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"Wire Rope Replacement at Broadway Bridge"

by

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WIRE ROPE REPLACEMENT AT BROADWAY BRIDGE

CITY OF NEW YORK

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INTRODUCTION

Broadway Bridge is a tower drive vertical lift bridge dating to 1964. The bridge, which crosses the Harlem River in the Bronx, NY, spans 304 ft. center to center of live load bearings and has a lift of 110 ft. The bridge provides a clear channel of approximately 280 ft. and a minimum vertical clearance of 135 ft. from MHW when fully raised. The bridge has a double deck; the lower deck support 6 lanes of vehicular traffic and a pedestrian sidewalk on each side of the roadway, the upper deck supports three tracks of NYCTA subway. As the bridge provides the only access between Manhattan's upper West side and the Bronx, it serves as a major thoroughfare for local traffic.

From April through August, 1996 all main counterweight ropes were replaced at Broadway Bridge. The construction work was performed with minimal disruption to vehicular, pedestrian and rail traffic. The auxiliary counterweight ropes at the South Tower were replaced over one weekend in August 1996 during which the bridge underwent a complete closure to traffic. The auxiliary counterweight ropes in the North Tower were replaced over two weeks in May 1997 with no disruption to traffic. This paper presents the rope replacement project from the vantage of the resident field engineer. The paper will focus on the construction process for the replacement of the main counterweight ropes as a collaborative effort between the Contractor and the engineering team to ensure a safe and trouble free project.

A brief summary of the cause of the rope replacement will be presented. The formulation of the construction strategy as well as safety considerations arising from the strategy will be addressed. The progression of construction will be discussed. Finally, the tensioning process will be examined.

DESCRIPTION OF SYSTEM BALANCE

The lift span is counterbalanced by two main counterweights, one at each end of the span. The gross weight of the lift span is approximately 5 million pounds and that of each counterweight is approximately 2 ½ million pounds. The lift span is connected to the counterweights with ninety-six 2 3/8" diameter wire ropes. The wire ropes are improved plow steel, preformed, right regular lay, 6x25 filler wire construction with hard fiber core.

The wire ropes are attached at each corner of the lift span, drape over sheaves located atop each of the towers and terminate at the counterweights. Four counterweight sheaves are located atop each of the towers, two (a pair) at each side. Each sheave supports twelve wire ropes. Each counterweight is suspended by a total of 48 wire ropes.

During operation of the lift span, the main counterweight ropes transfer over the sheaves as the span raises and the counterweight lowers. This transfer of rope from the span to the counterweight side of the sheave affects a considerable change to the system balance due to the weight of the wire ropes.

An auxiliary counterweight system is provided to compensate for this transfer. Auxiliary counterweights, traveling along guides on the span side of the tower legs, exert a force on the lift span to counterbalance the weight change caused by the transfer of the main ropes. Four auxiliary counterweights, weighing approximately 27,500 pounds apiece, are located at the corners of the lift span. Each auxiliary counterweight is suspended by two ropes. The auxiliary counterweight ropes are 1 5/8" diameter ropes composed of improved plow steel, preformed, right regular lay, 6x25 filler wire construction with hard fiber core. Each pair of auxiliary ropes is supported by an auxiliary counterweight sheave which is mounted at mid height on the span side of the tower leg. There are four auxiliary counterweight sheaves, one at each corner of the lift span. The ends of the auxiliary ropes opposite the auxiliary counterweight terminate at a pivot connection located at the transverse center of each end of the lift span. Each pivot connection secures four ropes, two from each sheave at that end of the span.

IMPETUS FOR REPLACEMENT

An in-depth inspection of the wire ropes was conducted in 1993 by Charles Birnstiel, Consulting Engineer, P.C. for Hayden|Wegman as funded by the New York City Department of Transportation. The inspection consisted of a thorough hands-on examination of all ropes. Seven locations on each rope were cleaned to bare metal and visually inspected. Areas selected for inspection included the rope terminations, sheave tangent points and areas at which the ropes contact guide castings. Experience has shown that the selected areas provide reliable indication of rope integrity. No extraordinary means were used to inspect normally inaccessible areas. Tension, lay, and diameter measurements were also taken for each rope. Three wire ropes were removed from the bridge and tested to failure.

The preliminary results of the hands-on inspection indicated that the ropes were in satisfactory condition with minor exceptions. The results of the destructive tests, however, indicated that the ropes had significantly less capacity than expected.

Inspection of the test specimens revealed that all three ropes had failed in the vicinity of the lift span splay casting. Examination of the ropes at the origin of failure revealed the presence of significantly greater corrosion than noted during the field inspection. As the ropes chosen for the destructive testing were selected as a representative sample, the likelihood existed that additional ropes exhibited similar corrosion at this area.

Subsequent inspection was conducted to substantiate that the noted corrosion was in fact a typical condition. Hydraulic jacks were used to jack a representative number of ropes away from the lift span splay casting. Inspection of the normally inaccessible portion of the ropes confirmed that corrosion existed on each inspected rope. Apparently the slight gap which existed between the rope and the top of the casting allowed debris to enter and accumulate in this area. Additionally the limited access prevented adequate maintenance. The accumulated debris trapped moisture and fostered an environment favorable for corrosion.

The Roebling Wire Rope Handbook, a respected authority on wire rope usage, has the following comments regarding corrosion:

> *Every precaution should be taken to avoid corrosion. A rope that has become corroded to any appreciable degree is a dangerous rope to operate. Corrosion reduces the metallic area of a rope and weakens it in this way. Furthermore it mars the surface of the wires by creating stress raisers which promote the development of broken wires. Most important, however, is the doubt that is introduced concerning the true condition of the rope. While the condition of a properly protected rope can be ascertained with reasonable accuracy at any time throughout its life, that of a corroded rope is a matter of guesswork.*

Corrosion had been verified as a typical condition at the lift span splay casting. The destructive tests had removed any doubt as to the true condition of the ropes. Despite the fact that the ropes were in satisfactory condition except at the splay location, corrosion at this location was sufficient to decrease the strength of the ropes such that the capacity of the remaining ropes was in doubt. This necessitated the recommendation to replace all ropes.

PLANNING

Award of Contract

Regional Scaffolding and Hoisting, Inc. was selected as the prime contractor for the project. Regional employed CANRON, Inc. to perform the rope changeover operations.

New York City Department of Transportation (NYCDOT) and New York City Transit Authority (NYCTA) provided project administration and review.

Hayden|Wegman performed resident engineering services. Stafford Bandlow Engineering, Inc. was retained by Hayden|Wegman to provide engineering services to monitor the planning and day to day implementation of the wire rope replacement.

Safety Considerations

Broadway Bridge, as previously noted, supports three tracks of the NYCTA. The presence of rail traffic on the lift span imposed several limitations which would have a significant impact on the construction activities. The contract documents addressed the pertinent issues as follows:

- The upper deck of the lift span supports three electrified (3rd rail) tracks. During replacement operations, the tracks presented a safety hazard in the event that a swinging rope or falling objects contacted the electrified rail.

The specification called for the lift span to be raised 3 ½ feet to disconnect track power during raising or lowering of a wire rope.

- Electrical contact switches for track power exist at all four corners of the lift span. The switches are positioned immediately below the lift girder rope terminations. The exposed electrical switches presented a safety hazard to workers during operations at the lift span rope terminations. Construction work in the vicinity of the switches likewise presented a potential problem for the NYCTA, as falling objects could damage the switches and disrupt power.

  The specification called for protection to be provided at the switches to protect against falling objects and dripping fluids and for safety of workers.

- The schedule of the NYCTA afforded limited opportunity for bridge openings during normal working hours. Additionally the maximum duration of each bridge lift was 15 minutes.

  The specification called for one rope to be replaced per day during normal working hours.

Construction Scheme

The Contractor was intent upon increasing the rate of production of the work from the specified one rope replacement per day. The Contractor proposed using a crane as the hub of the replacement operation. Two barges moored side by side at the foot of the bridge would serve as the base of operations. One 180 ft. x 54 ft barge would serve as the working area for the crane, while a second, smaller barge would serve as storage for the new and old ropes. A crane with a 180 ft. boom and a 90 ft. jib would be utilized to perform all handling of the 178 ft. long ropes. While this method entailed significant overhead due to the crane and the barges, it suited high production work.

Obstacles to this method, however, included limited access to the ropes at the sheave as well as the safety issues posed by the electrified rail and vehicular and pedestrian traffic on the lift span. The Contractor was dissatisfied with the precautions taken in the specification to remedy these issues. The Contractor proposed alternate methods of addressing these issues which would be less obtrusive on vehicular, pedestrian and rail traffic and would not hinder the rate of production. Due consideration was given to the merits of the alternate methods and proposals were made as necessary to realize the viability of these methods.

Figure 1 depicts the location of the construction equipment as well as the safety measures discussed below.

Access

The shrouds over the sheaves prevented direct access to the ropes and increased the difficulty of handling the ropes at the tower. The Contractor proposed removing the shrouds by flame cutting to gain direct access to the ropes.

Removal of the shrouds would give direct access to the ropes, sheaves and machinery room. This would increase visibility, communication, ease of handling the ropes and the overall safety of the operation. Under these conditions the Contractor believed that he would replace more than the specified one rope per day.

At the completion of construction the shrouds were to be replaced via full penetration welds. During all flame cutting and welding operations, the ropes were covered with fire blankets for protection.

Electrified Rail

While the 3 1/2 ft. bridge lift to sever power during each replacement served to protect the workers, it posed an inconvenience to the Contractor, the community, the DOT and the NYCTA. Daily bridge lifts involved a significant manpower commitment from the DOT during operations and potentially prolonged the construction process while subjecting the community and the NYCTA to daily disruptions for more than a three month period. The Contractor believed that the bridge lifts could be avoided.

The basic issue underlying the cut-off of power during lifting operations was the protection of the workers as well as the NYCTA's interest. If a wire rope came into contact with the electrified rail during replacement operations, personnel handling the rope could be subjected to serious if not fatal injuries. Substantial damage could also result to the NYCTA's power supply. The Contractor's proposed method for the replacement called for always handling the ropes outside of the lift span truss. In this way the rope could not come into contact with the rail during routine lifting operations. The only deviant incidents which could result in the rope contacting the rail would be if the rope were dropped or an unrestrained end swung into the rail.

Potential causes for a rope being dropped during lifting operations were limited to the following sources: crane failure, rope clamp failure, and accidents during handling of the rope.

1. After a review of available data (equipment specifications) the crane was eliminated as a reasonable source of failure. The nominal weight of each rope was 1770 pounds. The minimum stated working capacity of the crane was 9558 pounds. This provided an excess capacity of 5.4 times the stated amount, which was considered to be ample for this application.

2. Friction type rope clamps were designed to have adequate capacity to hold the rope. However, as the clamps would be repeatedly installed and removed during operations, the integrity of the connections would be questionable. The possibility existed that not all connections would be made properly, thereby decreasing the safety of the clamp. The engineering team proposed using two independent rope clamps with separate lines. The redundancy of the connection allowed a safety factor in the event of failure of a clamp and afforded leeway for the unexpected during construction.

3. The method of handling the rope would be fail-safe. That is, the counterweight socket would be pinned at the counterweight termination prior to removal of either rope clamp.

The possibility of a rope swinging out of control would be addressed by installing tag lines at the lift span socket. The lift span end of the rope would be positively restrained by the tag line from the time it lifted off the barge until it was positioned at the lift span termination.

Traffic

The basic issue underlying the stoppage of traffic during lifting operations was the protection of the traveling public. As with the bridge lifts, however, stoppage of traffic presented a public inconvenience. The Contractor stated that the steps taken above to ensure safe handling of the ropes were sufficient to protect live traffic during replacement operations.

These steps were evaluated in terms of the protection which they afforded rail, vehicular and pedestrian traffic.

Rail:

Contractor had initially proposed mooring the barges and performing all work at that end of the bridge from the one location. The crane had sufficient reach with the boom and jib to reach both corners from the one location. The NYCTA, however, objected to the crane booming over the rails under any circumstances. As the ropes and terminations at each corner of the lift span were not located directly over the tracks, the NYCTA did not object to the Contractor performing work at the corner nearest to the crane provided the crane did not intrude upon the transit's envelope.

While the steps taken to handle the ropes were found to be satisfactory, questions were raised regarding the protection afforded rail traffic against falling tools and debris. With work being performed in the tower 150 ft. above track level, the possibility existed that hand tools or debris could fall or be dropped into the transit envelope.

A 2-ply netting was proposed to protect rail traffic from falling objects. The netting comprised a coarse (3") mesh coupled with a fine (1/4") mesh. The netting would be draped across the top of the lift span truss covering the width of the rail envelope and extending 25' out from the lift girder.

Vehicular:

The lift span supports three lanes of vehicular traffic in each direction. The ropes and lift span rope terminations at each side of the bridge are located immediately over the lanes of traffic. Viewing down from the tower one can see through the truss directly to the outer lane of the roadway. The inner lanes of traffic are partially protected by the deck for the railway.

The majority of the construction work would be performed directly over the roadway. This increased the likelihood of objects falling onto the roadway during routine work as well as during lifting operations. A rugged platform was proposed to shield the exposed lane of vehicular traffic from the construction activities. The platform would cover the width of the exposed lane of traffic and extend 30' forward from the lift span terminations. The inner lanes of traffic would be shielded by the deck and the netting installed across the top of the truss.

Pedestrian:

The lift span supports a pedestrian sidewalk on either side of the roadway. As the sidewalk would be situated between the work area at the lift span and the barges, work would be performed overhead on a routine basis. Steps would need to be taken to protect the public.

A safety bridge (overhead protection for the sidewalk) was proposed to protect pedestrians from construction activities. The safety bridge, which would be erected over the sidewalk, would cover the width of the side walk and extend 30' forward from the lift span terminations objects. During lifting of significant weights (i.e. shrouds or large equipment) or during burning and welding procedures, foot traffic would be diverted to the sidewalk on the opposite side of the span.

With the implementation of the above measures, it was concluded that the pertinent safety issues had been adequately addressed and that the community stood to benefit from a shorter construction period with fewer disruptions to traffic.

CONSTRUCTION

Project Milestones

Date	**Event**
April, 1996	Preparation of Procedures and Equipment
April 30, 1996	Removal of First Main Counterweight Rope
July 25, 1996	Replacement of Final Main Counterweight Rope
August 22, 1996	Clean Up Site and Remove Equipment
October 15, 1996	Initial Tensioning
August 24 and 25, 1996	Auxiliary Rope Replacment - South Tower
October 17, 1996	One Month Tensioning
May 12-16 and 19-21, 1997	Auxiliary Rope Replacment - North Tower
March 15, 1998	Six Month Tensioning

Construction Issues

The Contractor mobilized field operations to begin replacement of the wire ropes in April 1996. The safety measures previously outlined were implemented during the initial phase of the project. Specifics of the construction process and issues unforeseen during the planning stage were also addressed in the field at this time.

Rope handling

Safety measures had been devised to protect the public from harm during the construction process. Measures likewise had to be devised to protect the new ropes from damage during the construction process. Precautions had to be taken to avoid bending, crushing, kinking, twisting, unwinding, abrading or otherwise damaging the new ropes during handling. These abuses could decrease the capacity of the new ropes and/or shorten their service lives.

Primarily, the ropes could be damaged during storage, during removal from the rope reel and during installation.

During storage

The new ropes were shipped from the factory on rope reels having a diameter 26 times the nominal rope diameter in accordance with the contract specifications. The ropes were also lubricated during manufacture with a rust inhibitor to protect the wires until the wire rope dressing could be applied in the field after installation.

During removal from reel

A bar inserted through the center of each reel allowed the reel to be set horizontally on a frame which was fabricated for this purpose and mounted on the barge. The crane was then used to pull the rope from the reel. A timber wedged between the reel and the deck of the barge was used as a brake to control the rate at which the rope unreeled and to prevent the rope from "springing".

The ropes were laid out on the barge in an area which had been cleaned of dirt and debris. As the rope was picked off the barge during replacement operations, the rope was wiped with a towel to remove any dirt or debris which had settled onto the surface of the rope.

During installation

The rope clamps which had been previously agreed upon to ensure safe handling of the rope from the perspective of public safety did not address the possibility of damage which could occur to the rope during lifting. A procedure was formulated for handling the rope utilizing a deflector sheave.

A rope deflector sheave was fabricated to support the rope during lifting operations. The ratio of the sheave diameter to the rope diameter (D/d) was 25:1 to coincide with the AASHTO requirement for minimum reel diameter during shipment of new ropes. The deflector sheave incorporated one rope clamp through a bolted connection. The second rope clamp was independent of the deflector sheave and was to be installed several feet below the first. Each new rope was secured on the deflector sheave prior to installation. The crane would then pick the rope from the top rope clamp and the center of the deflector sheave. This decreased the localized loading of the small portion of the rope secured by the rope clamp and eliminated the problem of having the rope bend about a small radius at the rope clamp. See Figure 2.

When the counterweight socket from the rope reached the sheave access area it was secured by a 3 ton winch. The winch was used to pull the counterweight end of the rope over the sheave and down to the termination block where it was secured with a pin. When the deflector sheave entered the access area it was separated from the rope clamp and removed. The deflector sheave was secured with a come along for surety prior to removing the bolted connection. See Figure 3.

Reeving

The Contractor's procedure included the sequence according to which the ropes at a sheave would be replaced. The sequence proposed replacing the ropes consecutively, starting at the ring gear and working across the sheave. A review of this sequence against site/existing field conditions, however, revealed a conflict. The reeving of the ropes between the sheave and the upper counterweight deflectors did not allow free access to each rope for consecutive replacement. Ropes whose counterweight sockets terminated on the span side of the deflector support could not be independently removed due to interference between the sockets and the adjacent ropes which terminated on the approach side of the deflector support.

After evaluating this field condition, the Contractor revised the replacement sequence whereby a maximum of three ropes could be removed from the lift span at any one time during replacement to gain access to normally obstructed ropes. See Figure 4 for the rope removal and replacement sequence. The viability of this revised sequence was evaluated against the capacity of the ropes.

The capacity of a wire rope may be judged by its ability to withstand tensile loading, fatigue, abrasion and corrosion. In evaluating the capacity of the existing wire ropes for this sequence, consideration was given to tensile loading and fatigue of the ropes. Over the short period that multiple ropes would be removed from the bridge, abrasive and corrosive effects would have little influence.

The existing tensile capacity of the ropes had been determined through the break tests which were the impetus for this replacement. While the counterweight ropes had been originally designed with a safety factor of 8:1 as per AASHTO, the break tests indicated that the current safety factor had decreased. Under the Contractor's proposed replacement sequence with 3 ropes removed from one corner of the lift span, the safety factor for the remaining ropes at that corner would further decrease. Given the short duration for which the ropes would be removed from the span, this tensile capacity of the ropes was considered adequate for static loading.

Operation of the bridge has two affects on the ropes: it increases the loading on the ropes during acceleration and it subjects the ropes to fatigue as the ropes bend about the sheave. Broadway Bridge, however, operates infrequently. The majority of bridge lifts in the year prior to the replacement were for test openings. The infrequent operation of the bridge did not provide sufficient opportunity for fatigue to affect the integrity of the ropes over the duration of the replacement. In the unlikely event that the bridge did operate, the existing safety factor was still considered adequate to withstand operating loads.

Construction Period

Construction lasted approximately 22 weeks from April thru August 1996. While the ropes were replaced over the course of 57 working days, additional time was required for mobilization and breakdown at each corner of the lift span.

An average of 1.7 ropes were replaced per working day in which the Contractor performed replacement operations. On the most productive day the Contractor replaced 5 ropes. Over the same period an average of 2 ropes remained off the span overnight. At no time were more than 3 ropes off the span at one time. During the construction period there were only 11 bridge lifts, 8 of which were mandated for tensioning purposes. Figure 5 presents a histogram of rope removal, rope installation, and bridge operation throughout the replacement period.

Significant steps of the construction process are enumerated below.

Rope Removal

1. Loosen nut at lift span termination.
2. Secure rope with double rope clamps at tower location.
3. Take up on rope with crane sufficient for tension rod to clear lift girder and to remove slack in rope.
4. Pull counterweight pin.
5. Wrap counterweight socket in burlap to protect sheave during removal.
6. Take up on rope with crane sufficient for counterweight socket to clear the sheave.
7. Swing rope clear of lift span and lower to barge for disposal.

Rope Replacement

1. Lay out new rope on barge.
2. Measure off counterweight end to determine sufficient length to drape over sheave and reach counterweight termination.
3. Secure deflector sheave at marked location.
4. Pick rope with crane.
5. Guide lift span end with tag line secured at lift span socket.
6. Position boom of crane so that counterweight tail of rope arrives at sheave access area.
7. Secure counterweight socket with cable from winch located in tower.
8. Use winch to guide counterweight tail of rope over sheave and down to the counterweight termination.
9. Position deflector sheave at sheave access area.
10. Remove deflector sheave.
11. Insert pin at counterweight termination.
12. Come down with crane and guide tension rod into place at lift girder.
13. Install nut to secure tension rod.
14. Remove rope clamps.
15. Tension rope.

ROPE TENSIONING

> *Where ropes in a set operate under varying degrees of tension, maximum service cannot be obtained, since, obviously, some ropes are performing more work than others. Usually the ropes under the greater load will deteriorate first. However, due to the differential action and slippage that occurs during operation, the ropes under the lighter load sometimes will wear rapidly and deteriorate. This unnecessary abuse not only induces short service, but also uneven wear in the sheaves...[which if left uncorrected] the damage to subsequent sets of ropes will be progressively worse.*
>
> *It is particularly important to check them and to make the necessary adjustments during the period in which they are stretching and becoming set to the conditions of operation, since it is at this time that differences are most likely to develop.*
>
> *(Roebling Wire Rope Handbook)*

Requirements

The specification required that the ropes be tensioned following initial installation. Tensions were to be readjusted at one month and at six months after the initial tensioning. The specified criterion for acceptance of rope tensions was that the tension in a main counterweight rope should not differ by more than +/- 5 percent from the average rope tension at that corner of the lift span.

Following each round of adjustments, the bridge was to be operated through four lifts and the tensions rechecked. Any deviations in the tensions from the +/- 5 percent criterion would then be adjusted and the process repeated. Prior to final readings at the six month tensioning, the bridge would be operated through a cumulative total of at least 50 lifts

The specification required that the rope tension be determined via the vibration method.

Method

The Contractor investigated several alternate methods of determining the rope tensions including the use of an accelerometer and the use of a device which measured rope deflection for a given load over a known distance. The Contractor opted to use the vibration method on several grounds. Whereas the accelerometer and deflection methods require expensive equipment, the vibration method requires inexpensive equipment. The vibration method also requires no set up or handling time and has a quick turn around on results.

The vibration method is a means of determining the tension in a rope by measuring the time it takes the rope to oscillate a set number of times. The instruments necessary to perform the vibration method are limited to a stopwatch, preferably accurate to 0.01 seconds, a calculator and a straight edge. Baseline tension readings and recommendations for adjustments for the 24 ropes in a group at each corner of the lift span could be made within one hour.

Subsequent readings and recommendations for any rope within that group could be performed within 3 minutes.

Theory

The vibration method is based on the fact that a rope's frequency is dependent on its composition, unsupported length and tension. For a rope's natural frequency (first mode of vibration), its tension may be expressed as:

$$T = m \cdot (2 \cdot f \cdot L)^2$$

where

T = Tension
m = rope mass
f = frequency (cycles/sec)
L = unsupported length of rope

A rope's tension is therefore directly proportional to the square of its natural frequency. While a rope's tension cannot be directly measured with ease, determining the rope's natural frequency is a simpler task. Based on the preceding equation, percent difference in tensions among ropes in a group can be determined from the rope frequencies without knowledge of rope composition or unsupported length. With knowledge of rope composition and unsupported length, the actual tensions for the ropes can be determined.

Although we are primarily interested in determining the relative differences in tension among ropes in a group, calculating the actual tensions serves as a rough check to validate this method. The sum total of all tensions at one end of the bridge should equal the weight of the counterweight.

Implementation

Prior to construction baseline readings were taken for all ropes to establish the average rope tension at each corner of the lift span. Figure 6 depicts the location and identification of all rope groups. Immediately after installation the tension of each new rope was adjusted to the average value for that corner of the lift span. When all ropes at one corner of the lift span had been replaced, the initial tensioning of record was performed for that rope group. The bridge was operated four times, tensions were checked and adjustments were made as necessary. This process was repeated two more times at the one month and six month tensioning intervals.

The lift span socket of each counterweight rope is pin connected to a rope take-up whose threaded lower end is fastened at the underside of the lift girder via a nut. Rope Tensions were physically adjusted by turning these nuts to tighten or loosen the ropes. A HYTORC XLT-Series Square-Drive Hydraulic Torque Wrench with a custom manufactured socket generated the torque to turn the nuts.

Results

The Initial Tension Adjustments were completed on August 21, 1996 at rope groups 0500 and 0600 at the SW corner, which was the final corner to undergo replacement. The One Month Tension Adjustments were performed for all ropes on October 14, 15, 16 and 17, 1996. The Six Month Tension Adjustment were performed for all ropes on March 15, 1998.

The rope tension adjustments for the one month and six month periods were not performed at the specified intervals due to scheduling and other conflicts. The delay in the six month tensioning may have been advantageous for the ropes. Although the adjustments were performed approximately a year late, one year is a small timespan within the life of the rope. This delay allowed additional time for the ropes to adjust to their operating environment and for any aberrations to come to light.

Figure 7 provides an overview of the tension adjustment history for all rope groups. The intent of this figure is to chart how the ropes maintained their tensions throughout the tensioning period. The number of ropes requiring adjustment during each tensioning period are recorded, as well as the maximum percent deviation from the average rope tension. The maximum percent deviation following the tension adjustments is also recorded to indicate adjustment capabilities and to provide a base on which to judge subsequent readings.

The scope and magnitude of the tension deviations decreased over time with each subsequent tension adjustment. Fifty-five ropes required adjustment at initial tensioning, with a maximum deviation of 60.4 percent. Forty-five ropes required adjustment at the one month tensioning, with a maximum deviation of 21.4 percent. Only nineteen ropes required adjustment at the six month tensioning, with a maximum deviation of 7.6 percent.

The results indicate that even though the ropes are prestretched during manufacture, they do stretch and tensions fluctuate among ropes in a group as they adjust to the operating environment. There is a clear need for the tensions to be adjusted at regular intervals during the break in period.

As a side note, the following is presented:
The indicated maximum deviations for each rope group are a reasonable representation of the other deviant readings. The sole aberration occurred during the six month tension adjustments at the 0800 rope group. Rope 0801 exhibited a 21.4 percent deviation from average. The only other rope in the 0800 rope group which was out of tolerance exhibited a 7.9 percent deviation from average. The 21.4 percent figure is considered an aberration as it does not conform to the pattern exhibited by the other 95 ropes throughout the tensioning period (i.e. smaller percent deviations from average with each subsequent tension adjustment).

Discussion on Error Analysis and Limitations of Method

Throughout the course of this project the vibration method was used to determine rope tensions on over one thousand occasions. Data from these readings provide valuable information regarding the capabilities and limitations of this method.

Repeated measurements have demonstrated that precision is achievable within (+/-) 0.4 percent. During each test, two readings were taken on each rope. The ability to demonstrate the indicated precision was the basis for validating a reading.

Since the weight of the counterweight does not change (excluding the effects of debris and moisture), it can be used as a gross check on the tension readings. The sum of all tensions at one end of the bridge should be equal to the weight of the counterweight. The maximum variation in the weight of a counterweight over the duration of the project was 6.4 percent, as determined from the sum total of all ropes at one side of the bridge. The maximum variation in the load seen at one rope group was 10.9 percent.

The variations in the sum total of all tensions at one side of the bridge can be primarily attributed to seating effects. Apparently, friction at the trunnion and friction between the ropes and the sheaves varies dependent upon how the bridge is driven closed. The variations in the individual rope group tensions may also be attributed to seating effects, as the load redistributes among the four rope groups in a tower.

Despite variations in the overall tension at one side or one corner of the bridge, the relationship of the tensions for ropes in a group remains consistent for the short term. This group relationship may be best demonstrated by review of tension readings recorded on February 7, 1998 and March 15, 1998. These readings were taken prior to the adjustments for the Six Month Tensioning. The readings are pertinent because they were taken on separate occasions over a relatively short time frame during which the ropes underwent no significant changes (i.e. no adjustments and few openings). The overall tensions at each corner exhibited an average change of 2.1%, while the individual ropes exhibited an average change of only 1.3% from the average tension. Figures 8A and 8B present a graphical representation of these readings for all rope groups. A review of the graphical data reveals that the overall relationship of the ropes has remained consistent with few exceptions.

Limitations of the vibration method include the following:

- Forcing Function
  Access must be provided to the rope at an area where it can be forced into oscillation. At this bridge this was not a problem.

- Traffic on Span
  While vehicular traffic did not appear to have an appreciable affect on the readings, rail traffic did influence the readings on several occasions. Apparently this is due to the significant weight of the trains.

- High Winds and Slapping
  During high winds several ropes have been noted to vibrate at their natural frequency. In cases where adjacent ropes are vibrating, the ropes have a tendency to contact each other generating a slapping sound. This contact disturbs the natural frequency and invalidates the reading.

- Whipping
  In setting the rope into vibration, care must be taken to ensure that the rope is at its natural frequency. This may be visually verified. The rope should travel as a standing wave during vibration. A whipping action, which may be imparted into the rope when setting it into vibration, should be avoided

- Other Modes of Vibration
  Care should be taken to ensure that the rope is not set into any mode other than the first mode of vibration. While the rope tension can still be determined for other modes of vibration, it is increasingly difficult to excite the rope to each higher mode of vibration. Additionally the equation presented above would need to be modified for other modes of vibration. As previously stated the first mode of vibration may be visually verified. The rope should travel as a standing wave during vibration.

AUXILIARY COUNTERWEIGHT ROPE REPLACEMENT

The auxiliary counterweight ropes were also replaced as part of this contract. An overview of the auxiliary changeover is presented below. However, a detailed description of the construction procedures for the auxiliary replacement is beyond the scope of this paper.

The auxiliary counterweight ropes at the South Tower were replaced during one weekend in August 1996 during which there was a complete closure of the bridge to marine traffic. Work was performed over two 12 hr periods during which there was also a complete closure of the bridge to vehicular and rail traffic and track power was disconnected on the span. While the intention of the specification was to complete the changeover in both towers during this outage, work progressed slower than anticipated and only the South auxiliary counterweight ropes were replaced.

The auxiliary counterweight ropes at the North Tower were replaced over two weeks in May 1997. A different construction scheme than the one used for the South Tower changeover and additional safety measures were implemented to allow the work to be performed without disconnecting track power and closing the bridge to all traffic. Other than one overnight closure to marine traffic which was required during this construction period, the changeover was completed without incident.

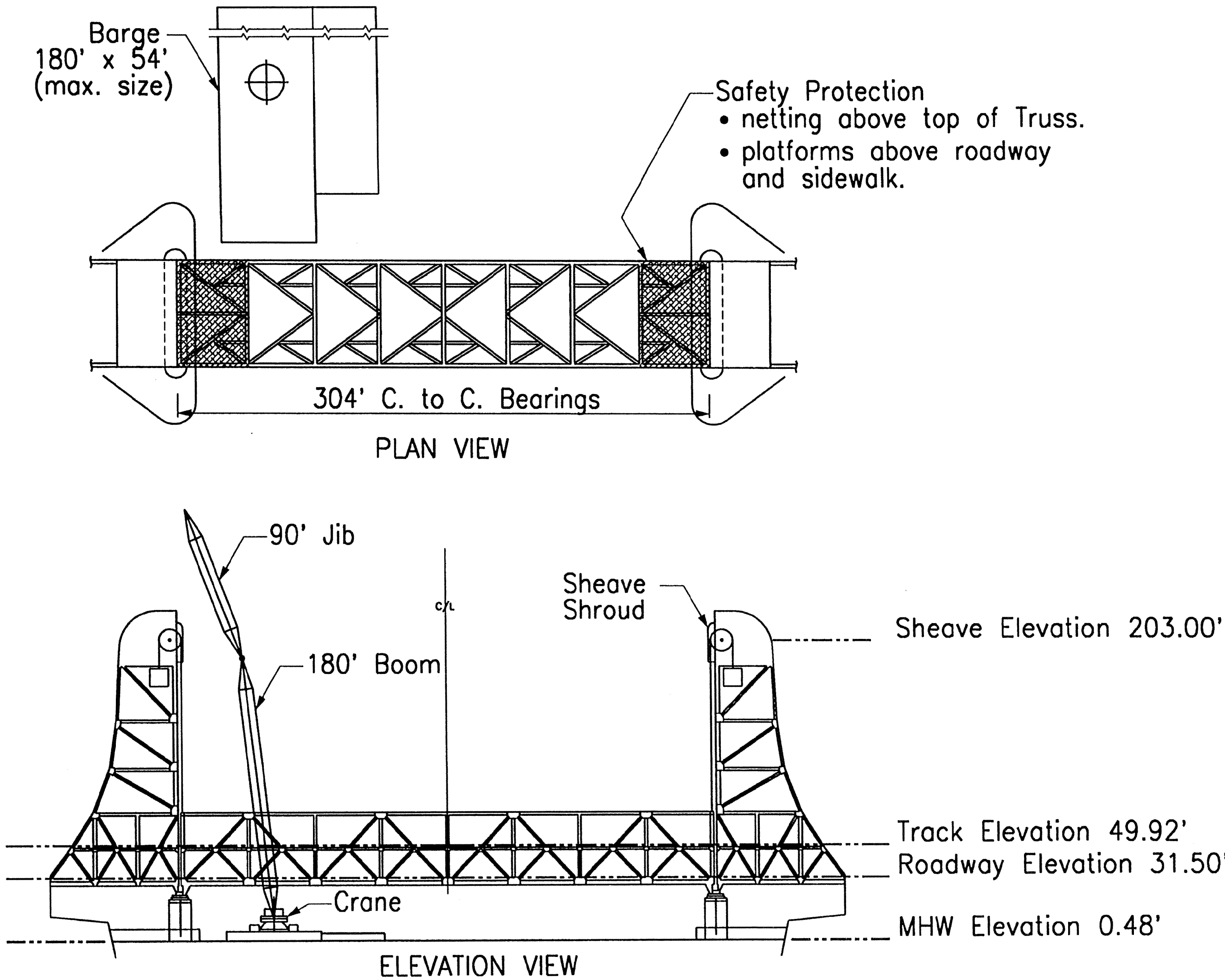

Figure 1. Location of Equipment and Protection

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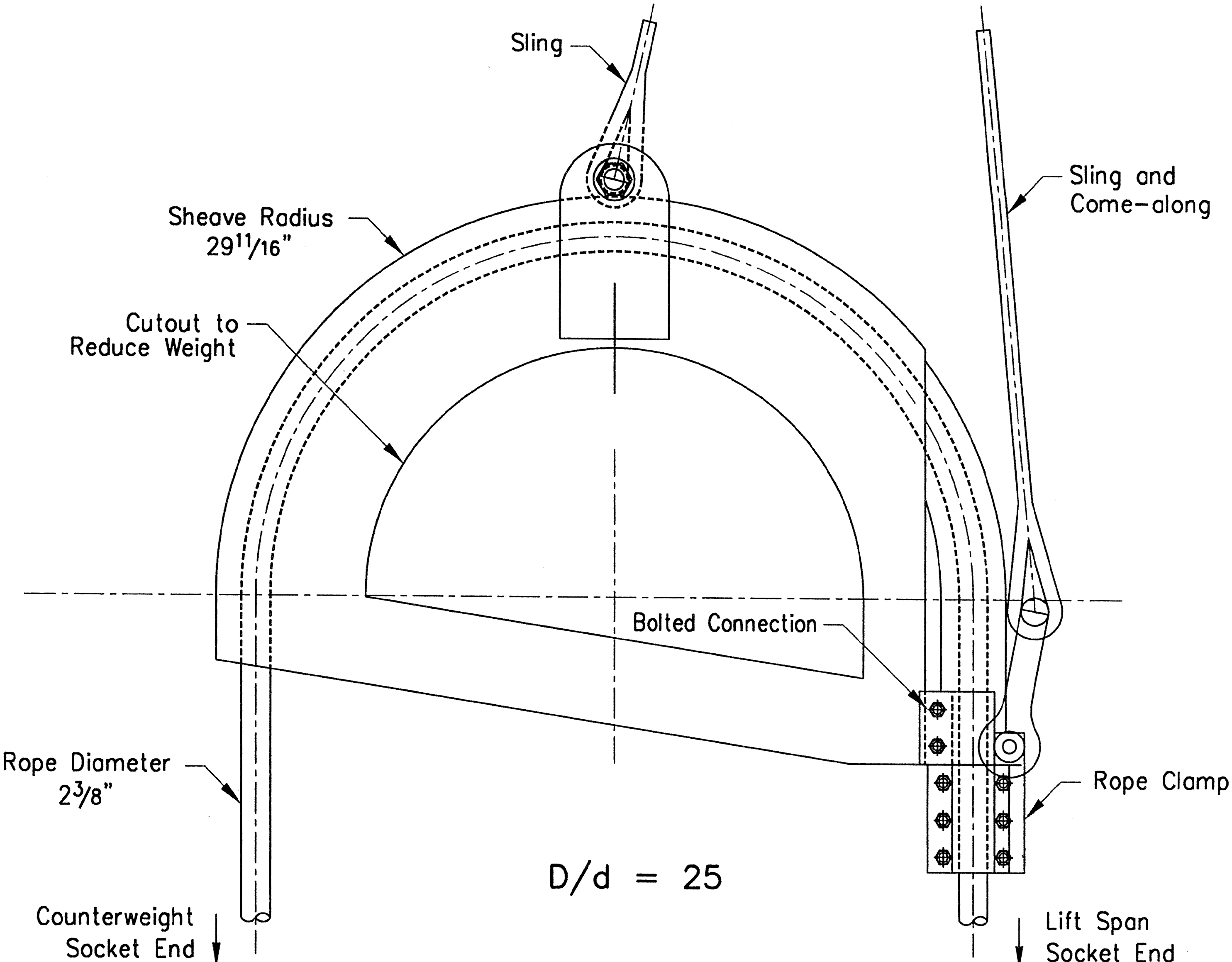

Figure 2. Deflector Sheave Weldment

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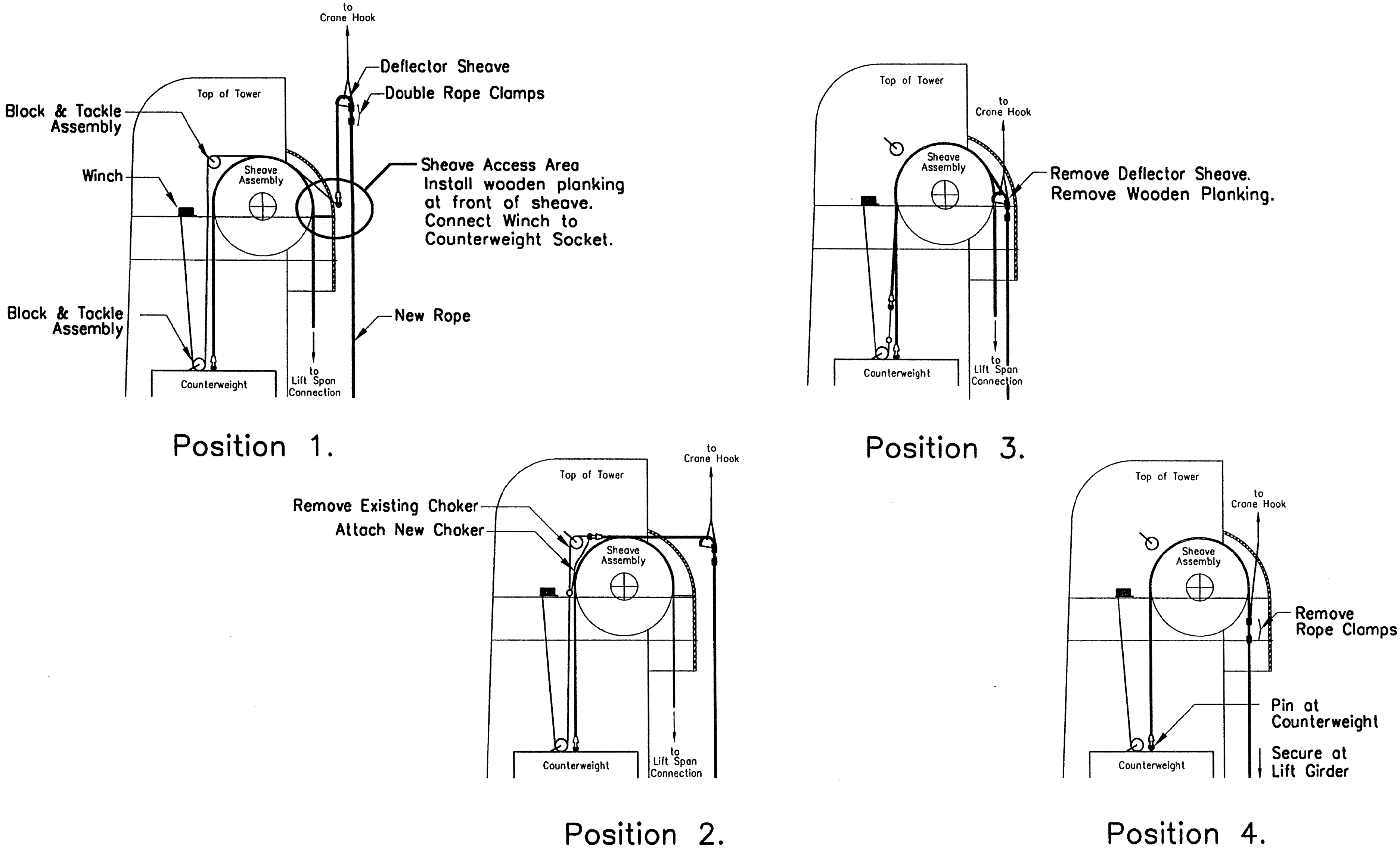

Figure 3. Handling of Rope during Installation.

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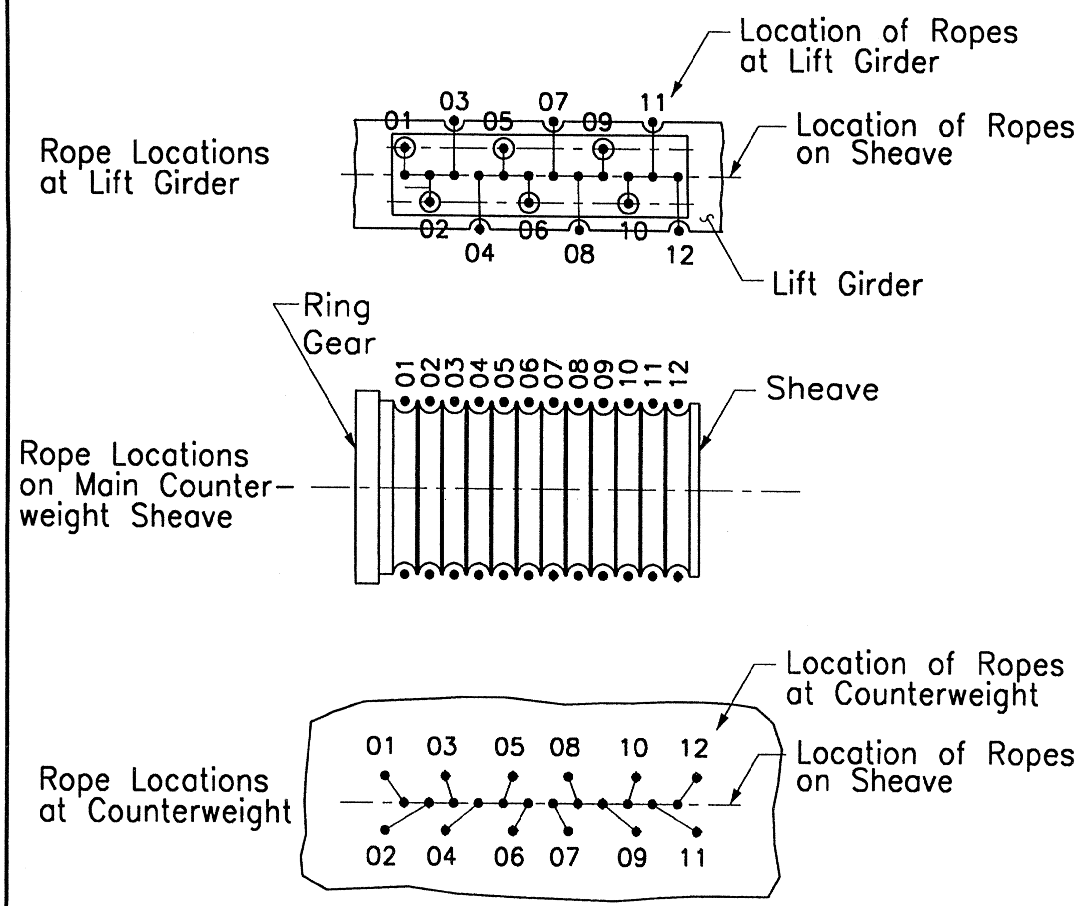

Rope Numbering System

Typical all Sheaves

Removal and Replacement Sequence

Typical all Sheaves

1. Remove Rope 11
2. Remove and Replace Rope 10
3. Remove and Replace Rope 12
4. Remove Rope 9
5. Remove and Replace Rope 8
6. Remove and Replace Rope 7
7. Replace Rope 9
8. Replace Rope 11
9. Remove Rope 2
10. Remove and Replace Rope 3
11. Remove and Replace Rope 1
12. Remove Rope 4
13. Remove and Replace Rope 5
14. Remove and Replace Rope 6
15. Replace Rope 4
16. Replace Rope 2

Figure 4. Sequence for Rope Removal and Replacement

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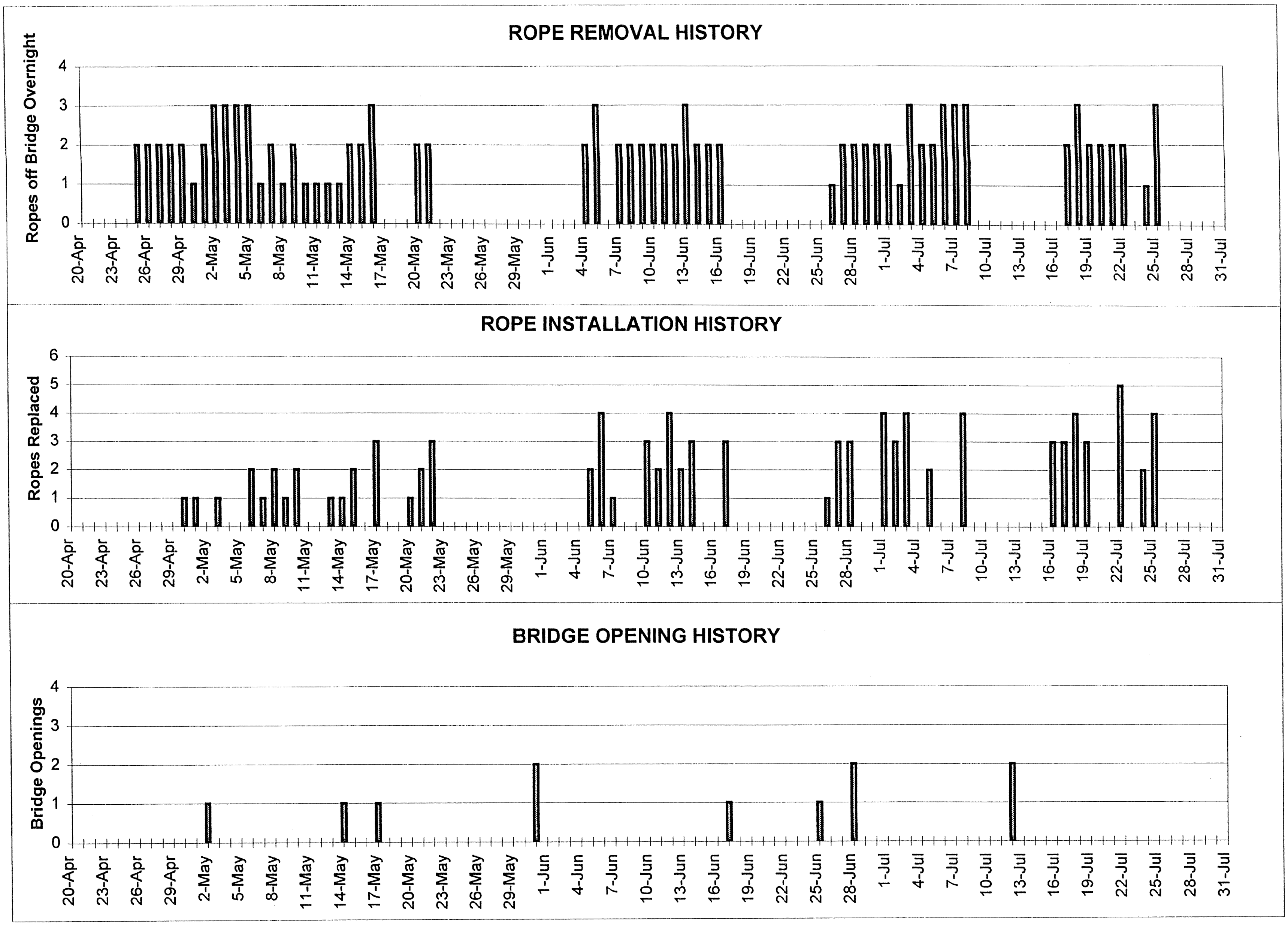
WIRE ROPE REPLACEMENT

Figure 5 - Rope Replacement Histogram



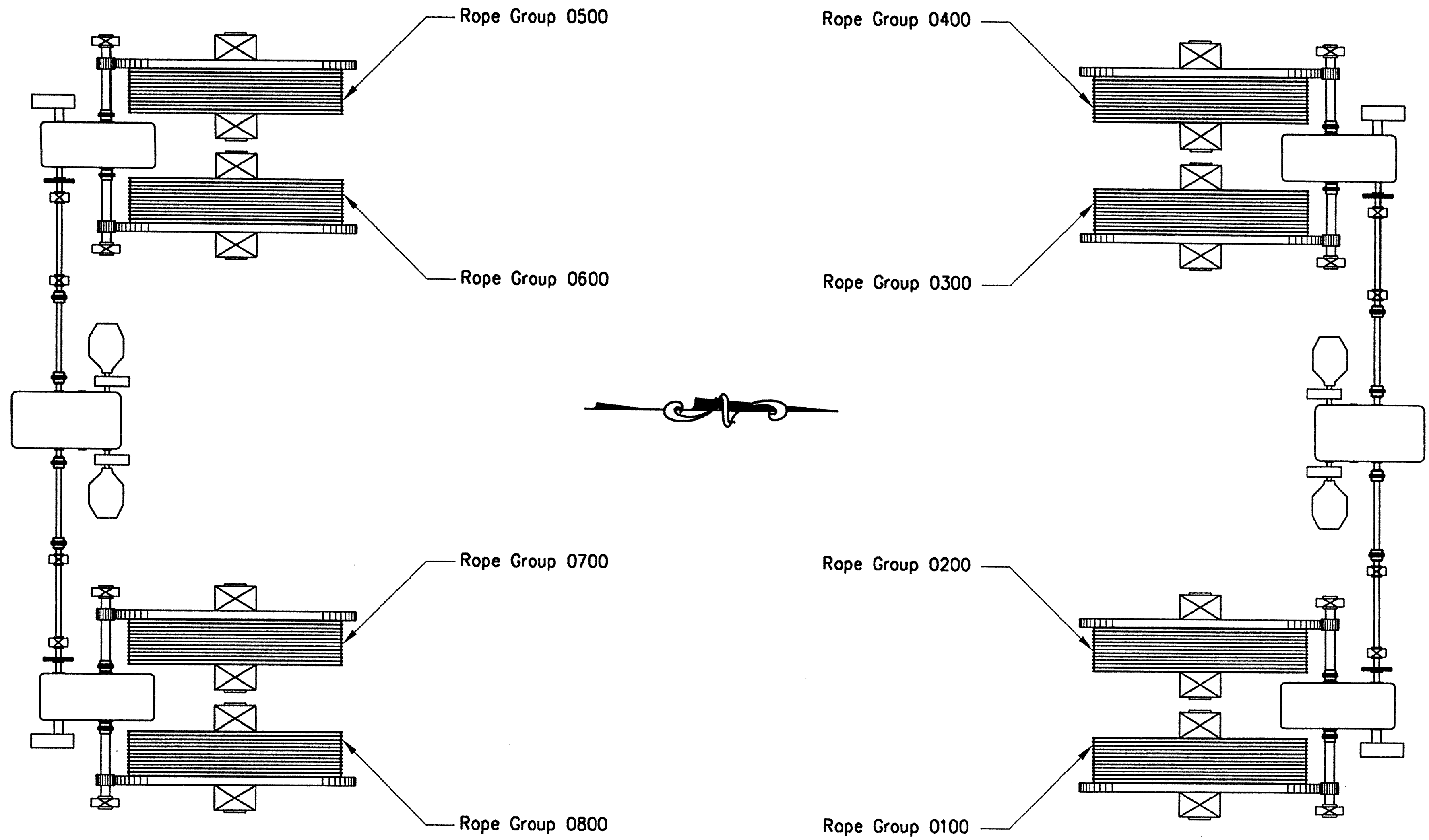


Figure 6. Identification of Rope Groups

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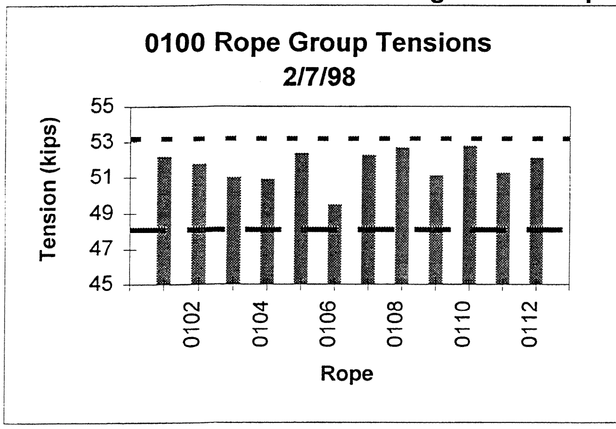
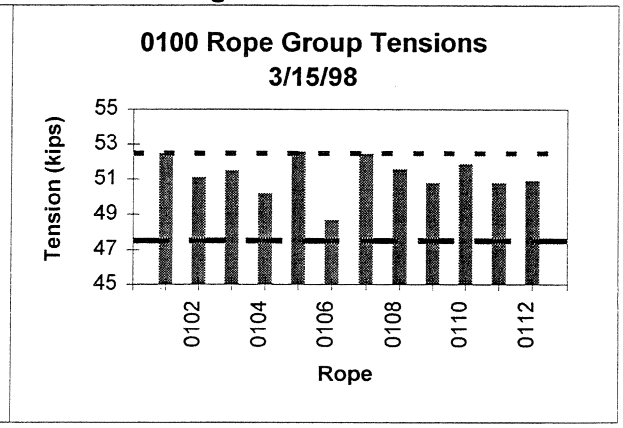
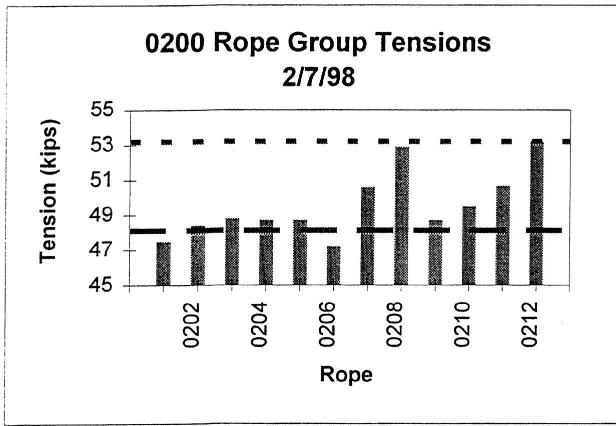
Figure 7. Tension Adjustment History

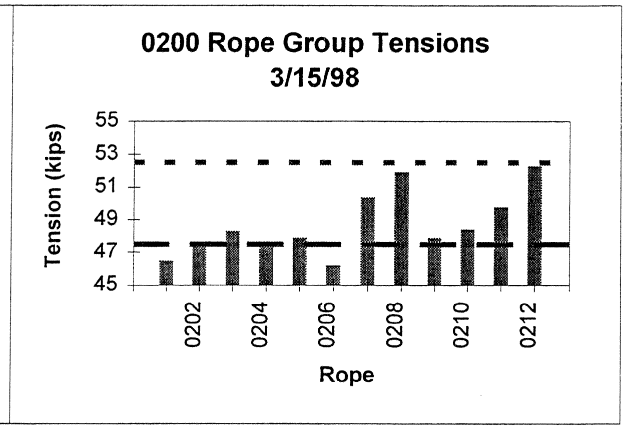
		ROPE GROUP							
		0100	0200	0300	0400	0500	0600	0700	0800
Initial Tensioning	Ropes Requiring Adjustment	10	9	7	7	8	8	3	3
	Max Percent Deviation prior to Adjustment	60.4	46.6	17.4	21.9	49	25.8	11.5	15.5
	Max Percent Deviation after Adjustment	4.9	4.9	3.3	4.4	4.5	4.8	1.5	2.4
One Month Tensioning	Ropes Requiring Adjustment	8	5	6	3	8	5	6	4
	Max Deviation prior to Adjustment	19.8	21.4	10.8	10.9	16.7	16.2	10.1	14.6
	Max Percent Deviation after Adjustment	3.8	4.2	2.4	4.1	5	2.6	3.4	3.4
Six Month Tensioning	Ropes Requiring Adjustment	3	4	0	0	4	5	1	2
	Max Deviation prior to Adjustment	5.2	7.6	4.9	4.9	6.5	6.9	7.1	(21.4) 7.9
	Max Percent Deviation after Adjustment	3.6	4.3	-	-	4.2	3.1	3.5	4.2

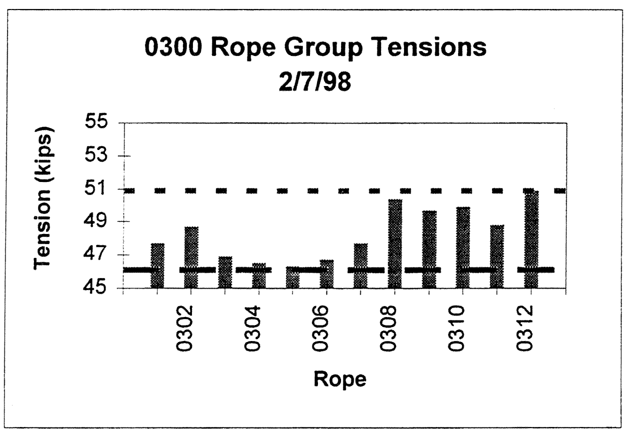
BROADWAY BRIDGE
WIRE ROPE REPLACEMENT
Figure 8A. Rope Tension Readings

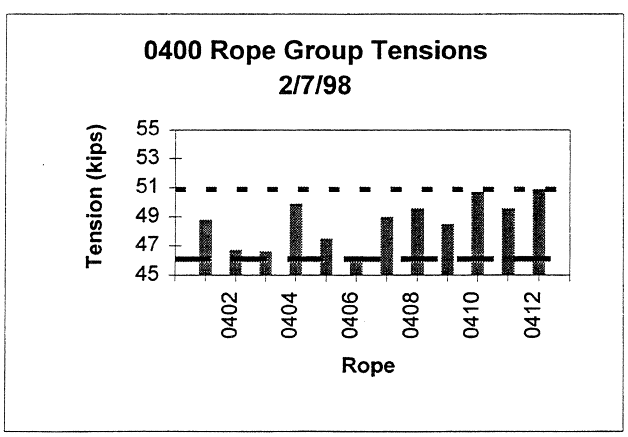












BROADWAY BRIDGE
WIRE ROPE REPLACEMENT
Figure 8B. Rope Tension Readings