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REPLACEMENT OF THE COUNTERWEIGHT ROPES AND SHEAVES ON THE RIO GUAIBA BRIDGE, PORTO ALEGRE, BRAZIL

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GENERAL

The Rio Guaiba bridge is a vertical lift bridge which carries the Brazilian highway No. BR 290 across the Guaiba river at the port city of Porto Alegre, Brazil. The bridge was designed in 1955 by a consortium of firms with Leonhardt and Andra of Stuttgart, Germany as the lead designer responsible for the design of the bridge superstructure. The counterweight system and machinery were designed and supplied by the Brazilian firm of Fichet E. Schwarz-Hautmont, of San Paulo, Brazil. The bridge was opened to traffic in 1958.

The Rio Guaiba bridge serves as an important link for the Brazilian state of Rio Grand do Sul, serving as the primary connection between the city of Porto Alegre and points south and west and into Uruguay, which sits on the southern border of this state. Porto Alegre, with a population of over 3,000,000 is the largest city in southern Brazil.

In July 1997, the Brazilian investment group, CONCEPA, (Concesioaria da Rodovia Osorio-Porto Alegre S/A) was awarded a concession contract to operate and maintain the 112 Km stretch of Brazilian highway No. BR-290 that extends from the city of Osorio westward to Eldorado du Sul just west of the city of Porto Alegre. Operation and maintenance of the Rio Guaiba lift bridge was included as part of this concession contract.

With the concession contract awarded, CONCEPA performed an initial inspection of the bridge and found that several of the counterweight ropes had broken wires. In order to assess the severity of these findings, CONCEPA engaged Steinman International Inc., USA, a unit of the Parsons Transportation Group, in February 1998 to perform a detailed inspection of the counterweight rope system. This inspection included inspection of the counterweight and safety ropes, of the corresponding sheaves, and of the mechanical and electrical systems.

The Steinman team performed the inspection in April 1998, and found that the integrity of the original counterweight ropes was severely compromised by the numerous broken wires found in each of these ropes. The inspection also found several defects in the counterweight sheaves. After reviewing the design and performance of the existing counterweight rope system, it was recommended that an alternative counterweight rope system be designed and installed in order to maintain continued operation of the bridge.

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BRIDGE DESCRIPTION

The Rio Guaiba Bridge is a tower driven vertical lift bridge with the span drive motors and lifting machinery mounted within the piers below the deck level at each end of the lift span. The 55.8 meter long, 18.3 meter wide lift span is a steel deck girder bridge with an orthotropic deck. In addition to carrying four lanes of highway traffic, the bridge also has a 1.15 meter wide sidewalk on each side for the numerous pedestrians that cross the bridge.

Like most vertical lift bridges, the lift span is balanced by counterweights located at the four corners of the span. For aesthetic purposes, the counterweights and sheaves have been enclosed inside the counterweight towers and are hidden from view. These counterweight towers are 48 meters high, U-shaped in plan and constructed of reinforced concrete.

The horizontal clearance of the navigation channel is 54 meters, while the vertical navigation clearance is 10 meters with the lift span in the lowered position and 37 meters in the fully raised position. The total lift height is 26.5 meters.

The original counterweight rope arrangement for the bridge included a single four-part continuous counterweight rope supplemented by two independent single-part safety ropes in each tower. Both the counterweight and safety ropes were 58mm in diameter and constructed of eight strands with a lay length of approximately 380mm. The ultimate strength of these original ropes was estimated to be 160,000 kg. Each of these single counterweight ropes was supported by four counterweight sheaves at the top of the tower and three equalizer sheaves resulting in four parts of one continuous rope supporting the bridge in each corner. The counterweight ropes were anchored on the counterweight side. The original construction also included a separate pair of safety rope sheaves located between the counterweight sheaves to support and guide the safety ropes. Each of the six sheaves located at the top of the tower were identical in design and had one groove that carried one rope, either one part of the main counterweight rope or one safety rope.

The lift span was raised and lowered using operating ropes and an electro-mechanical drive system located in each pier. Four (4) downhaul ropes are connected to the lift span at each pier. One downhaul rope was connected to the bottom of each counterweight. The uphaul and downhaul ropes are wound onto separate drums. All operating rope drums on one pier are synchronized and interconnected by the machinery system. The machinery system consists of an enclosed speed reducer, open bevel and straight spur gears and cross shafts. Each pier has one 40 kw electric motor to drive the lift span. There is also one 10 kw electric motor that is used to drive the span in the event of a main motor, control system or power failure. Synchronization between piers is maintained using a power synchro-tie system with an additional electric motor in each pier. In the event of a power failure a 35 kw diesel powered generator is located in the east pier.

The total lift span weight is approximately 400 Metric tons, balanced by approximately 105 Metric tons at each tower. The Rio Guiaba Bridge experiences 4 to 5 bridge openings per day, totaling approximately 1,700 bridge openings each year.

INSPECTION FINDINGS

1. Counterweight and Safety Ropes:

Visual inspection of the original counterweight ropes at all four towers of the bridge found multiple wire breaks in virtually every strand of all four parts of these ropes that pass over the main sheaves. At the worst location there were at least four broken wires in each of the 8 strands within one lay length. Typically, where several concurrent wire breaks were found, the ends of the wire breaks were observed to have moved slightly apart. Close examination of the ropes found that each strand had at least four (4) broken outer wires on the inside face of the rope (that part which is in contact with the sheave). The quantity of wire breaks observed within a single lay length was considered to have resulted in a significant reduction of the rope strength.

Close inspection of the original counterweight ropes found the ropes to be lubricated but the lubricant did not appear to have penetrated to the core of the ropes. As a result, some corrosion was visible at scattered locations throughout the length of the rope and at some of the broken wire locations. There was also excess lubricant present at the tower tops on the ropes, sheaves, support beams and floor.

Discussions with the maintenance and operating personnel indicated that the ropes were not lubricated for the first twenty-five years of operation. At that time, wire breaks were first observed and lubricant was then first applied to the ropes.

The safety ropes, on the other hand, were observed to be in good condition with some wire wear evident on those lengths of the rope that came in contact with the sheaves. None of the wires of the safety ropes were observed to be broken. The lubricant on these ropes was similar to that found on the counterweight ropes.

2. Counterweight and Safety Sheaves:

The original design provided six identical sheaves at the top of each tower. Four of these sheaves supported the counterweight ropes and two supported the safety ropes. The pitch diameter of the original sheaves was 2,320 mm. Each sheave was designed to support one rope and to rotate around a non-rotating shaft on a sleeve bearing. The original sheave design was an open spoke design with 6 spokes supporting the sheave rim. Each spoke consisted of a pair of unconnected 4" x 3" x $^3/_8$" T-shapes. Although not connected, each of the T-shapes was welded to the hub and to the sheave ring.

Inspection of the main counterweight rope sheaves found cracks in the welded connections of these sheaves. Typically, these cracks were observed to occur at the connection of the sheave spokes with the sheave rim. At one sheave, two adjacent spokes had both legs completely severed. As this sheave rotated, these cracks would open and close due to the varying magnitude and direction of the stress.

Inspection of the safety rope sheaves found these sheaves to be in good condition. No evidence of cracking was observed on the sheaves of the safety ropes.

As part of the inspection, all of the counterweight and safety ropes were vibrated by hand and the frequency of the first mode was measured. Using this information it was possible to calculate the approximate tension in each of these ropes. The calculated tensions in the main counterweight ropes varied from 19,570 kg to 22,970 kg while the tensions in the safety ropes varied from 6,600 kg to 8,000 kg. With the weight of each counterweight estimated to be 105 metric tons at each corner, the theoretical tension in each counterweight rope was estimated to be between 20,250 kg to 23,000 kg. Using the tensions measured at the time of the inspection the factor of safety for the most heavily loaded rope was 6.9:1.

DISCUSSION OF INSPECTION FINDINGS

The wire breaks observed on the counterweight ropes were attributed to the ropes running under tension on sheaves with diameters that were too small relative to the rope diameter (Sheave diameter to rope diameter ratio of 39:1). As the ropes passed over the sheaves, the ropes were subjected to increased bending stresses as well increased contact pressure between the rope and the sheave. Using a relatively small diameter sheave, as in this case, increased the variation in the bending stresses and also the contact pressures.

In addition to the undersized diameter sheaves, the dimensions of the rope groove in the sheave rims were observed to be improperly designed for the referenced counterweight ropes. Specifically, the contour of the sheave groove did not provide sufficient support for the rope resulting in additional pressure being applied to the ropes during operation of the bridge. This additional pressure resulted in flattening or distortion of the rope and prevented the necessary free sliding between individual wires as they passed over the sheave. This condition results in increased stresses being applied to the wires. Measurements of the counterweight rope diameter at select locations confirmed that the rope had indeed flattened and had assumed an elliptical shape as a result of the improperly designed sheave grooves.

The current AASHTO specifications for movable highway bridges specifies that the ratio of sheave diameter to rope diameter is preferred to be 80:1 with a minimum ratio of 72:1.

The original counterweight rope system also lacked appropriate redundancy with only two safety ropes of the same diameter left to carry the load carried by the four part rope. Failure of the continuous counterweight rope would result in all of the load being transferred to the safety ropes either gradually or suddenly depending on the type of failure.

The factor of safety of the original 58 mm diameter main counterweight ropes was 6.1:1 assuming that the ropes carried the entire load. Computing the factor of safety in this manner considers direct load only and neglects the effects of the ropes bending over the sheaves. If the entire load were transferred to the safety ropes, the factor of safety would be 3.05:1. These factors are less than the current AASHTO specified ratio of 8:1. If the main and counterweight ropes each had been equally tensioned the factor of safety would be 9.17:1.

The failure of the original sheaves was attributed to an overstress condition due to the small cross sectional area of the spokes. The spokes were fabricated from two rolled T sections and welded to the hub and the rim. The location of the failure was the welded connection of the spoke to the rim. This condition was observed only on the sheaves for the counterweight ropes. No cracks were observed at these locations on the sheaves for the safety ropes.

The existing sheaves had a bronze bearing within the hub and a non- rotating shaft. No problems were observed with these bearings.

Based on the above, it was determined that the small diameter of the existing sheaves, the variation in bending stress and the contact pressure between the rope and sheave caused wear and fatigue damage to the wires resulting in broken wires at the wear marks.

DESIGN

The first scheme considered to repair the bridge was to replace the ropes and sheaves in kind. This option has the lowest design cost. This Idea was quickly eliminated because it would not correct any of the causes of the problems that were discovered. The failure of the original counterweight ropes was attributed to the improper ratio of the sheave diameter to the rope diameter. To correct the problems of the existing system the following design goals were established:

1. Replace all failed components.
2. The new components would fit into the existing towers and attach to the span and counterweight with a minimum of significant modifications.
3. The sheaves and ropes would be designed and selected so that fabrication would be possible in South America.
4. The new design would have ropes that share the load equally and are redundant.
5. The design of the replacement system will in general follow AASHTO recommendations for moveable highway bridges. Specifically the following criteria would be considered:
    a. Rope construction.
    b. Sheave design and construction.
    c. Sheave to rope diameter ratio.
    d. Allowable stresses and factors of safety.

Consideration was given to using a sheave with the same pitch diameter as the existing sheave (2320 mm (91.34 inches)). To achieve a 72:1 ratio of the sheave diameter to the rope diameter, ropes of a diameter of 32 mm (1.268 inches) would be required. AASHTO recommends using fiber core ropes with 6 strands of 19 main wires each made from improved plow steel. The ultimate strength of a 32 mm diameter rope made from improved plow steel is 57,140 kg (126,000 pounds). Sixteen of these ropes per tower would result in a factor of safety of over 8.5:1. In order to accommodate sixteen ropes per tower within the available clearances, four ropes were located on each of four sheaves. This arrangement was selected and the four new sheaves were located at the locations of the existing main counterweight rope sheaves. Locating the new sheaves in this manner would allow the safety ropes and sheaves to remain installed during a portion of the construction period if desired. Also there would be space available between all of the sheaves to allow inspection, lubrication and cleaning.

Although alternative rope sizes were considered the arrangement of sixteen 32 mm ropes was chosen as the optimum.

The new sheaves are of welded construction with two webs and eight spokes. The design of the sheaves follows traditional designs with the rim supported by two webs. Each sheave carries four 32 mm ropes spaced 40 mm, 80 mm, and 40 mm apart respectively. New flanged bronze bearings are installed in the hub of the sheave and the new non-rotating shafts are mounted in the existing fixed pillow blocks. Grease grooves are located in the non-rotating shaft.

Lift spans typically have counterweight ropes that deviate from the vertical plane in order to allow the ropes to be close together at the sheave, decreasing the length of the sheave and far enough apart at the connections to allow room for the sockets and take-ups. These deviations from the vertical plane generally occur in two directions, along or parallel to the sheave axis and, perpendicular to the sheave axis. AASHTO defines these as transverse deviation and longitudinal deviation respectively and also specifies maximum deviations. In this design there is no transverse deviation but longitudinal deviation is used to separate the sockets into two rows.

Adjustable connections were desired so that the rope tensions could be easily equalized during construction and at subsequent times. Most adjustable rope connections are splayed to produce a deviation from the vertical plane in the transverse direction to allow room for the sockets and take-ups. On this bridge the shape of the towers limits the size of the connections in this direction. Using threaded sockets and no transverse deviation minimized this dimension. Threaded sockets were provided at both ends of the ropes. The sockets for the ropes for each sheave are arranged in two rows of two and are parallel to each other.

AASHTO only recommends the use of zinc filled sockets. It was decided to use swaged sockets for the following reasons:

1. Lower cost of installation.
2. Ability to swage sockets using local facilities
3. Threaded sockets were available.
4. The sockets could be installed closer together because of the smaller socket diameter.
5. Swaged sockets are common on small diameter ropes but not common for rope diameters larger than two inches.

The ropes on one sheave are equalized with respect to the other sheaves using an equalizing system. An equalizer bar is used at each counterweight connection to equalize the tension between the ropes on the inboard sheaves. Each outboard sheave rope group is equalized to the nearest respective inboard sheave rope group using an equalizer bar located at the connection to the span. All connections where movement will occur are provided with steel pins and self-lubricating bronze bushings. All equalizers are stabilized by relative locations of the holes in the bar: the pins for the rope connections are higher than the pins for the span or counterweight connections.

Consideration was given to not equalizing the connections. This would have been difficult because the guide rail separates the two equalizers on the span and its location would have prevented the installation of a single beam that connected all ropes to the span.

CONSTRUCTION

Test specimens of the ropes were fabricated using the same threaded sockets to be used on the bridge. The specimens were tested to destruction. The rope failed above the specified ultimate strength and the rope connection to the sockets or the sockets themselves did not fail.

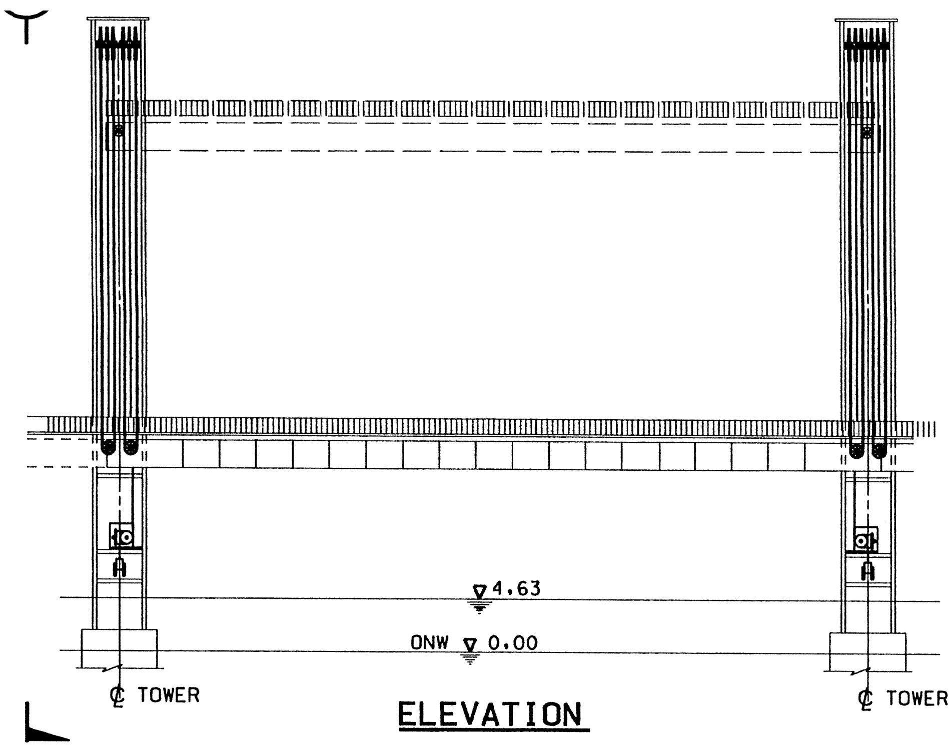
The removal and installation work was performed at one pier at a time. First the counterweight was connected with rods to a jacking frame supported by jacks. The counterweights were raised with the jacks and then set on blocks. The ropes and sheaves were cut into pieces and lowered from the towers with hoists. The safety ropes were removed at the same time as the main ropes. The equalizer sheaves at the span and counterweight connections and pins were removed. The pillow blocks supporting the sheave shafts were match marked with their locations and removed with the shaft and sheave hubs. The pillow blocks were retained for reinstallation.

The new equalizer bars and rope anchorages were installed at the span and counterweight connections. The sheaves, shafts and pillow blocks were raised to the tops of the towers and placed in position with a crane. The ropes were raised over the sheaves one at a time and connected to the span and counterweight. The counterweights were lowered until they were supported by the new ropes. After final adjustments and test operations the lift span was retuned to service.

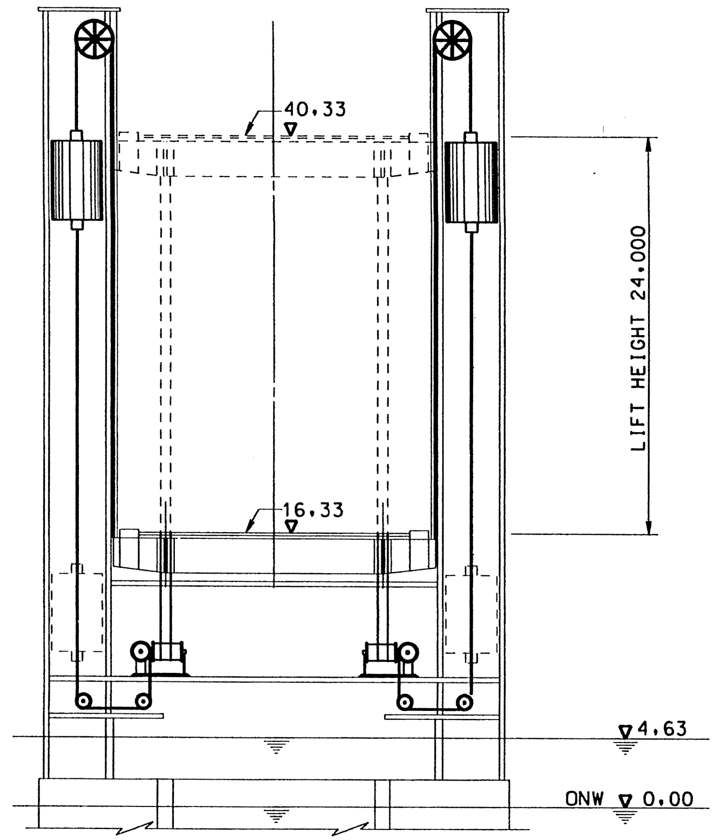
CONCLUSIONS

After the bridge had been returned to service the owner reported that the lift span operated faster more smoothly and used less power after the rehabilitation was performed. If we investigate the bending resistance of wire rope according to the AASHTO formula we calculate a new coefficient of .0041 versus the existing coefficient of .0075. The resistance due the rope bending has been reduced by nearly half. This is however a very small part of the total resistance of the span to motion. It may be reasonable to assume that the sheave bearings and shafts provide less resistance in new condition than in the existing condition.

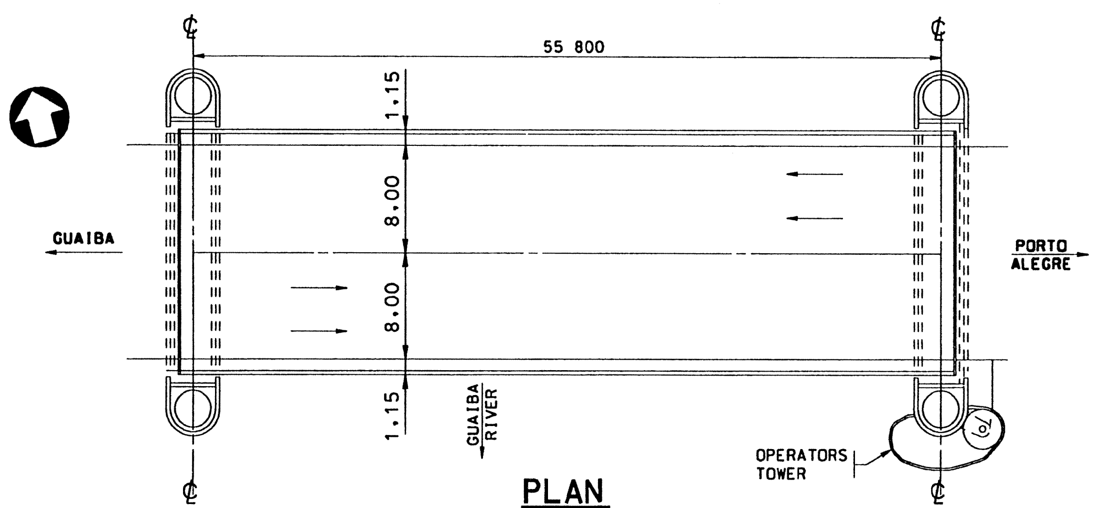
The rehabilitation work performed on this bridge demonstrated that it is possible to improve a very unique structure by applying established size ratios, traditional and nontraditional construction details with a greater number of smaller sized components.



ELEVATION



VIEW B



PLAN

RIO GUAIBA BRIDGE

DETAILED INSPECTION OF COUNTERWEIGHT ROPES AND MECHANICAL COMPONENTS

PLAN AND ELEVATION

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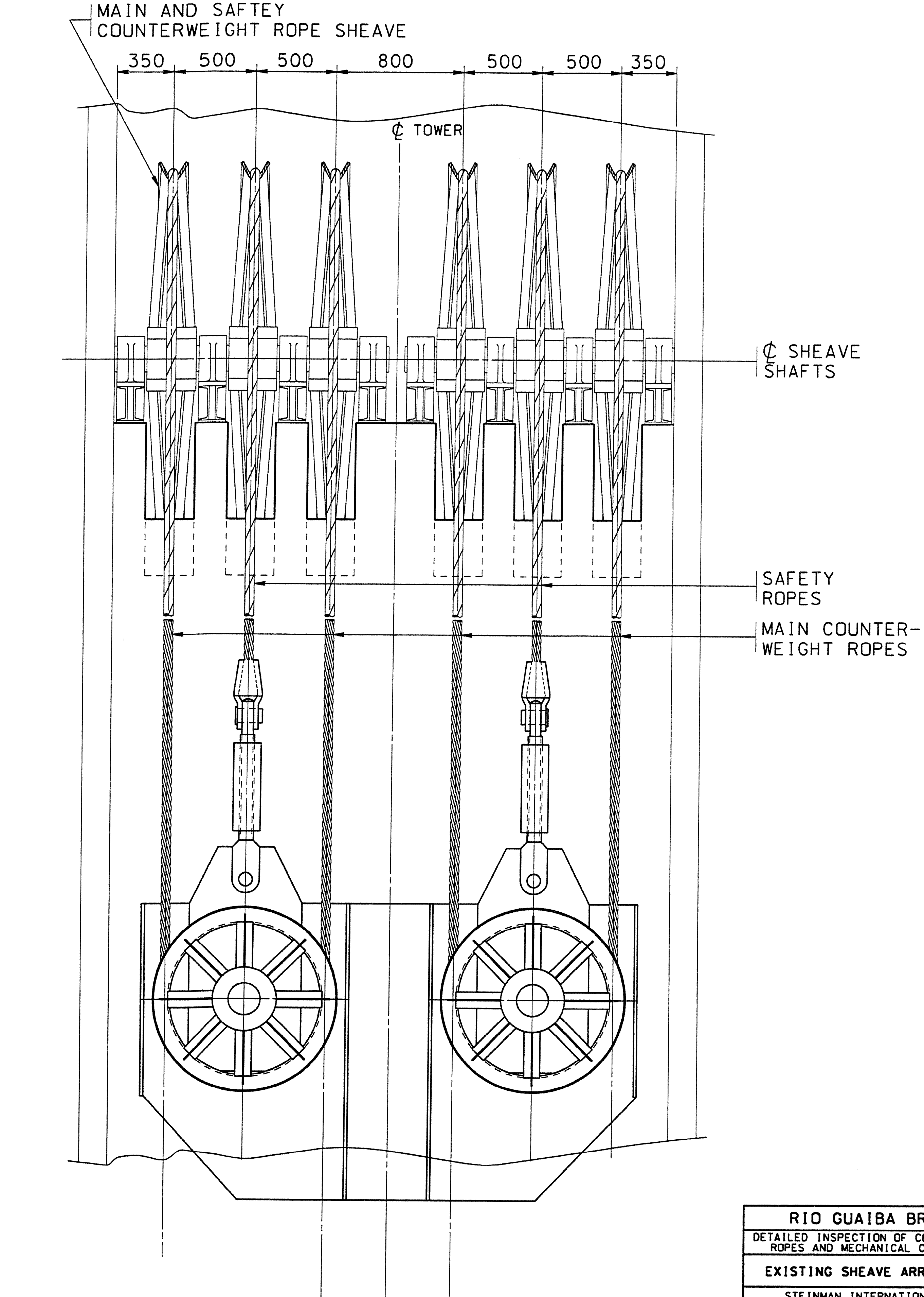
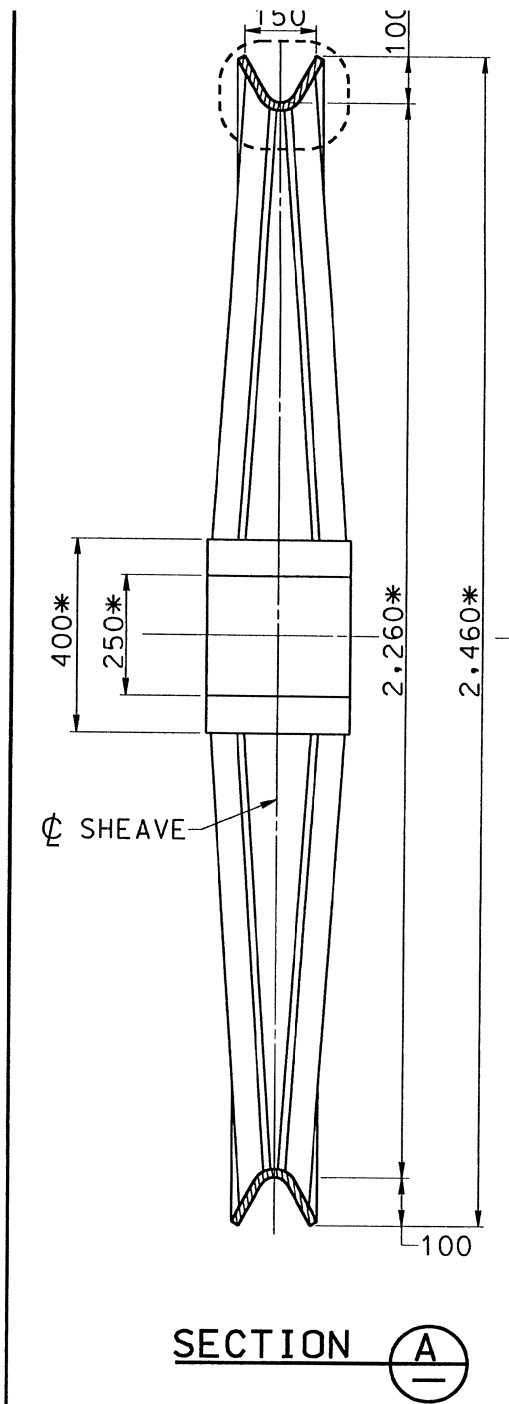
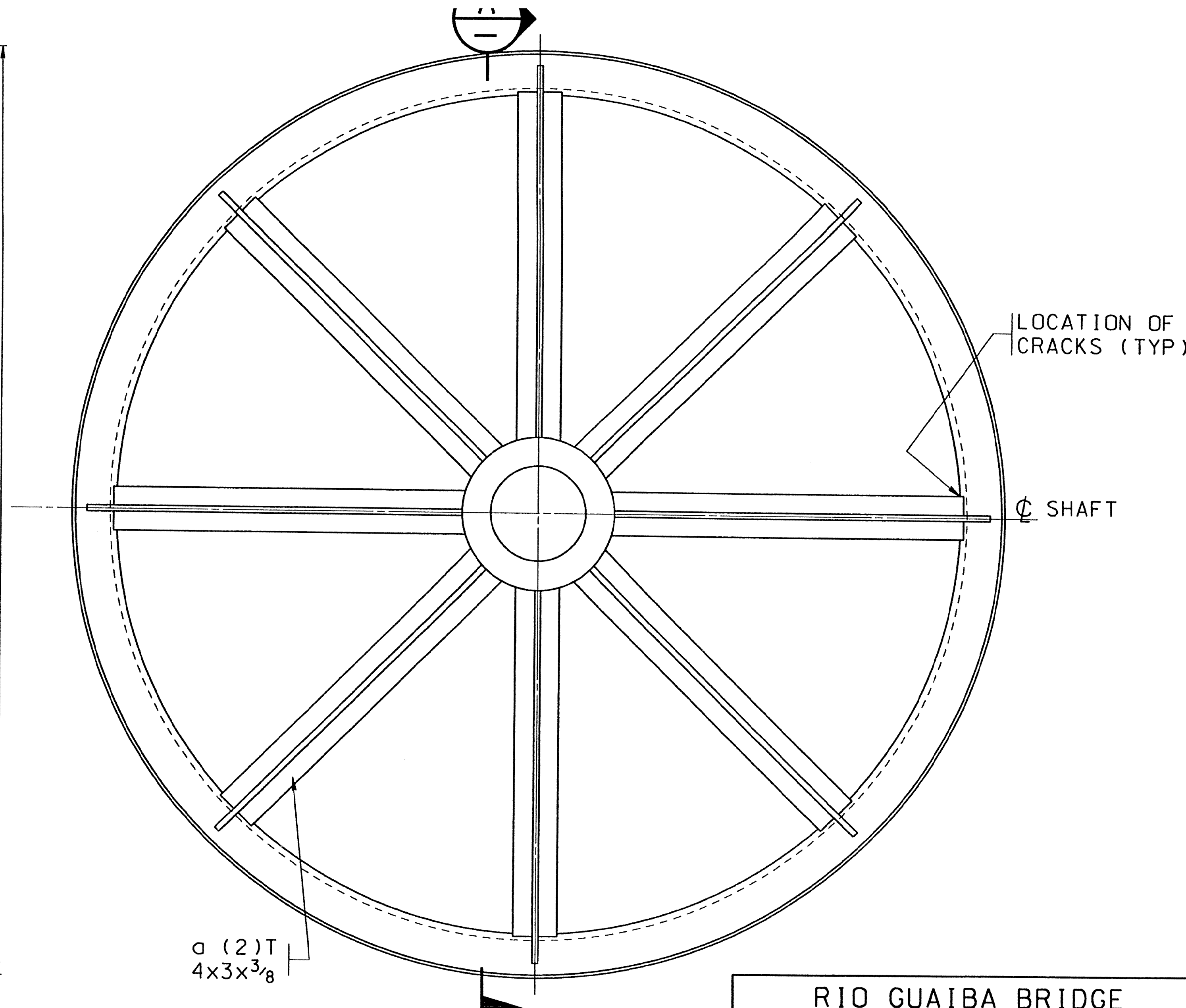


RIO GUAIBA BRIDGE
DETAILED INSPECTION OF COUNTERW ROPES AND MECHANICAL COMPONE
EXISTING SHEAVE ARRANGEM
STEINMAN INTERNATIONAL INC
FIGURE NO.2   AUGUST 20



SECTION A



ELEVATION

RIO GUAIBA BRIDGE
DETAILED INSPECTION OF COUNTERWEIGHT ROPES AND MECHANICAL COMPONENTS
ELEVATION AND SECTION OF EXISTING MAIN COUNTERWEIGHT SHEAVE

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