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"Strain Gauge Testing of Movable Bridge Brakes", Michael J. Abrahams, III,
Parsons Brinckerhoff Quade Douglas, NY

Disclaimer

Abstract

Brakes on mechanically driven movable bridges are sized to equal the motor torque, to provide braking forces adequate to slow and stop the bridge, and to hold the bridge against wind forces. Designers typically assume that the specified brake torque is established by factory setting, and that the brake forces assumed during design will exist in the field.

This paper will discuss an investigation of the braking forces in a large swing span which had experienced several failures of its operating machinery. By using pinion-mounted strain gauges, it was determined that there was a very large difference in braking forces between those anticipated in design and those measured in the field. It was found that adjusting the brakes could be quickly accomplished using strain gauge readings.

The paper will describe the results of the investigation, explain the mathematics of converting measured strain to torque, and provide suggestions for applying this technique to existing and new bridges.

Introduction

The George P. Coleman Bridge is one of the world's largest swing spans. Opened is 1953, the bridge carries two lanes of Route 17 over the York River between Yorktown and Gloucester, Virginia. The bridge has two 500-foot, center pivot, swing spans, see Figure 1, to provide a 450-foot-wide navigation channel. The bridge was designed to meet the requirements of providing for marine traffic, which is primarily composed of large Navy vessels serving two Naval installations up river. At the same time, the bridge height had to be minimized in order not to obscure the viewscape from the nearby Yorktown Battlefield, a national park which was the scene of the battle which proved to be a turning point in this country's war of independence. In fact during placement of the bridge's caissons, ship timbers and hardware were encountered that are believed to come from a ship of the English fleet participating in the battle.

Since its construction in 1953, the bridge has experienced numerous main pinion shaft failures, primarily on the north pier. In July of 1988, the most recent failure occurred, fracturing the pinion shaft on drive 3 and a portion of the rack.

A study was undertaken to determine the most probable cause of the repeated machinery failures, and to propose modifications to enable the bridge to operate reliably.

Arrangement of Machinery

Each swing span is powered by three independent drives, each drive consisting of a 20-hp motor, a thrustor brake, an enclosed triple reduction 56:1 right angle reducer, an additional open single reduction gear set, and a drive pinion engaging a circular rack. The overall drive ratio is 163:1, excluding the rack and pinion. The center wedges are driven by two independent motor/reducer sets mounted adjacent to the bridge main drives. The dead weight of each movable span is supported on a 36-inch-diameter bronze bearing, with four sets of two balance wheels riding on a track just inside the curved rack. Figures 2 and 3 show the general arrangement of the machinery.

Brake Controls. Bridge operation is controlled by a trolley-type controller in the bridge house, with individual positions for each of the three independent thrustor brakes, as well as six power points for the motors. When stopping the span, the operator selects the number of brakes to be applied, but must always pass through brake 3 to get to brakes 2 and 1. Thus brake 3 always sets before the other two. This results in brake 3 taking a much higher proportion of the stopping force. Most pinion shaft failures occurred in drive set N-3, which was subjected to these higher forces. There is no synchronization or load transfer device between drives to equalize motor and brake torques.

Open Gearing. The open gearing consists of the rack, three drive pinions, and three sets of open single reduction gearing.

The rack consists of nine 30-degree segments with a pitch diameter of 36.608 feet and a circular pitch of 2-1/2 inches. The rack is cast carbon steel and is cast integrally with the balance wheel track, except for three 30-degree segments where there is no rack.

The machinery on the south pier has operated in a generally satisfactory manner since the bridge's completion in 1953. One pinion shaft and brake were replaced five to seven years ago. The arrangement of the machinery on the south pier is a mirror image of the layout on the north pier.

Machinery Testing

In May 1989, tests were conducted by others to simultaneously measure the torques in each of the main pinion shafts on each pier, examine the brake wheels, and measure the spring lengths in the brakes. Dual-arm strain gauge rosettes were installed on each pinion shaft and connected to a strip recorder to plot the variation of strain in the shafts as a function of time during a bridge opening/closing cycle. The sequence and timing of brake setting/releasing was also recorded on the chart, as was the angular position of the span.

Drive 3 on the north pier (drive N-3) was out of service, consequently shaft strains were not measured. All of the drives on both piers, with the exception of N-1, exhibited similiarly shaped strain curves, with the braking strains approximately three to four times higher than the accelerating strains. The braking and accelerating strains were approximately equal on N-1. During the testing, the motors were held to power point 4 (PP4) on the north pier, while the south was capable of running at full power (PP6).

Drive N-2 recorded the highest strains on the bridge, with strains of 350/50/1,200 microinches (accelerating/running/braking). This is due in part to the fact that drive N-3 was inoperative, and that drive N-1 carried a much smaller load, with strains of 300/20/400. Normally, drive N-3 would be the first to brake, whereas during these tests drive N-2 was the first. The brake on N-1 set too late to effectively help stop the span, forcing N-2 to work on its own. Drives S-1 and S-2 were nearly equally loaded, with strains of 530/60/1,000. Drive S-3, which brakes first, had shaft strains of 230/20/1,200.

While these peak strains were similar to the north pier, there was a more effective sharing of loads between the drives of the south pier, which may partially explain the much lower incidence of shaft failures on the south pier. In addition, drive N-2 produced most of the accelerating and braking torque for the north span, while S-3 produced minor accelerator torques, but most of the braking torque. This may affect the fatigue life of the shaft.

The peak braking strain on S-3 and N-2 is unknown, as the chart only read to 1,200 microinches, and for both drives the pen left the chart. Consequently, the peak strain may be much higher.

Computed Forces. The torsional strains of the main pinion drive shafts were used to calculate various forces in the machinery and the allowable and design loads were computed using the 1988 AASHTO "Standard Specifications for Movable Highway Bridges." These forces were then compared to the original design loads from the 1949 design calculations.

The rack and pinion tooth loads were calculated for four conditions: accelerating, running, braking, and 1.5 times the motor torque. The pinion shaft was checked for the measured braking forces and 1.5 times the motor torque using both rigid and flexible supports. The actual torque currently produced by the brakes was calculated, as was the torque necessary to hold the span against an unbalanced wind. For the pinion shaft, pinion teeth, and bearings, the effects of varying material strengths were investigated. A summary of loads is given on Table 1.

TABLE 1

Tooth Loads

RACK TOOTH LOADS

-	Constant Running (as tested)	6.0k
-	Existing Braking (as tested)	146.3k
-	Existing Acceleration (as tested)	42.6k
-	Brakes Set to 250 ft-lbs	61.5k
-	1.5 x 20HP (w/losses)	66.7k
-	Brakes Set to 181 ft-lbs (20 HP)	44.5k
-	Brakes Set to 180 ft-lbs (5 mph wind)	44.3k
-	Allowable, Cast Steel (88 Code)	33.4k
-	Allowable, Cast Steel (as designed)	42.9k

PINION TOOTH LOADS

-	Loads Identical to Above	-
-	Allowable, Class G Forged Steel (88 Code)	39.3k
-	Allowable, Class G Forged Steel (as designed)	44.7k

The average shaft torsional strain during span acceleration was 350 microinches; during constant speed running the average torsional strain was 50 microinches; and during braking, the peak torsional strain exceeded 1,200 microinches. The rack and pinion tooth load corresponding to these conditions is 42.6/6.0/146.3 kips(k), respectively.

The allowable tooth load using the current AASHTO code for the cast steel rack is 33.4k. The original calculations used a design tooth capacity of 42.9k with an overstress of 100% allowed for accelerating or braking, as was common practice at that time. This overstress is not allowed today. The lower capacity given by the use of the new code is a result of a code provision reducing the allowable tooth load by 20% for gearing not assembled in a common frame.

The current braking strain results in a tooth load over four times the current allowable. If the brakes are set to 250 foot-lbs (to stop the bridge in the design time using two of the three drives) a tooth load of 61.5k, twice the allowable, results. If the brakes are set for 180 foot-lbs (to hold the bridge against a 5-mph unbalanced wind with two drives) the tooth load is 44.3k. Calculating the tooth load for 1.5 times the rated motor horsepower (20 hp), as called for in the 1988 code, results in a tooth load of 66.7k, again twice the allowable.

Thus, if the excessive braking strain and acceleration were restricted, and the brakes were set for 180 foot-lbs, the existing rack would be overstressed by approximately 33%. This would be a significant improvement over the measured overstress of over 300%. A similar condition exists with the pinion. The allowable tooth load for the original A237 Class A forged alloy steel (now known as A668 Class G forged alloy steel) using the 1988 code is 39.3k, about one quarter of the existing braking tooth load of 146.3k. After the brakes are adjusted to 180 foot-lbs, the teeth would be overstressed only 13% for Class G pinions.

Repeated applications of high braking forces may also result in the formation of cracks in the pinion shaft. The analysis showed that the critical section was near the top of the shaft, where the cross section of the shaft is at a minimum due to a keyway and shoulder for the hub of gear G1. This portion of the shaft is also subjected to unanticipated bending stresses due to the pinion shaft frame flexibility, in addition to the high braking loads. Field observation indicates that the top of the frame is rigid, while the bottom, near the pinion, deflects. This would tend to concentrate stresses in this stiffer area. Pinion shafts available for examination failed at this location.

Thus the primary reason for the breaking of the pinion drive shafts appeared to be the high stresses associated with the application of the brakes. These high stresses then were further increased due to shaft deflection, as well as a keyway and reentrant corner.

Brakes. The brakes are GE thrustor type, model C12 9516-464. In order to evaluate the brake effectiveness, the spring from the nonworking brake was removed and tested by a materials testing laboratory. The spring force vs length test indicated that while there appeared to be some loss of force when compared to the values shown in the instruction manual furnished with the brake, the difference was not significant.

It was learned that the brake shoes had been replaced a number of years ago and that the type of material used for the lining was not known. Based on a conversation with General Electric, it was learned that the original linings were asbestos and that the coefficient of friction of this material was 0.3. However, this material is no longer used due to environmental problems associated with asbestos, and if a different material was substituted at the time of the lining replacement, this could affect braking forces. Contacts with a number of manufacturers of brake lining materials indicated that materials currently available have a much higher coefficient of friction, 0.4 to 0.6, and thus could cause a large increase in braking forces. It is interesting to note that the commentary to the 1988 AASHTO specification, Section 2.5.7, indicates a coefficient of 0.30 to 0.40 for brake materials, generally.

A number of manufacturers of lining material indicated that it was possible to obtain lining material with a coefficient of friction of 0.35, close to that used for the original brakes. A nearby machine shop was located with the appropriate material and, as part of the testing program described below, the shoes on two of the brakes were relined. The remaining brakes, which set second or third in the sequence, were not relined.

Based on the above, it was decided to reset the brakes to obtain a braking torque equal to that intended in the original calculations. The braking force would satisfy the requirements of AASHTO, and be equal to or exceed the motor torque. A value of 180 foot-lbs was used. It was decided that the brakes would be reset by mounting a strain gauge on the drive pinion and by adjusting the brakes while monitoring the strain in the pinion as the bridge operated. Knowing the design braking force and overall gear ratio, it was an easy task to calculate the desired shaft strain.

Testing Methodology

Installation. Strain gauges were installed on the pinion and brake shafts and arranged to measure torque. A schematic of the installations is shown on Figure 4. This arrangement provided cancellation of unwanted signals such as bending or tension/compression. The strain gauge bridge on the pinion shaft was wired to a signal conditioning amplifier which in turn was wired to an oscillograph recorder. The cable between the strain gauge bridge and the conditioning amplifier was allowed to wrap around the pinion shaft during the operational test. A schematic of the instrumentation equipment is shown on Figure 5.

Test Procedure. The actual test consisted of two distinct steps: calibration and acquisition of data. The calibration procedure and theory are explained in the next section. Data acquisition was commenced by starting the oscillograph recorder a few seconds before the bridge started its opening cycle.

The brake was manually released to obtain a zero stress condition for the brake and pinion shafts. Next, the bridge was opened in several steps and the brake applied at each step to bring it to a stop. The strains were recorded throughout the procedure. During closing, the same braking procedure was followed and stops were made at several stages.

Calibration. Calibration of the data acquisition system was performed by simulating a known strain value with a precision resistor and obtaining a permanent record of the deflections obtained. The simulated strain was equivalent to a known torque which is obtained by using the equations shown below. Once a permanent record was obtained on the oscillographic chart, the trace deflection was directly related to the shaft torque.

The equation that relates torque to strain is as follows:

For a round shaft

$$\tau = \frac{16T}{\pi d^3}$$ (1) p. 284, Strength of Materials, Timoshenko

For the case of pure shear

$$\tau = \frac{\epsilon E}{(1+\mu)}$$ (2) p. 60, Strength of Materials, Timoshenko

For a two-gauge bridge

$$\tau = \frac{\epsilon E}{2(1+\mu)} = \frac{\epsilon E}{2.6}$$

For a four-gauge bridge

$$\tau = \frac{\epsilon E}{4(1+\mu)} = \frac{\epsilon E}{5.2}$$

By substitution

$$T = \frac{\pi d^3}{16} \times \frac{\epsilon E}{2.6}$$ for two gauges

$$T = \frac{\pi d^3}{16} \times \frac{\epsilon E}{5.2}$$ for four gauges

In order to calibrate the data acquisition system, a precision resistor was used. The equation that relates simulated strain to shunt resistance is

$$\epsilon = \frac{R_G \times 10^6}{GF(R_{SH} + R_G)}$$ 3) Teledyne Engineering Services, Technical Report TR-21140 (902), December 28, 1989.

d = diameter of shaft

ϵ = strain along principal axis

E = modulus of elasticity

GF = Gauge Factor of strain gauges

μ = Poisson's ratio

R_G = resistance of strain gauges

R_{SH} = resistance of precision resistor

T = torque

τ = torsional stress

Calibration of the strain gauge installation was accomplished by using a 500,000-ohm precision resistor. The resistor was hardwired inside the conditioning amplifier.

It was found that one could quickly adjust the brake force using the double nuts and threaded rod on the brake. After one or two openings and closings, the brakes were adjusted to the desired torque within a range of values.

To simplify the testing and reduce expenses, each of the three brakes on each pier was strain-gauged and adjusted individually. The brakes were adjusted in the same order they set: #3, #2, then #1. To maximize the load on the brake in question, the brakes "upstream" of it were hand-released. Under windy conditions this was not always possible, as the bridge could not be controlled with only one brake. When more than one brake was released, a team member was stationed near the released brakes to set them in case of emergencies.

Although considerable time may be required to properly install and calibrate the gauges due to access and weather difficulties, once the gauges are in place, the brake adjustment takes place very quickly. After adjusting all the brakes it was observed that the bridge operation during braking was considerably smoother than before adjustment. It was also found that after adjusting a couple of brakes, one could adjust the other brakes to a roughly correct position by eye without the use of the strain gauges.

It has been proposed that monitoring of the brake forces with strain gauges be incorporated into a regular maintenance sequence for this bridge.

Discussion: Braking as a Cause of Failure

It has been observed on other swing bridges that significant distortions and straining of pinion components take place during braking. It is believed that this could be associated with incorrectly adjusted brakes. In this instance the brakes appeared to be correctly set, based on factory literature, yet testing showed the braking forces to be far in excess of those specified and the probable cause of pinion failure. The reasons for the difference in braking forces, specified vs measured, are not known, but the difference could be due to a number of reasons, including changes in the brake shoe linings or improper setting of the brakes.

Conclusion: Recommendation for Strain Gauge Testing

Strain gauge testing is becoming more common in movable bridge construction and is now frequently required for the balancing of bascule bridges. The technology of strain gauges is not new and is, in fact, well established.

It is proposed that strain gauge testing be used for calibrating the brakes and braking forces in movable bridges. This testing is applicable to the investigation and rehabilitation of existing bridges as well as the construction of new bridges. It is recommended that the appropriate sections of the AASHTO and AREA specifications be revised to suggest the use of strain gauge testing during machinery installation to establish brake forces at the levels anticipated in the design.

Acknowledgements

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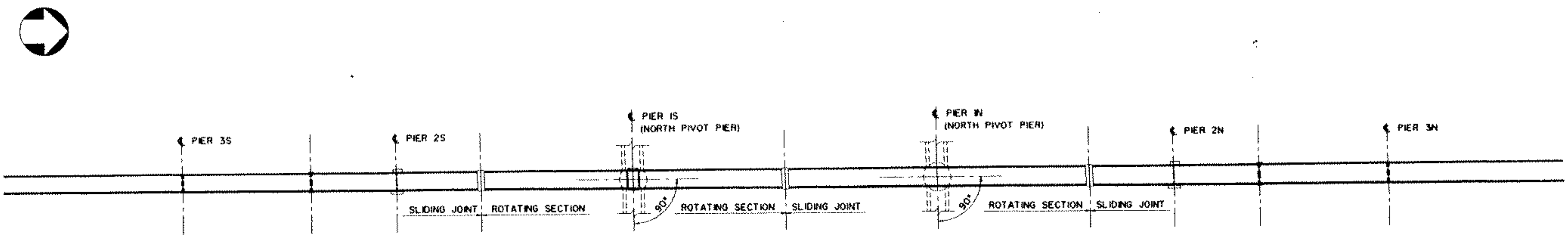
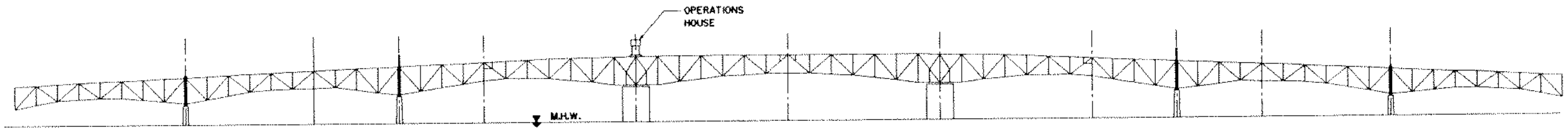


PLAN



ELEVATION

GENERAL VIEW OF SWING SPAN

FIGURE

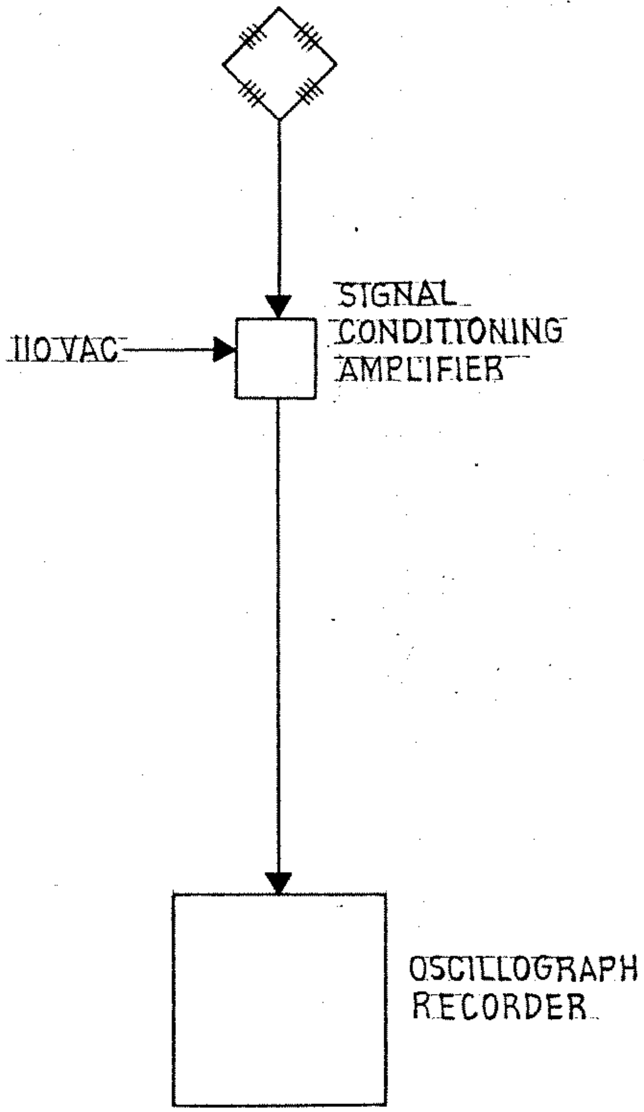
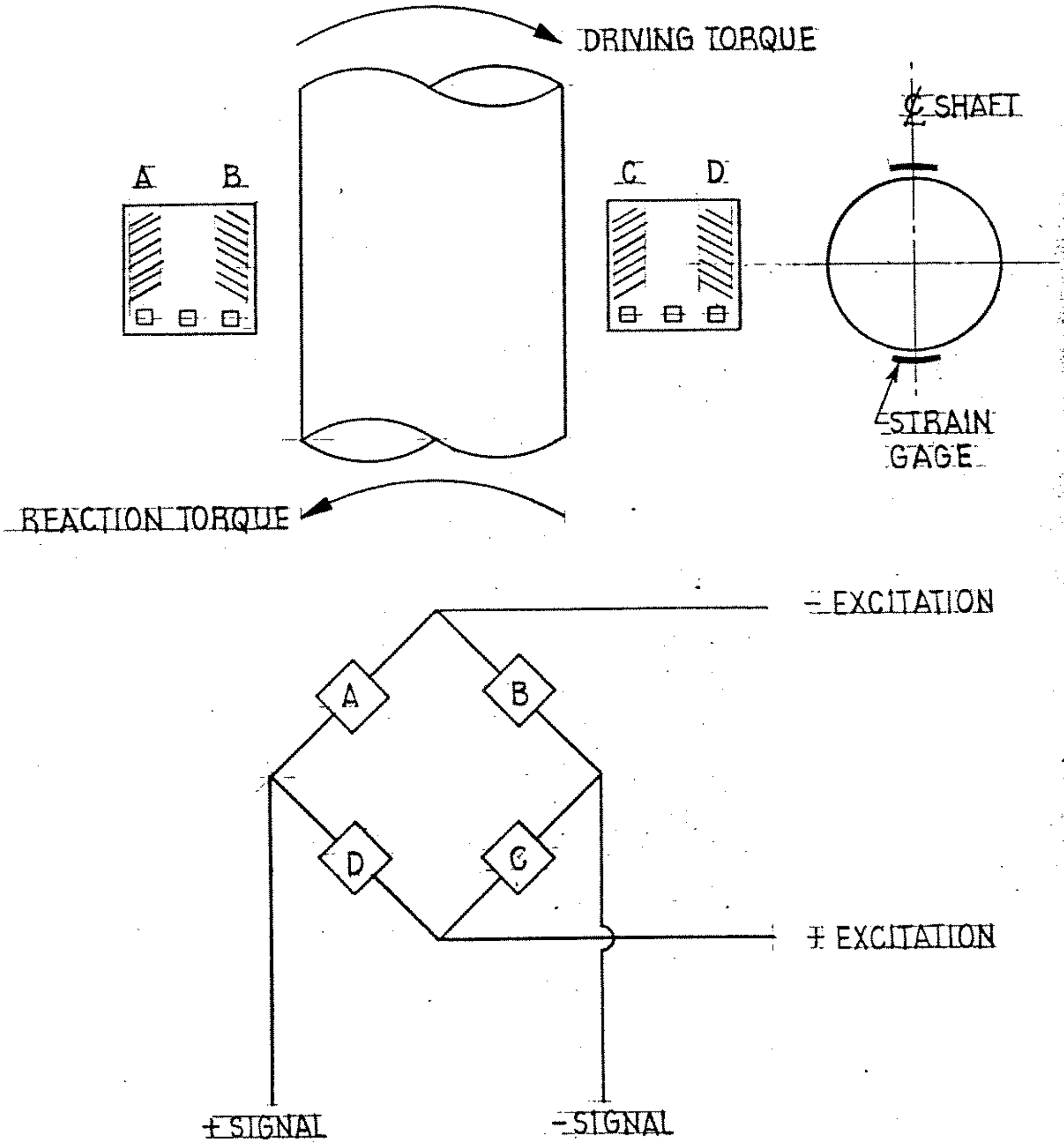


FIGURE 5. DATA ACQUISITION EQUIPMENT SCHEMATIC



STRAIN GAGE READINGS UNDER LOAD

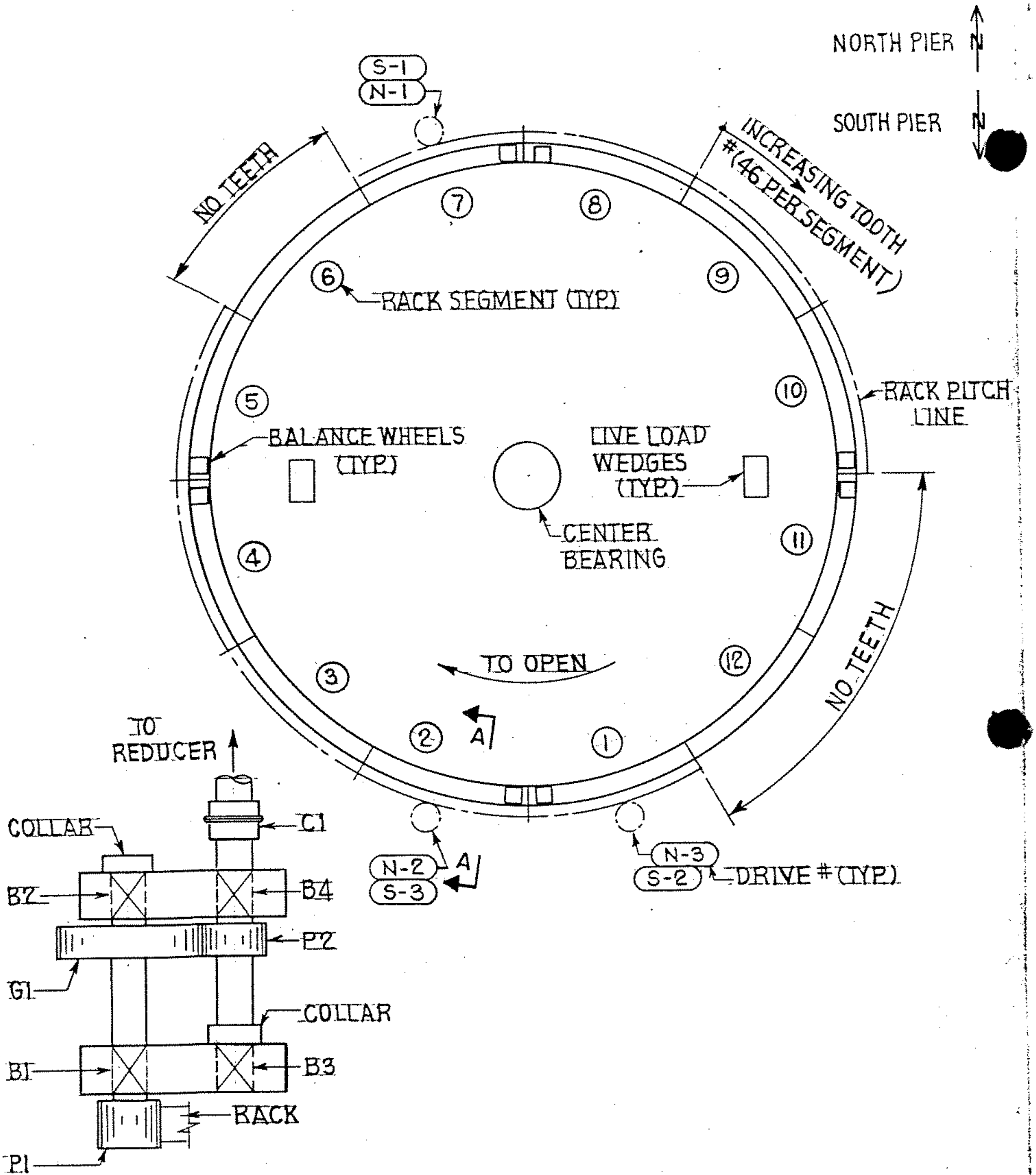
LOAD	A	B	C	D	BRIDGE STATE
TORQUE	+	−	+	−	UNBALANCED
BENDING	−	+	+	−	BALANCED*
SHEAR	+	−	−	+	BALANCED*

* SIGNS CHANGE AS SHAFT ROTATES, HOWEVER NET EFFECT ON BRIDGE IS TO REMAIN BALANCED

\+ DENOTES GAGE IN TENSION

− DENOTES GAGE IN COMPRESSION

FIGURE 4. STRAIN GAGE INSTALLATION TO MEASURE TORQUE



ELEVATION A-A

FIGURE 3. GENERAL ARRANGEMENT AT PIER TOP

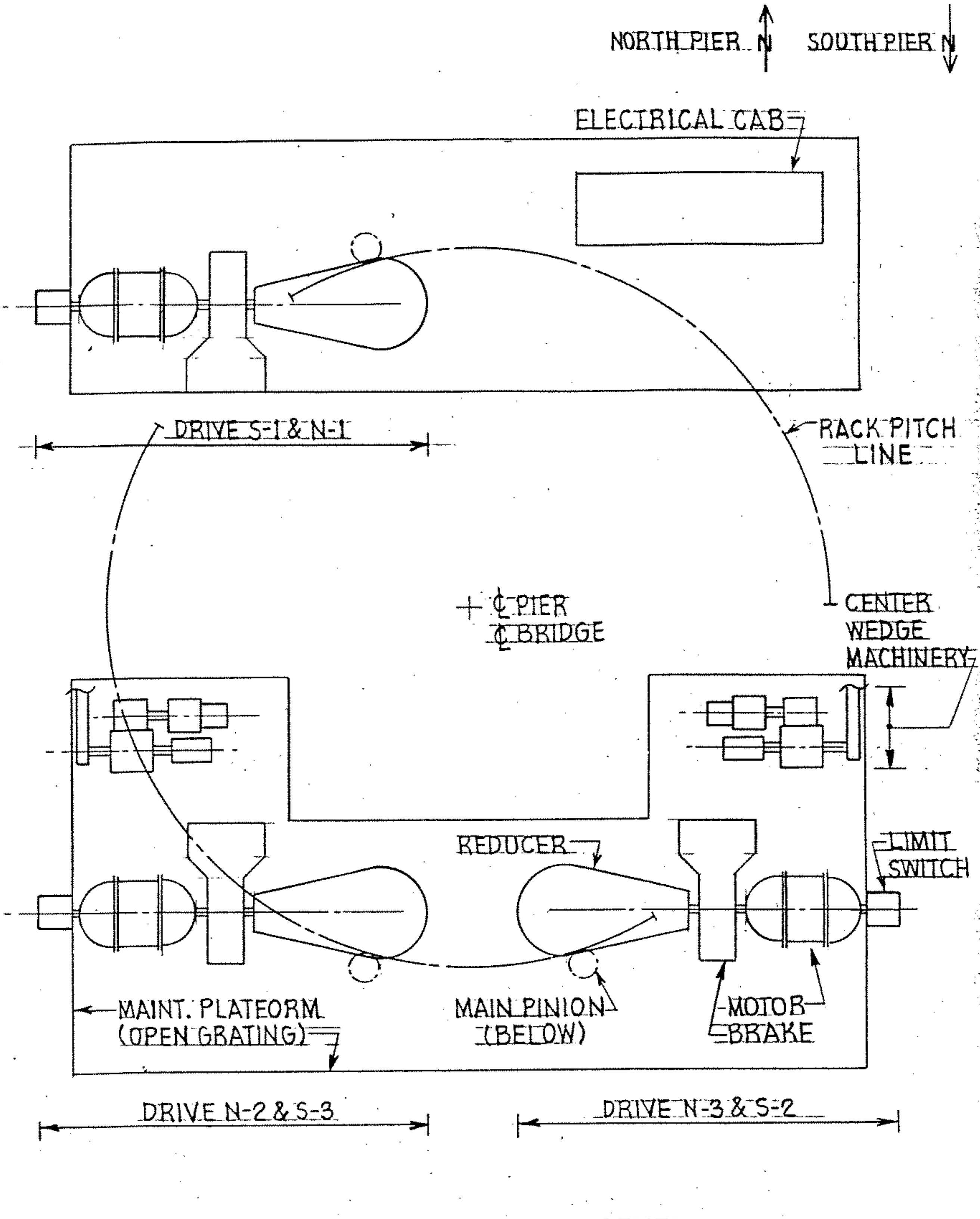


FIGURE 2. GENERAL ARRANGEMENT AT MACHINERY PLATFORM