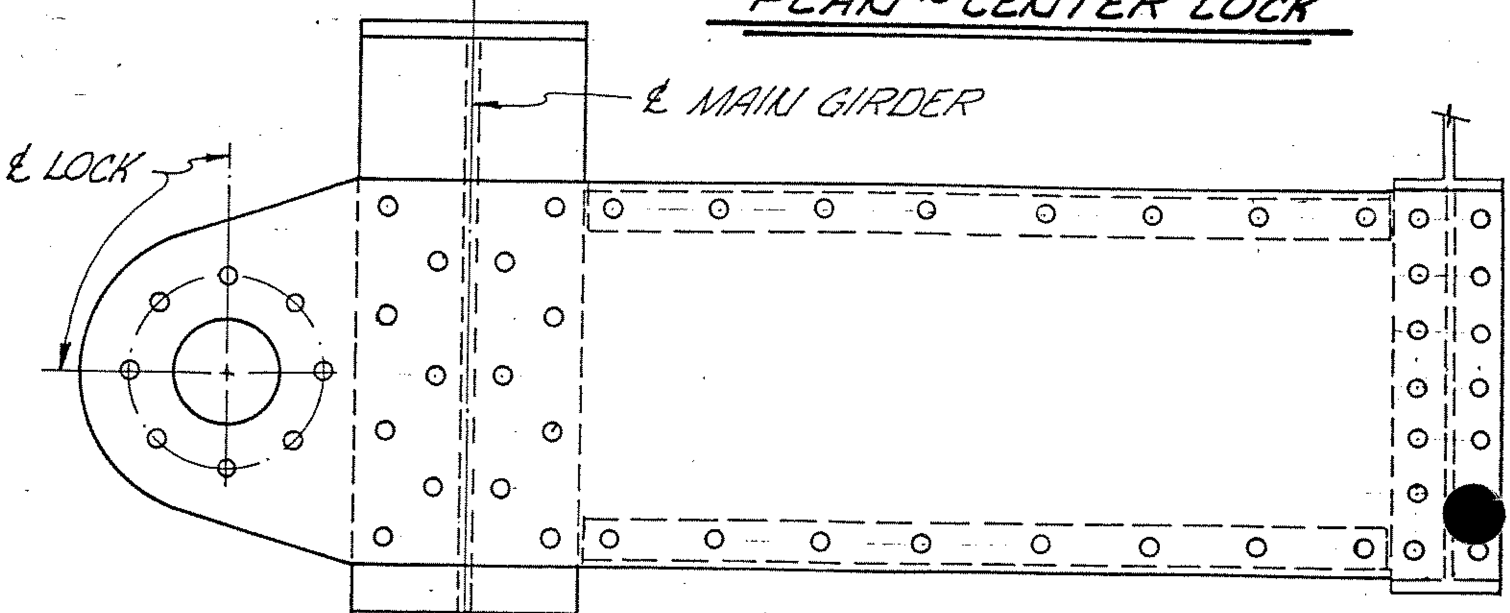
Identifying the source of these problems determined the solution. Recommendations were made to seal the elongated bolt holes by plug welding, align the pinion shaft, drill and ream new bolt holes, tighten bolts to specifications and install a new coupling. Two of the new bolts recommended were to be turned bolts installed at opposite corners of the new flanged pillow block. Turned bolt holes in the structure and pillow blocks were to be drilled and reamed together at assembly and after shaft alignment. The remaining two bolts were to be high strength bolts conforming to ASTM A 325. Nuts for the new turned and structural bolts on the pillow block were recommended to be prevailing torque nuts. The use of round bolt holes and tightened bolts increase rigidity, reduce wear and decrease maintenance cost.

CONCLUSION

Machinery requires a unique approach for bolted connections. Load reversal, vibration and impact are forces commonly found in bridge machinery. These connections are also required to compensate for construction tolerances and operational wear. On top of these requirements, bolt assemblies are installed in harsh operating environments and then neglected for years. Many components, devices and techniques are available to compensate for loads, vibration, environments and wear. Their application can enhance the performance and operation of machinery bolted connections.

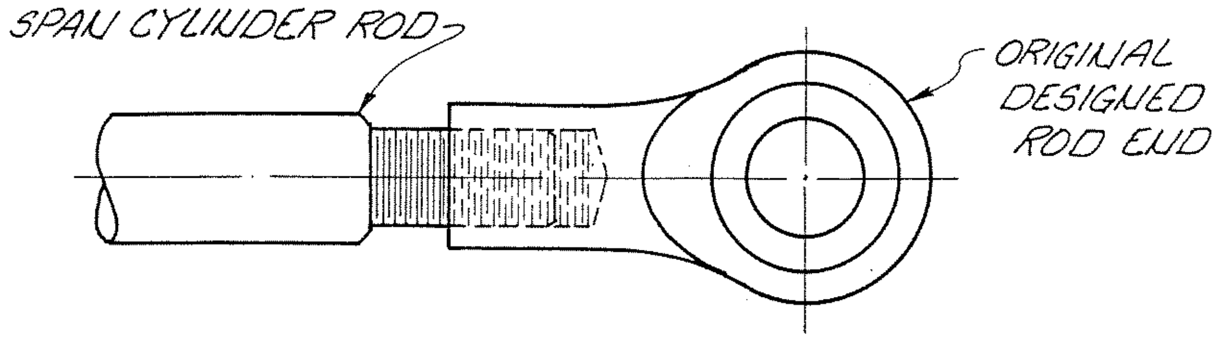


PLAN ~ CENTER LOCK



VIEW A-A

PLATE: 1A


SPAN CYLINDER ROD
ORIGINAL DESIGNED ROD END

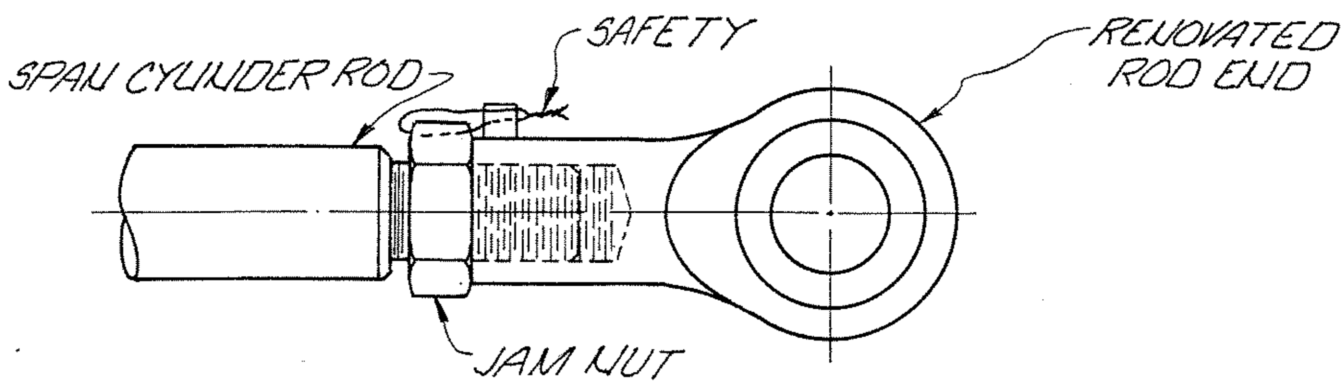

SAFETY
SPAN CYLINDER ROD
RENOVATED ROD END
JAM NUT

PLATE: 2 A

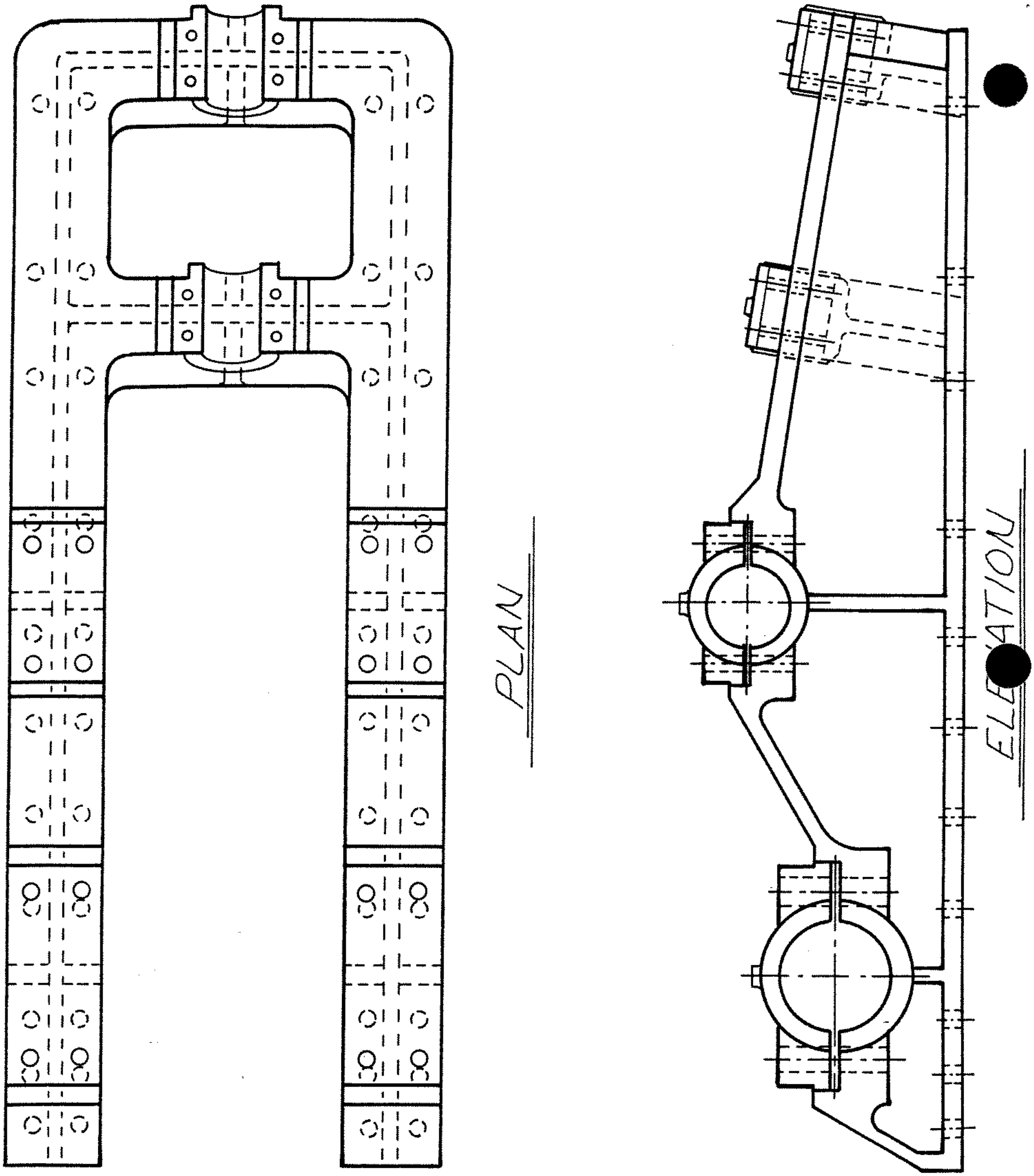
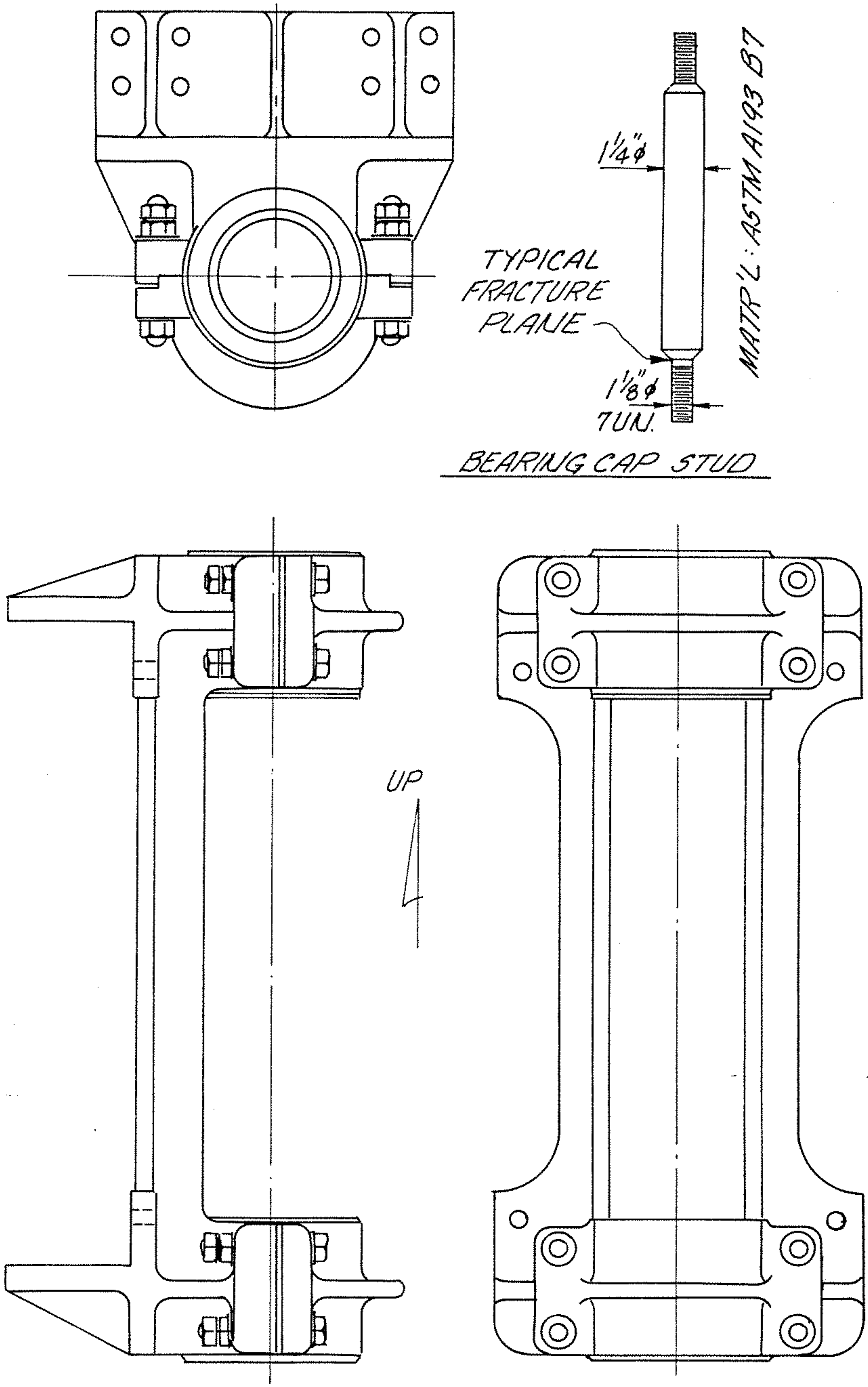
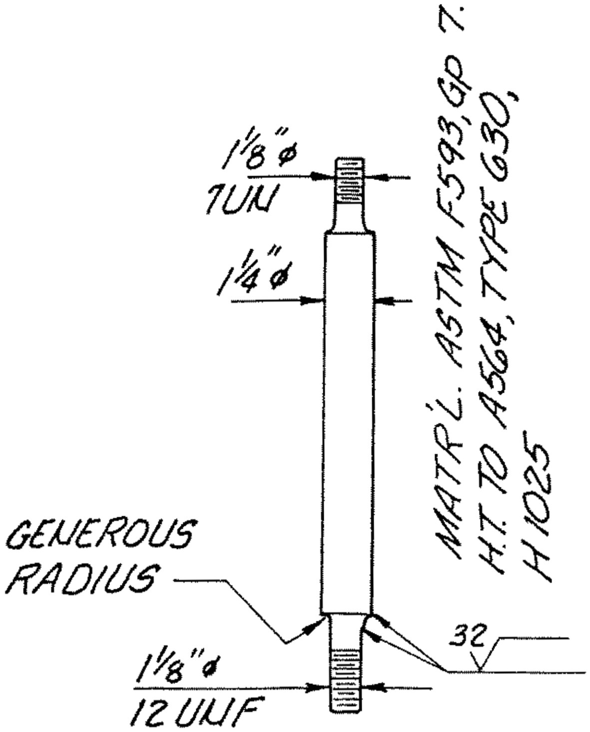


PLATE: 3A



1¼"ϕ
MATR'L: ASTM A193 B7
TYPICAL FRACTURE PLANE
1⅛"ϕ 7UN.
BEARING CAP STUD
UP

PLATE: 4A



BEARING CAP STUD

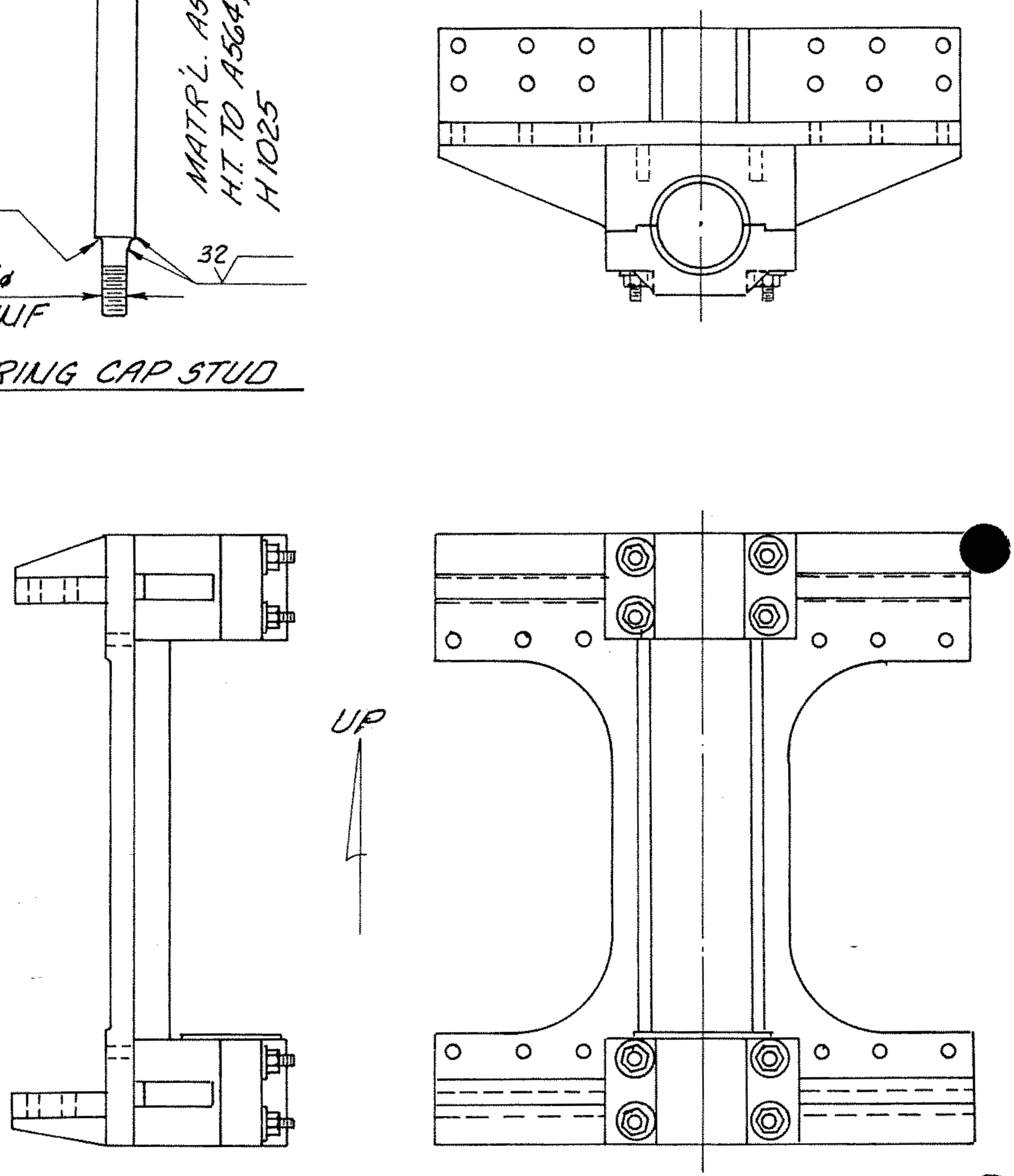
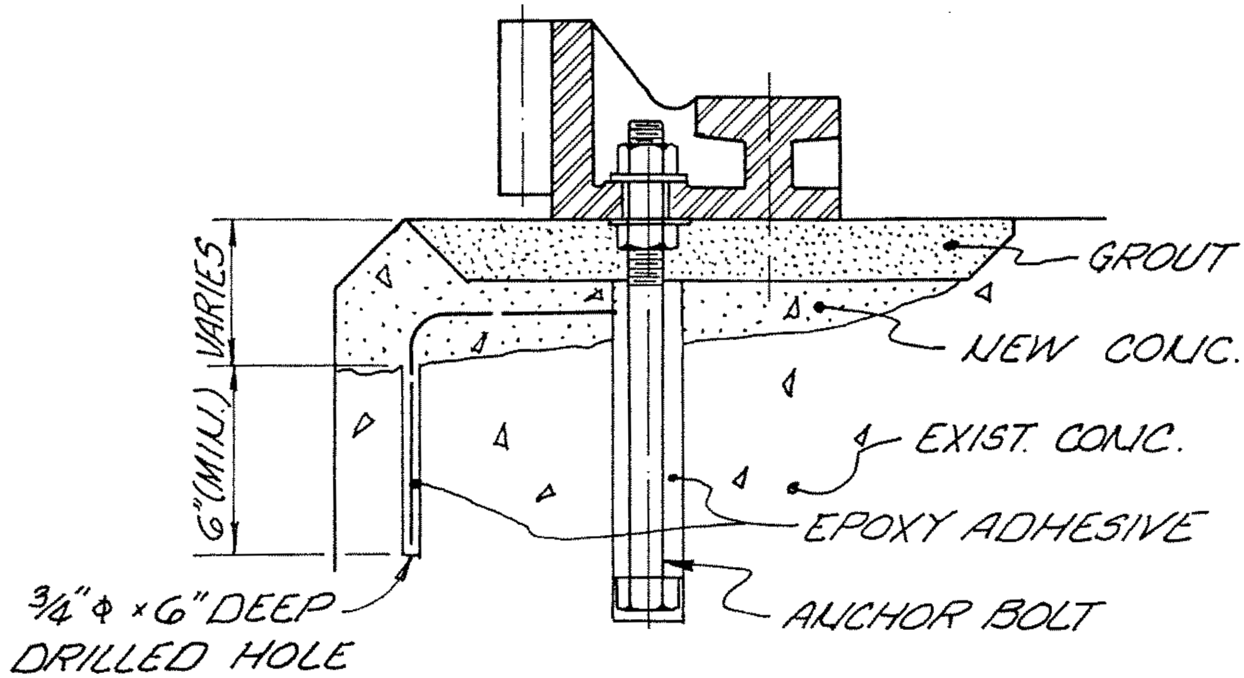
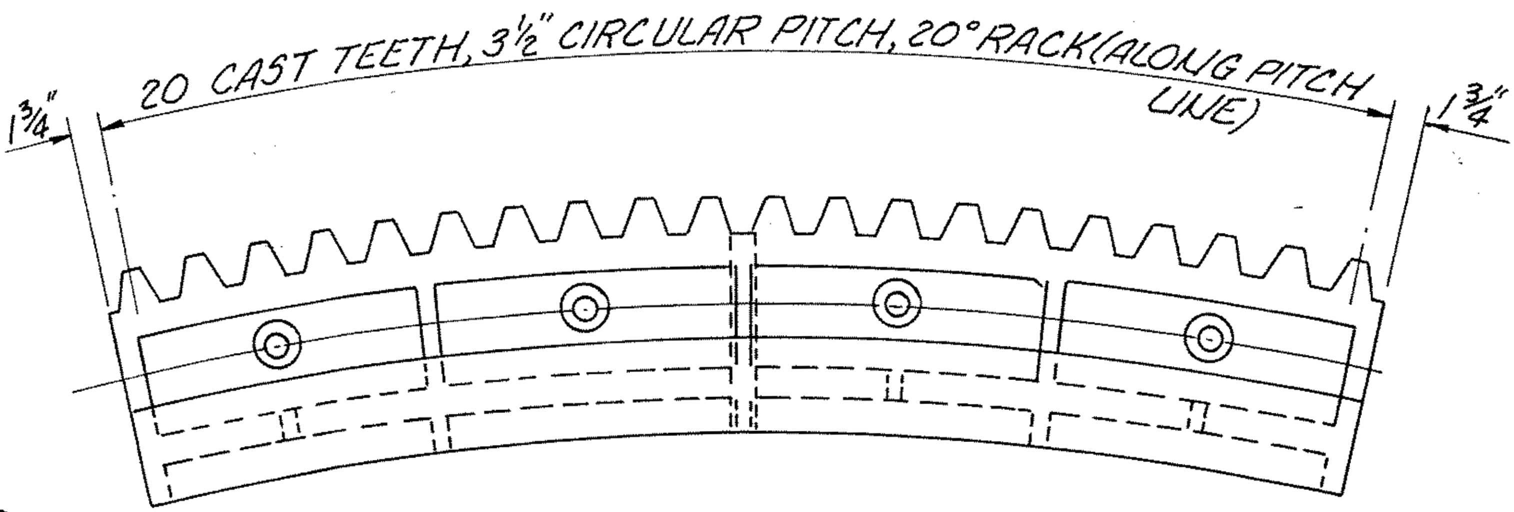


PLATE: 4B


GROUT
NEW CONC.
EXIST. CONC.
EPOXY ADHESIVE
ANCHOR BOLT
6"(MIN.) VARIES
3/4"Φ × 6" DEEP
DRILLED HOLE

TYP. REPAIR


20 CAST TEETH, 3½" CIRCULAR PITCH, 20° RACK (ALONG PITCH LINE)
1¾"
1¾"

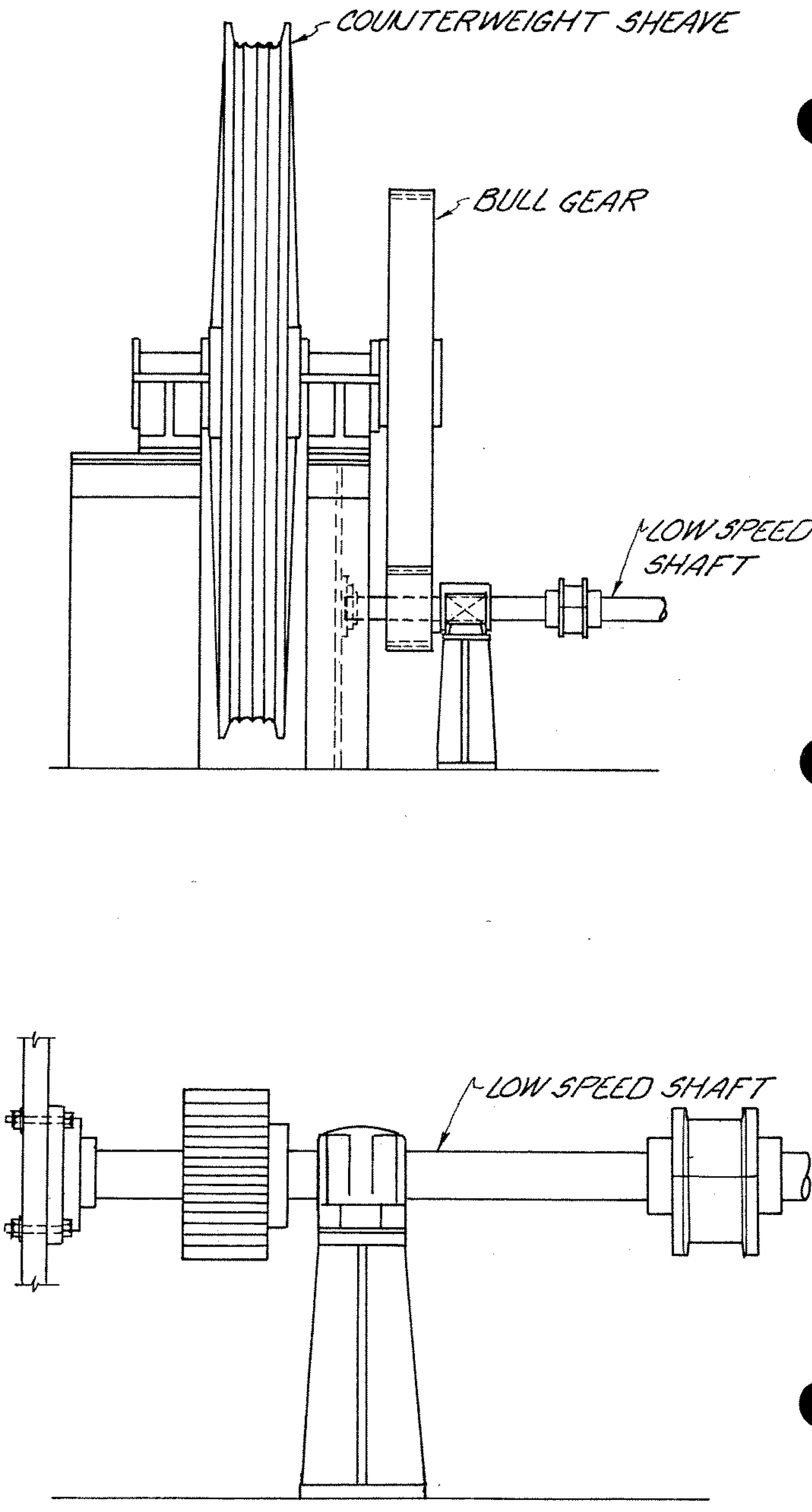

COUNTERWEIGHT SHEAVE
BULL GEAR
LOW SPEED SHAFT
LOW SPEED SHAFT

PLATE: 6A