LIFTING CHAIN DESIGN FOR TAINTER GATES AND ROLLER GATES

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INTRODUCTION AND SUMMARY

This paper is a follow-up to a technical paper presented at the 2001 Infrastructure Systems Conference. Lifting chains (utilizing pins, rollers, and sidebars) are used extensively within the U.S. Corps of Engineers for both roller and tainter gates. The applications of this type of chain for Lock & Dams 3 through 10 on the Upper Mississippi River will be discussed. All the lifting chains on these dam gates have been replaced as part of a major maintenance and major rehabilitation program (MMMR).

A number of different issues pertaining to lifting chain will be examined. This includes material selection, corrosion prevention, first cost, and life cycle cost. An engineering analysis of this type of chain will be presented. Maintenance issues will be examined.

Although sprockets and chain are interrelated, sprocket design will not be analyzed in this paper.

Lifting chains for the dam gates falls under the category of a tension linkage chain and also the broader category of an Engineering Steel Chain. The lifting chains consist of pins, sidebars, and rollers (see Figure 1).

The gate lifting chains for Locks and Dams 3 through 10, on the Upper Mississippi River, have been replaced. This work has taken place over the last 15 years as part of the MMMR program. A number of different chain designs have been used with varying degrees of success. The sprockets for all the chains have been reused. The sprockets date back to the original lock construction in the 1930's.

The latest design for the tainter gate chains at Locks 5A, 6, 7, 8, and 9 incorporate aluminum bronze sidebars, aluminum bronze rollers, and stainless steel pins and collars. There are no bushings or bearings between the aluminum bronze sidebar and the stainless steel pin. This design is based on a similar chain design at Robert C. Byrd Lock and Dam on the Ohio River.

The tainter gate chains at Locks 5A, 6, 7, 8, and 9 were inspected during the flood event of Spring 2001. All the chains are in excellent condition. No problems have been reported with the chains. The chains have been in service since 1997.

The chain design using stainless steel pins and aluminum bronze sidebars can be a viable alternate to using wire rope for lifting applications on dam gates.

TYPICAL TAINTER GATE CHAIN INSTALLATION

TERMINOLOGY

It is important to differentiate how a lifting chain for a tainter gate or roller gate is different then a bicycle chain beyond the obvious size and strength differences. There are several chain standards and a chain manufacturer's association that classifies various chain types.

The American Chain Association (ACA) includes a number of chain manufacturing companies. The ACA has published a number of design manuals for chain and sprocket design including the handbook 'Chains for Power Transmission and Material Handling, Design and Applications' (1).

The chain industry, chain manufacturers, and ACA make a distinction between Roller Chain and Engineering Steel Chain. In general, Roller Chain is used for power transmission between sprockets at moderate to high speeds. The chain speed, sprocket design, and kinematics between the sprocket and chain are crucial. Roller Chain is manufactured per ANSI/ASME B29.1 (see standards paragraph below). The tension members between pins (side plates) are called link plates. This type of chain is generally produced in large quantities. The size and strength ratings are relatively low.

Engineering Steel Chain is intended for a wider variety of applications including materials handling, conveying, and other industrial uses. The Engineering Steel Chain is usually manufactured in smaller quantities, has greater strength, more corrosion resistance, greater shock resistance, and designed to be used in severe environments. The chain is manufactured per several standards including ANSI/ASME B29.10 and B29.15. The side plates are called sidebars. The pin-bushing area is referred to as the chain joint. The sidebars establish the chain pitch (see Figure 1).

The ACA defines tension linkage chain as a chain application where the main function is to move a load slowly, intermittently through a short distance, or to hold a load. These types of chains are used for hoisting, supporting counterweights, etc. The function of a tension linkage chain is to transmit a moving force using chain tension hence the nomenclature.

Lifting chain for roller and tainter gates thus falls under the category of a tension linkage, Engineering Steel Chain. The following definitions are used in this paper:

- Pitch is the distance between the centers of adjacent chain joint members or center-to-center distance between adjacent pins,
- Sidebars are tension members connecting the chain joints, and
- Pins connect one link section to another. Pins are the shear members between the inner and outer sidebars.

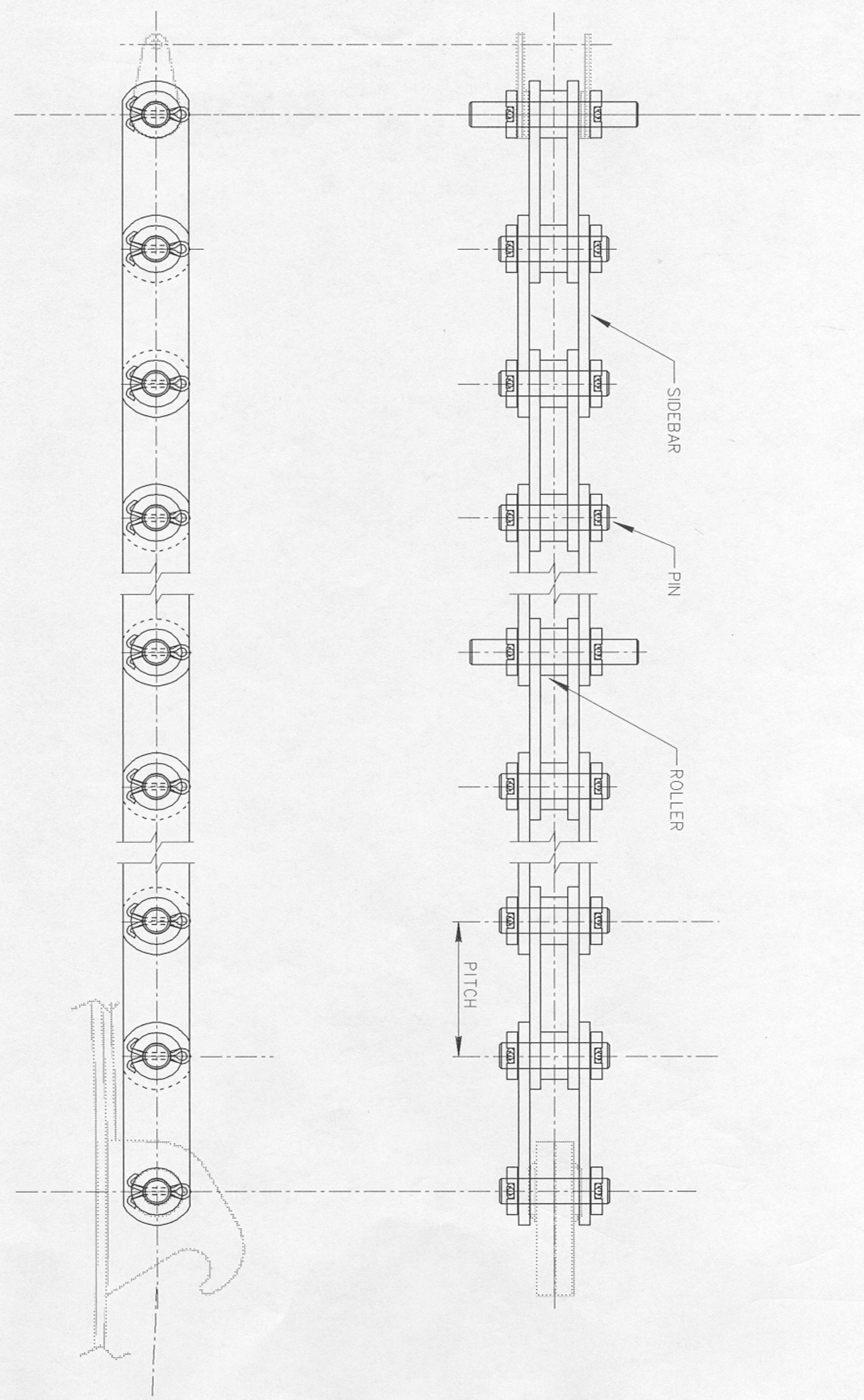

Figure 1
CHAIN ASEMBLY

STANDARDS

The American National Standards Institute (ANSI) and American Society of Mechanical Engineers (ASME) both publish standards for chain as stated above. These standards are written in English units although the latest editions of these standards have the metric equivalent (for reference only). In fact, the basic design of the chain in ANSI B29.1 is written in English units. The roller diameter is defined as 5/8 times the pitch. There are manufacturers, however, that make a true metric chain. Also, the European DIN (German) Standards and the International Standards Organization (ISO) categorize metric chain.

It should also be noted that the majority of the ANSI/ASME standards concern chain used in power transmission rather then lifting applications. However, this difference is generally irrelevant. The loading on the chain is basically the same and in both applications the chain is going over a sprocket. The biggest difference between power transmission and lifting application is likely to be the speed. In lifting applications, the chain travel will be extremely slow.

ANSI/ASME B29.1M (1993), Precision Power Transmission Roller Chains, Attachments, and Sprockets list a series of standard roller chain. However, this standard only classifies chain up to a pitch of 3.0 inches. ANSI B29.1 assigns standard number designations to chain based on pitch, chain width, and roller diameter. The chain sizes given in B29.1 are generally inadequate for a majority of tainter gate and roller gate lifting applications. The primary benefit of this standard is that any chain manufactured according to it will fit over any corresponding sprocket manufactured to the standard. The chain of one manufacturer will replace the chain of another manufacturer.

ANSI/ASME B29.10M (1994), Heavy Duty Offset Sidebar Power Transmission Roller Chains and Sprocket Teeth, only standardizes offset sidebar type of chain. This standard is an Engineering Steel Chain standard and includes chain with a pitch up to 7 inches (177.8 mm) and a minimum ultimate strength of 425,000 pounds (1890 kn).

EXISTING AND NEW GATE LIFTING CHAIN

The roller gates for Locks and Dams 3 through 10 require a single lifting chain and the tainter gates require two lifting chains per gate. There are 45 roller gates total and 52 tainter gates that require lifting chain in the Saint Paul District. Roller gate chain is considerably stronger then the tainter gate chain. The roller gate chain pull ranges from 230,000 pounds (1022 kn) to 340,000 pounds (1511 kn). The required tainter gate chain pull is 77,000 pounds (342 kn) divided equally between two chains (38,500 pounds or 171 kn per chain). The roller gate chain uses multiple sidebars (4) per link section to meet the higher load capacity (see Figure 2). The tainter gate lifting chain uses two sidebars per link section.

The majority of the original tainter gate chain designs (from the 1930's) used offset side bar roller chain as opposed to straight side bar roller chain. Prior to the MMMR program of chain replacement, at least some sections of roller gate and tainter gate chain were original and dated back to the 1930's. Any original chain sections that were underwater were severely corroded and the sidebars and pins were frozen in place. The original chain had no provisions for lubrication of the chain joint area.

The primary benefit of offset side bar type of chain is that the links are all identical. Offset sidebar chain can be used in odd or even number pitches. The new chain designs for Locks 3 through 10 utilize straight sidebar chain. The primary advantage of using straight sidebar chain is that the chain is easier to manufacture and for a given sidebar plate thickness, the straight sidebars will have more strength. Straight sidebar chain consists of inside and outside links and sections of this chain type must be used in even number of pitches (lengths). This chain can also be constructed without rollers. However, in gate lifting applications, the rollers are necessary for reducing friction as the chain is going over the sprocket.

The existing sprockets on the Locks 3 through 10 dam gates were reused. This required new chain to match the old chain in pitch. The required pitch for a majority of the tainter gate chains is 10" (254 mm) and the required pitch for the majority of the roller gate chain was either 12" (304.8 mm) or 13" (330.2 mm).

The design of the lifting chains has evolved over the course of several supply contracts. Roller gate chain supply contracts were issued in 1986, 1988, and 1992. A tainter gate chain supply contract for Lock and Dam 10 was issued in 1996. The tainter gate chains at Locks 5A, 6, 7, 8, and 9 were replaced in 1997 and 1998.

Several bearing and bushing designs have been used for the chain joint area. Lube-free bushings were used in the chain joint for the tainter gate chains at Lock and Dam 10. These designs are discussed in more detail in the paragraphs CHAIN DESIGN and MAINTAINABILITY below.

Several gate lifting chain designs, including those on the Ohio River and Mississippi River Locks 11 through 22, were investigated for possible use in the latest chain supply contract for Locks 5A through 9. Robert C. Byrd Lock and Dam (on the Ohio River) utilizes stainless steel pins and aluminum bronze sidebars for the lifting chain design. This was the design used for the Locks and Dams 5A, 6, 7, 8, and 9 tainter gate chain supply contract.

ROLLER GATE LIFTING CHAIN

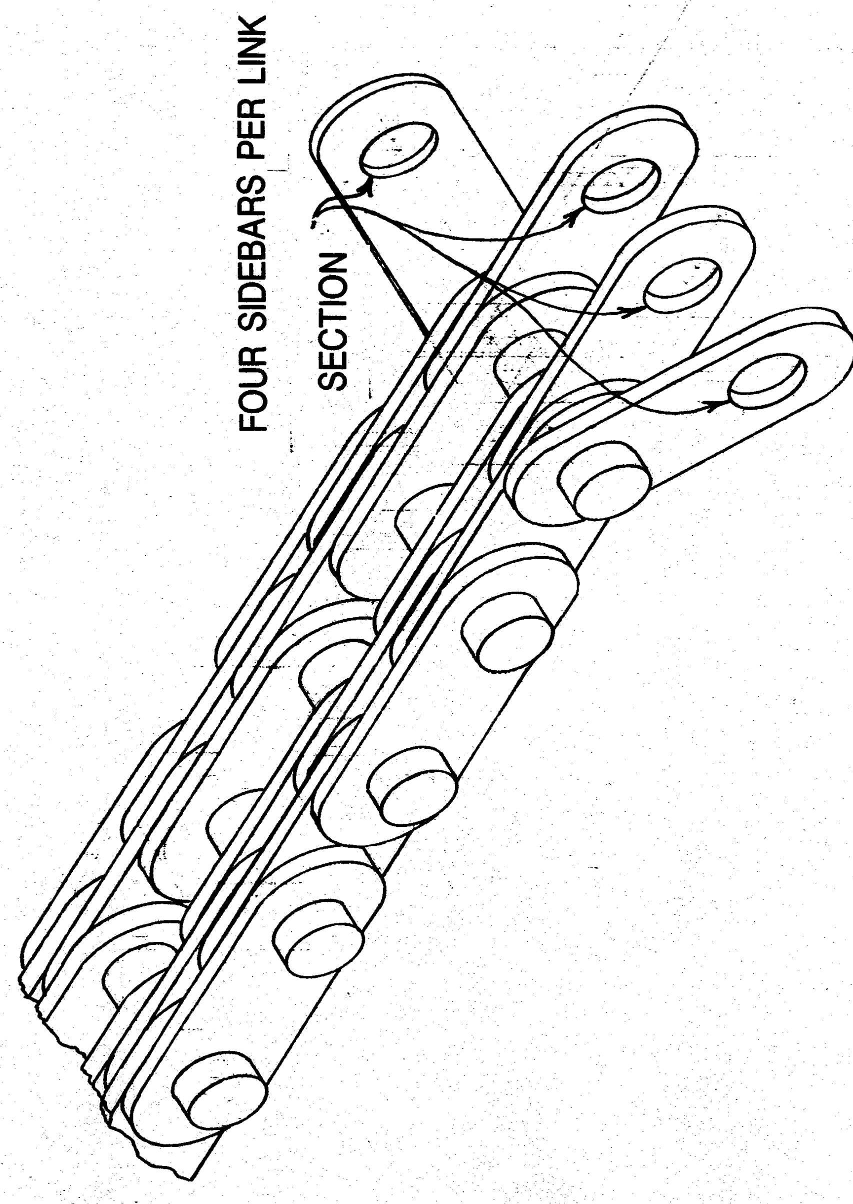

FIG. 2

LOCK 8 CHAIN ON THE REUSED SPROCKET

MATERIAL SELECTION

Material selection is likely the single most important feature of the lifting chain design. The type of material used for the chain will impact the strength, corrosion resistance, and overall life of the chain. Proper material selection must be made to insure a 50-year life for the lifting chains.

The lifting chain used on tainter gates and roller gates will at a minimum be subjected to rain, snow, etc. The portion of the chain that connects to the gate, however, will be submerged in the river. This will subject the chain to silt and debris. Because the dam gates are rarely moved completely out of the water, the lower section of chain will be submerged for a majority of its service life. This lower portion of chain will also be subjected to sandblasting and paint over spray when the dam gates are being painted.

For the MMMR program, several material types have been used for the lifting chain. The initial designs for the MMMR program used 1045 steel sidebars (sandblasted and painted) and 4150 or 4142 steel pins with nickel plating. Metallizing (Monel coating) was also used on the sidebars.

Because of the use of steel sidebars, it is likely that the submerged portion of the gate chains will need replacing over the next 50 years (even with metallizing or painting).

The most recent lifting chain design, as stated earlier, utilizes aluminum bronze sidebars and stainless steel pins. Both of these materials should provide adequate corrosion protection to allow the chain to last 50 years. Aluminum bronze is manufactured per ASTM B505 and a 62,000 psi (427,586 kPa) minimum yield strength is specified.

The stainless steel pins are manufactured per ASTM A564 Type XM-25 Condition H1050. This stainless steel is equivalent to Type 304 stainless steel for corrosion resistance. The primary disadvantage of using this type of stainless steel is that it was developed by one manufacturer and is not readily available from other manufacturers. Other options for the stainless steel include using ASTM A564 Type 630. This material is very close in properties to XM-25 and is available from more manufacturers. There are some disadvantages of using Type 630 stainless versus XM-25. The Type 630 stainless is more difficult to machine and must be age hardened prior to using. A comparison of the stainless steels is provided below in Table 1:

Table 1

	ASTM A A564 Type XM-25, H1050	ASTM A564 Type 630, H1025
Min Tensile:	145,000 psi	155,000 psi
Min Yield:	135,000 psi	145,000 psi
BHN:	321	331

BHN is Brinell hardness number

COST

The cost of the lifting chain will primarily be a function of the materials used. The first chain supply contracts (for the roller gates) all used 1045 steel for the sidebars. The sidebars were then painted or metallized. Pins were either 4150 or 4142 steel with nickel plating.

Although carbon steel materials will have the lowest initial cost, it is likely that the underwater portions of the chain will need replacement over 50 years. The stainless steel and aluminum bronze chain design will thus have a lower life cycle cost including maintenance costs. Also, the nickel plating of the pins approaches the cost of a stainless steel pin.

The cost for various combinations of materials has been estimated (per pound of chain). Cost estimating the chain on a per pound basis allows comparison of different designs. The chain length and size becomes irrelevant. The following Table 2 summarizes the chain costs between the various supply contracts. All costs have been converted to 2001 dollars.

The cost figures include all machining, assembling, and shipping.
All stainless steel chain using ASTM A564 Type XM-25 (both sidebars and pins) will approach $10 to $11 per pound of chain. The Saint Paul District has not used this material combination of chain.

The first supply contract for roller gate chain was higher in cost then the next two contracts because only 4 chains were ordered. 23 roller chains were fabricated in the second supply contract and 18 chains in the third. This allowed machining, assembly, and shipping costs to be spread over more chains.

Chain designs using a non-lubricated bushing will have a relatively high cost. This was the case for the tainter gate chain at Lock and Dam 10. This design was not continued because of the high cost of the bushings. Each bushing was approximately $20.

Table 2 - Chain Costs

Contract # and Year	Chain Type	Cost/Pound of Chain
1 - 1986 (4 Roller Gate Chains)	Steel Sidebars with Nickel Plated Pins and Grease Fittings	$4.8
2 - 1988 (23 Roller Gate Chains)	Steel Sidebars with Nickel Plated Pins and Grease Fittings	$3.3
3 - 1992 (18 Roller Gate Chains)	Steel Sidebars with Nickel Plated Pins and Grease Fittings	$3.4
4 - 1996 (Tainter Gate Chain for Dam 10)	Steel Sidebars and Nickel Plated Pins with Non-Lube Bushing	$8.7
5 - 1997 (Tainter Gate Chain for Dams 5A to 9)	Aluminum Bronze Sidebars and Stainless Pins	$6.5

CHAIN DESIGN

The new chain designs for the MMMR program are designed for a 50 year service life. Several design considerations need to be analyzed to insure this 50 year life. Strength and material selection are probably the most important. As discussed above, the material selection will dictate how much the chain will corrode over 50 years (in particular the lower section of the chain). There are other design considerations that need to be analyzed, however. This includes yield strength, shear strength, fatigue strength, bearing stress at the chain joint, bearing clearance at the chain joint, and shock loading.

The ANSI/ASME standards define minimum ultimate strength (MUS) as the tensile load in pounds (or kilonewtons) at which a chain, in the condition at the time it left the factory, may break in a single load application. The yield strength of the chain should be 40% to 60% of the MUS. The chain also should be designed for shock loading. An example of this would be when a gate falls against a slack chain. The ACA Design and Applications Handbook lists a service factor of 1.4 to 1.7 for heavy shock loading. Several of the lock sites have broken chain in the past when a gate has been dropped against a slack chain or when slack chain was generated to provide additional momentum for breaking a frozen gate loose. Even though these practices are not recommended by the designers, the lifting chain will likely be subjected to these conditions over its service life.

Since the lifting speed of dam gates is very slow, the chain/sprocket design is not paramount. The main factor for the chain is the ability to hoist and hold the load from the dam gates and perform under all service conditions.

The interface between the pin and sidebar of the chain (or the chain joint) will be the highest stress area of the chain. A chain failure will result from either a sidebar or pin failure in this area. At the chain joint area, the sidebar will be in tension and shear. Corrosion in the chain joint area may cause the pin not to rotate as the chain is going over the sprocket causing damage to the gate hoist machinery. The bearing clearance necessary in the chain joint will depend on the materials used for the sidebar and pin. A minimum clearance of .005" is used in the current chain design. This value should be doubled or tripled if steel sidebars and pins are being used.

The pin undergoes bending stress in the center between sidebars and also shear stress at the chain joint. Both of these values need to be calculated.

An appropriate design standard is necessary to adequately design the chain joint area and determine a bearing stress. The American Association of State Highway & Transportation Officials (AASHTO) standard for bridges can be used for this purpose. In particular, the design constraints for pins, rollers, and rockers for bridges can be utilized. This standard makes a distinction between bearing stress on pins subject to rotation versus non-rotating pins. The chain joint should be classified as a rotating joint as opposed to a non-rotating joint. The standard also sets an allowable shear stress (Fv) of 40% of yield for the pin.

The AASHTO standard also helps determine whether a bushing or bearing is required. The AASHTO Specification for Highway Bridges, 15th Edition, 1992, Section 10 (Structural Steel), Part C (Allowable Stress Design), Table 10.32.1A permits an allowable bearing stress of 80% of yield for pins not subject to rotation. This specification allows a bearing stress of 40% of yield for pins subject to rotation. The standard states the effective bearing area of a pin shall be the diameter multiplied by the thickness of material on which it bears (the sidebar for instance).

The AASHTO standard for pins, rollers, and rockers is meant to eliminate galling in the pin/rocker area (ie. chain joint). The AASHTO standard implies that stress values below 40% of yield strength will avoid galling and that a bushing or bearing is not required. The standard only recognizes structural steel and alloy steel materials, however. Galling results from metal to metal contact. When a cohesive force between two metals exceeds the strength of either metal, adhesion or cold welding will occur. Under high stresses, cold welding will occur more rapidly and over a wider area. For instance, galling will likely occur when the chain is loaded up to and beyond yield limits. Galling is also a particular concern when stainless steels are mated with other stainless steels. Thus, if no bearing or bushing is used with an all stainless steel chain (sidebar and pin), the 40% of yield value may need to be lowered. The surface finish at the chain joint will also affect the rate of galling. The smoother the surface finish, the less likely galling will take place.

Self-lubricating bushings were used in the chain joint for the tainter gate chain at Lock and Dam 10. These bushings were pressed into the sidebars. A 25 ksi load rating was specified.

The current chain design using aluminum bronze sidebars and stainless steel pins will act like a bushing/pin interface. These two metals have good compatibility in terms of their bearing properties. These materials also have a fairly low corrosion potential (from dissimilar metal corrosion or galvanic corrosion). The lower the potential difference, the less likely galvanic corrosion will occur. The "Metals Handbook"(2) lists a potential difference of +79 millivolts between aluminum bronze and 304 stainless steel in dilute sea water. This compares to +904 millivolts between zinc and copper.

Fatigue strength of the chain should be considered in the chain design even though the chain speed is slow. It should be noted, however, that fatigue strength is not likely to be the limiting factor in the chain design. The dam gates are usually raised and lowered several times each week. If it is assumed that the gates will be raised and lowered 3 times per week, then over a 50 year period, the chains will be cycled nearly 10,000 times. As each chain link section goes over the sprocket, it will be subjected to maximum tension. The link section will then be slack as it goes over the sprocket and is coiled up in the chain rack. Dam operators generally allow tainter gates to freeze in place during the winter and regulate pool levels with roller gates.

MAINTAINABILITY

A primary goal of the latest chain design was to either eliminate or reduce the amount of maintenance necessary on the gate lifting chains. It takes a crew of 4 people one week to bulkhead a single gate, temporarily support the dam gate, and grease the lifting chains (2 per tainter gate or one per roller gate). Thus, switching to a non-lubricated chain offers a significant cost savings over 50 years.

The MMMR program also offered the opportunity to use wire rope as opposed to lifting chain for moving the dam gates. Chain replacement offers several advantages, however. First, the existing gate lifting machinery could be reused. Also, using chain instead of wire rope requires less maintenance over 50 years. Wire rope needs to be lubricated on a regular basis. Any damaged part of chain can be replaced while wire rope must be completely replaced.

The original (1930's design) lifting chains for the tainter gates and roller gates were lubricated in a number of different ways. All of these lubrication methods allowed oil and grease into the water. Some of the lock sites lubricated the chain with 30W motor oil. Other sites used diesel fuel or waste oil. None of these methods allowed any lubricant into the chain joint since the bearing clearances were too tight.

The initial lifting chain supply contracts incorporated a grease lubrication system. The pins were installed with a grease fitting and drilled to allow grease to flow into the chain joint area. Although, the grease ports worked well initially, there is a number of them now that will not accept grease. All the lock sites with grease fittings have reported problems. This system offered no advantages from a maintenance standpoint. Also, any excess grease still ended up in the river.

The lube-free bushings were investigated and used for the tainter gate lifting chain at Lock and Dam 10. Kamatics Corporation and Marine Industries Corporation both manufacture bushings capable of the required load rating. Marine Industries manufactures the bushing line called Thordon. A Kamatics bushing was used for Lock and Dam 10 chain. This bushing used a 304 stainless steel housing with Karon V polymer composite liner. The Karon lining can also be applied to other materials including manganese bronze. The primary disadvantage of using the lube-free bushings is cost.

The current chain supply contract uses no bearing or bushing in the chain joint. The chain joint is designed as a bushing, however, since the sidebars are made of aluminum bronze and the pins are made of stainless steel. This design will eliminate the need for greasing of the chains.

ZEBRA MUSSELS

Zebra mussels have become more prevalent in the Upper Mississippi River system within the last several years. During the recent dewatering of Lock and Dam 5A and Lock and Dam 4, zebra mussels were found completely covering the bottom of the lock chamber several inches thick. The zebra mussels attach themselves to submerged gates, intake valves, grating, concrete, etc. At a minimum, the submerged portion of the gate lifting chain needs to be designed to reduce or eliminate zebra mussel attachment. Material selection needs to be made to reduce or eliminate zebra mussels from attaching to the chain.

Testing and research by the U.S. Army Corps Of Engineers Waterways Experiment Station (WES) and the Construction Engineering Research Laboratory (USACERL) have shown that zinc and copper are toxic to zebra mussels.

The latest design of the chains, as stated above, use aluminum bronze sidebars and rollers. The specific alloy is UNS No. C95500 which is composed of 78% copper.

The recent inspection of the chains during the Spring of 2001 indicated little zebra mussel attachment to the lifting chains at Locks 5A through 9. Some zebra mussels were attached to the stainless steel collars and pins but no mussels were attached to the aluminum bronze sidebars.

LOCK 7 CHAIN
Note the presence of zebra mussels on the gate and on the stainless collars and pins but not on the aluminum bronze sidebars or rollers

REFERENCES

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