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"Load Sharing of Vertical Lift Machinery"

by

Jeff Newman, P.E., Modjeski and Masters, Inc.

The Use of Load Sharing Devices for Tower Drive Vertical Lift Bridges

Jeffrey W. Newman, P.E.
Modjeski and Masters, Inc.
Harrisburg, Pennsylvania

INTRODUCTION

Whether you are designing a new vertical lift bridge or rehabilitating an old vertical lift bridge, proper design depends on knowing the loads for each component. The ideal condition is for the loads to be evenly shared between the drive pinions. This paper addresses concerns for the designer and owner regarding the possible lack of load sharing of drive pinions for tower drive vertical lift bridges. In particular, two railroad bridges shall be discussed that are relatively long and narrow. Therefore, design guidelines that are referenced shall be limited to the current AREA Manual for Railway Engineering.

TRADITIONAL DESIGN

Traditionally, tower drive vertical lift spans have been designed to operate without active differentials. The unstated assumption is that load sharing will occur due to lack of rigidity or independence of each corner of the lift span. Some lift spans do have differentials that are used solely for transverse leveling during seating, but are locked during all other span movement. In fact, AREA does not permit active differentials during span operation:

> AREA 6.5.36.7 states "......Equalizing devices shall not be used between pinions on opposite sides of the span, but adjusting devices shall be provided between such pinions, to permit transverse leveling of each end *(side)* of the span."

The problem is that each corner of the lift span is not independent, and there is some degree of rigidity, especially in the transverse direction. If all corners of a lift span operated independently, all four corners would tend to easily achieve firm contact during seating. However, vertical lift bridges frequently need to be adjusted to obtain firm seating at all four corners. Therefore, AREA requires the aforementioned adjusting devices. Traditionally, this lack of independence has been ignored in design and serious overloads can be experienced as a result.

CASE 1

The first case is a tower drive vertical lift that is 366 feet long and 20 feet wide (center-to-center of trusses). Each tower drive utilizes a 40 HP AC motor that is coupled to a double reduction enclosed gearbox. Each of the low speed shaft extensions drive through a clutch (adjusting device), floating shaft, and finally couple to a drive pinion that engages the sheave ring gear (see Figure 1).

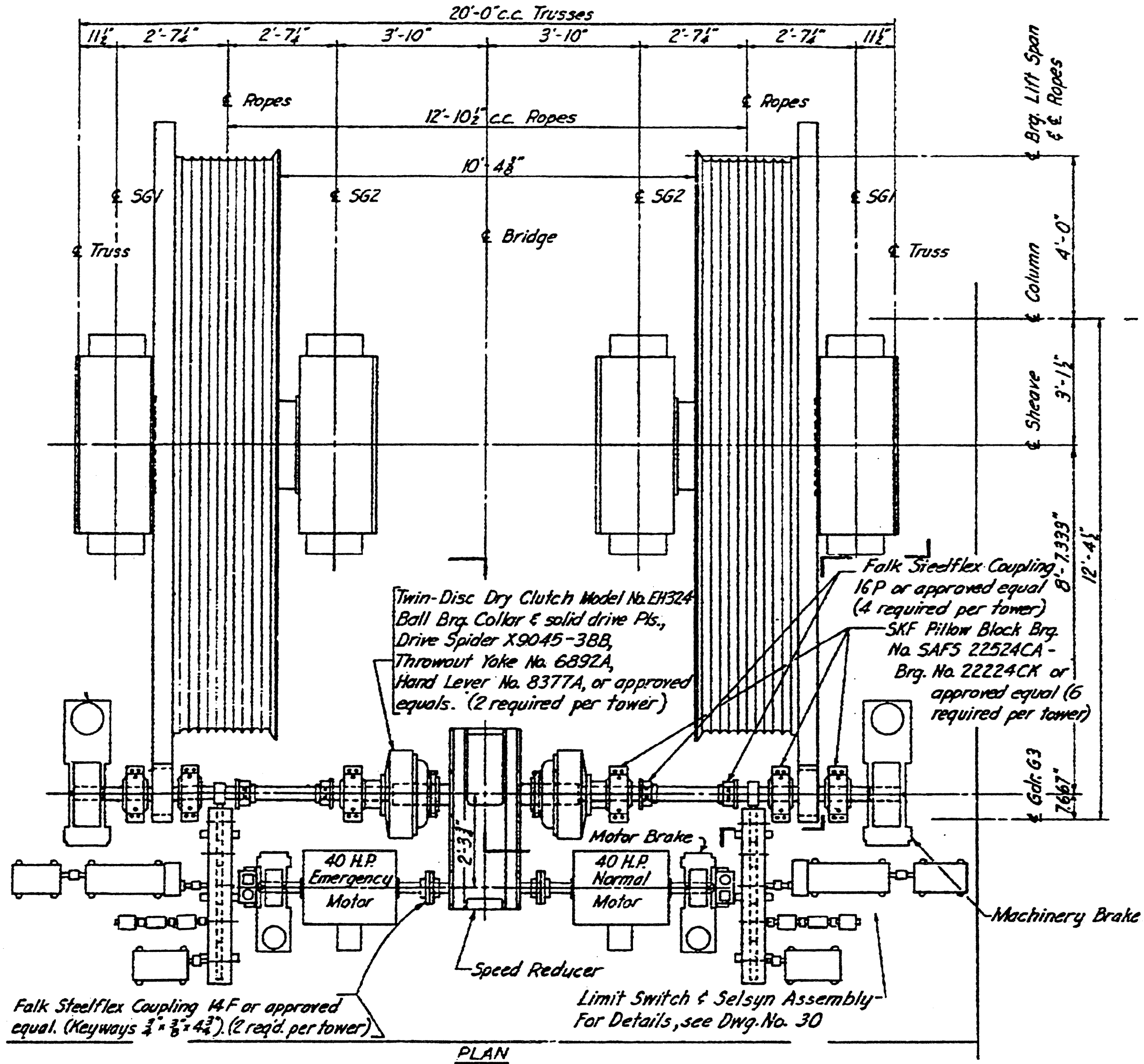

Figure 1: Machinery Layout for Case 1

As can be seen, the counterweight ropes are very close transversely (12'-10 ½" center-to-center) due to the width of the bridge.

The movable span was put into operation in 1971 and did not experience any significant problems until 1992, at which time the northwest pinion shaft failed (See Photo 1 and Figure 2). After replacement of the northwest pinion shaft, the southwest pinon shaft was removed for examination (see Figure 2 and Photos 2 and 3). Photos 2 and 3 are of the southwest pinion shaft which displayed fractures emanating from two keyways and torsional distortion. A small gear (which showed no signs of distress) is mounted in this location which drives only electrical components such as; rotary cam limit switches, skew indicators, selsyn transmitters, and height indicators.

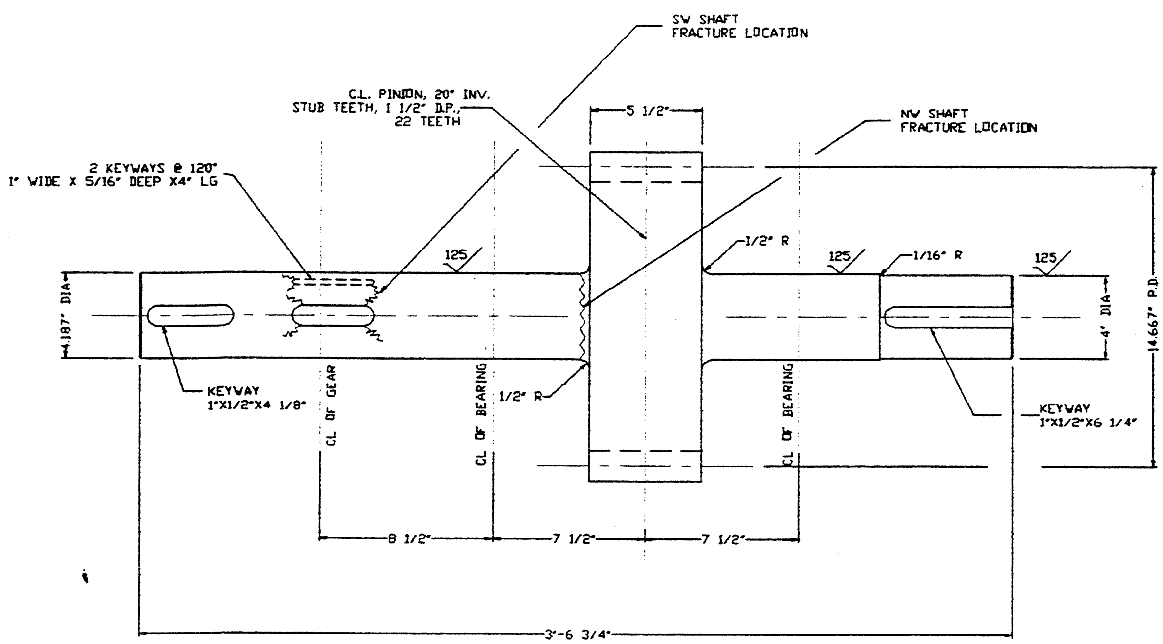

FIGURE 2: MAIN PINION SHAFT FRACTURE LOCATIONS

Detailed calculations were made in an attempt to determine the source of the fractures. First, the traditional design loading was checked to verify compliance with AREA. Then, analyses were performed to determine the loads required to produce keyslot distortion, fatigue cracks emanating from keyways, and fracture of the northwest pinion shaft at the pinion fillet radius. The results are summarized as follow:

1. Traditional Design Loading - Traditional design according to AREA would utilize 150% full load torque (electric motor is the prime mover) and normal braking forces at basic allowable stresses.

Motor: 40 HP, 600RPM (nominal), 5% to 8% slip
Reducer Ratio: 25.63:1 ratio
Pinion Shaft Material:
Steel Forging, Class C1 (Assumed to be the old ASTM A235, C1)
Equivalent is ASTM A668, Class C (S_{yt}=33 ksi, S_{ut}=66 ksi)

Rated Motor Torque: $T = \dfrac{5252*40HP}{570RPM} = 369lb-ft$ (100% FLT)

Torque to Each Pinion (assuming load sharing):

$$Tp_{100} = \frac{369*25.63}{2shafts} = 4{,}729lb-ft \text{ at 100\% FLT}$$

$$Tp_{150} = 4729*1.5 = 7{,}093lb-ft \text{ at 150\% FLT (AREA design load)}$$

$$Tb = \frac{2*400*25.63}{2shafts} = 10{,}250lb-ft \text{ (AREA braking load)}$$

2. Keyslot Distortion of the Southwest Pinion Shaft - The distortion was obviously due to torsional yielding of the shaft. Calculations showed that 23,000 lb-ft of torque was required to produce torsional yielding, (equal to 485% of rated motor torque if the pinions load shared).

3. Fatigue Cracks at the Ends of Keyslots on the Southwest Pinion Shaft - A fatigue analysis was performed that included the effects of stress concentration factors at the roots of the keyslots. As previously noted, the keyslots are for a small pinion that has little load and induced bending would be negligible. Therefore, the fatigue analysis concentrated on fluctuating torsional loading. The results showed that repeated torsional loads from zero to 10,420 lb-ft for one million cycles would be required to produce fatigue fracture (equal to 220% of rated motor torque if the pinions load shared).

4. Fatigue Fracture of Northwest Pinon Shaft at Pinion Shaft Fillet - This section of the shaft experienced bending stress reversal cycles (from separating forces between pinion and ring gear) and fluctuating torsional loading. Fatigue analysis indicated that cyclical torsional loading of zero to 11,800 lb-ft would be required for one million cycles to produce fatigue failure (equal to 250% of rated motor torque if the pinions load shared).

From the analysis performed, it appeared that consistently high overloads (at or above 250% of rated motor torque) would be required to produce the fatigue fractures and failures. While this seemed unlikely, it seemed nearly impossible to experience a motor overload of 485% to produce the yielding of the southwest pinion shaft. The best way to determine the actual torsional loads was to strain gage the pinion shafts.

Strain gaging was performed and revealed the torsional loads and distribution of loads to the northwest and southwest pinion shafts. The northwest shaft was assuming all of the positive torque (driving torque required to lift the span) and the southwest shaft was transmitting all of the negative torque (driving torque required to close the span). The pinions were not load sharing at all (see Figure 3). This resulted in all of the motor torque being transmitted to one of the pinion shafts at a time, which effectively doubled the normal design loads (see Figure 4). In addition to relatively high mean torsion during the opening cycle, excessive torsion was repeatedly experienced in the northwest pinion shaft during the start of opening and at the nearly closed slowdown. The southwest pinion shaft experienced relatively low mean torsion, but experienced high overloads during the nearly open slowdown, the start of closing, and during seating. The lack of load sharing resulted in stresses that exceeded the endurance limit stresses and resulted in fatigue fracture. Extremely high overloads were experienced by the southwest shaft during seating which were probably responsible for the torsional yielding.

There are three primary reasons for the high overloads experienced on this bridge and these are given here for consideration:

1. Pinions Not Properly Indexed - Inspection showed that the northwest and southwest pinions were poorly indexed. Even though the operating system was installed with two adjustment clutches per tower, they were apparently never utilized. Both clutches were frozen in the engaged position. It required over eight hours and use of some custom-made pancake jacks to disengage just one of the adjustment clutches.

2. Poor Pinion Mesh - The pinion and ring gear meshes were found to have excessive and unequal backlash.

3. Rigidity of Span - If all corners of the span acted independently, indexing and pinion alignment would have little effect on load distribution during span movement. However, long bridges that are narrow have very high rigidity transversely.

Of the reasons listed above, items 1 and 2 are relatively simple to correct. The owner must make certain to include proper pinion indexing into regularly scheduled maintenance. Pinion and ring gear meshes should be carefully checked during installation and should be verified during regularly scheduled machinery inspections. Item 3 is a function of the overall bridge design and cannot be modified, but why is this of concern if pinion indexing and mesh are acceptable? The answer is similar to the reasons for having load sharing devices (such as differentials) on other types of bridges (bascules and swing spans). Even with a good starting point, pinions can quickly loose their indexing due to pitch variations in gearing, eccentricity of the ring gear, variations in counterweight sheave diameters, counterweight rope slippage (especially if the span live loads are not properly shimmed), or slippage of the indexing mechanism. In Case II, we will consider what was done (inadvertently) to ensure load sharing regardless of span rigidity.

CASE II

This tower drive vertical lift bridge is over 500 feet long and only 27 feet wide. The drive machinery utilizes a locking differential which disengages and allows the differential to be active during seating, but is to be engaged (locked) during all other span movement. Originally, the differentials for this bridge were locked using a linkage that is actuated with a heavy weight. The clutch was designed to be released only when a thruster would lift the weight and operate the linkage. However, during inspection of the lift span in 1984, it was noted that the locking clutches for the differentials had been locked in the disengaged position and had not been used for several years. Even to this day, fourteen years later, the differentials remain unlocked. This lift span is quite active and has had no report of significant mechanical problems related to the span drive machinery.

It is unknown when and why the differentials were unlocked on this bridge. Perhaps problems similar to those described in Case I were occurring. The end result is that the pinions will load share equally as long as the differential remains active.

Conclusions

1. Owners of existing tower drive vertical lift bridges should make pinion indexing a part of regularly scheduled maintenance.

2. Pinion and ring gear meshes should be checked for proper installation (including equal and acceptable backlash) during initial installation and during routine inspections.

3. Perform strain gaging to determine if load sharing is occurring and establish the operating and peak loading to each pinion shaft. This can be included as an additional item when performing strain gage balancing.

4. Carefully inspect shafting (especially at keyways and changes in diameter), couplings (open for internal examination), and gearing for signs of distress and cracks.

5. The AREMA should consider allowing use of active differentials on long bridges that are narrow. Criteria should be established as to when active differentials can and should be used for tower drive vertical lift bridges. (Highway bridges tend to be much less rigid transversely and therefore active differentials may not be appropriate for use).

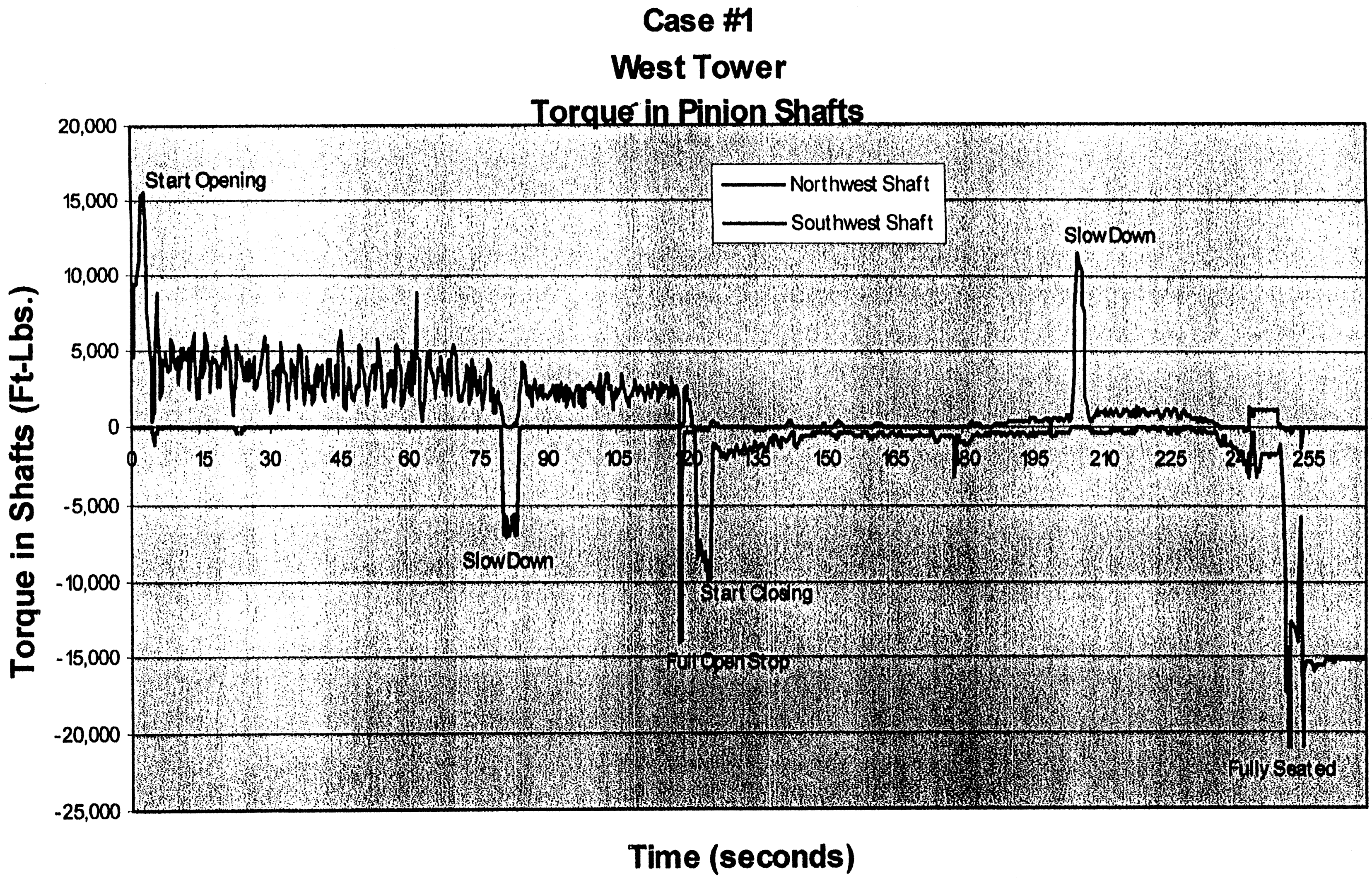

FIGURE 3 - PINION SHAFT TORSION DURING SPAN OPERATION

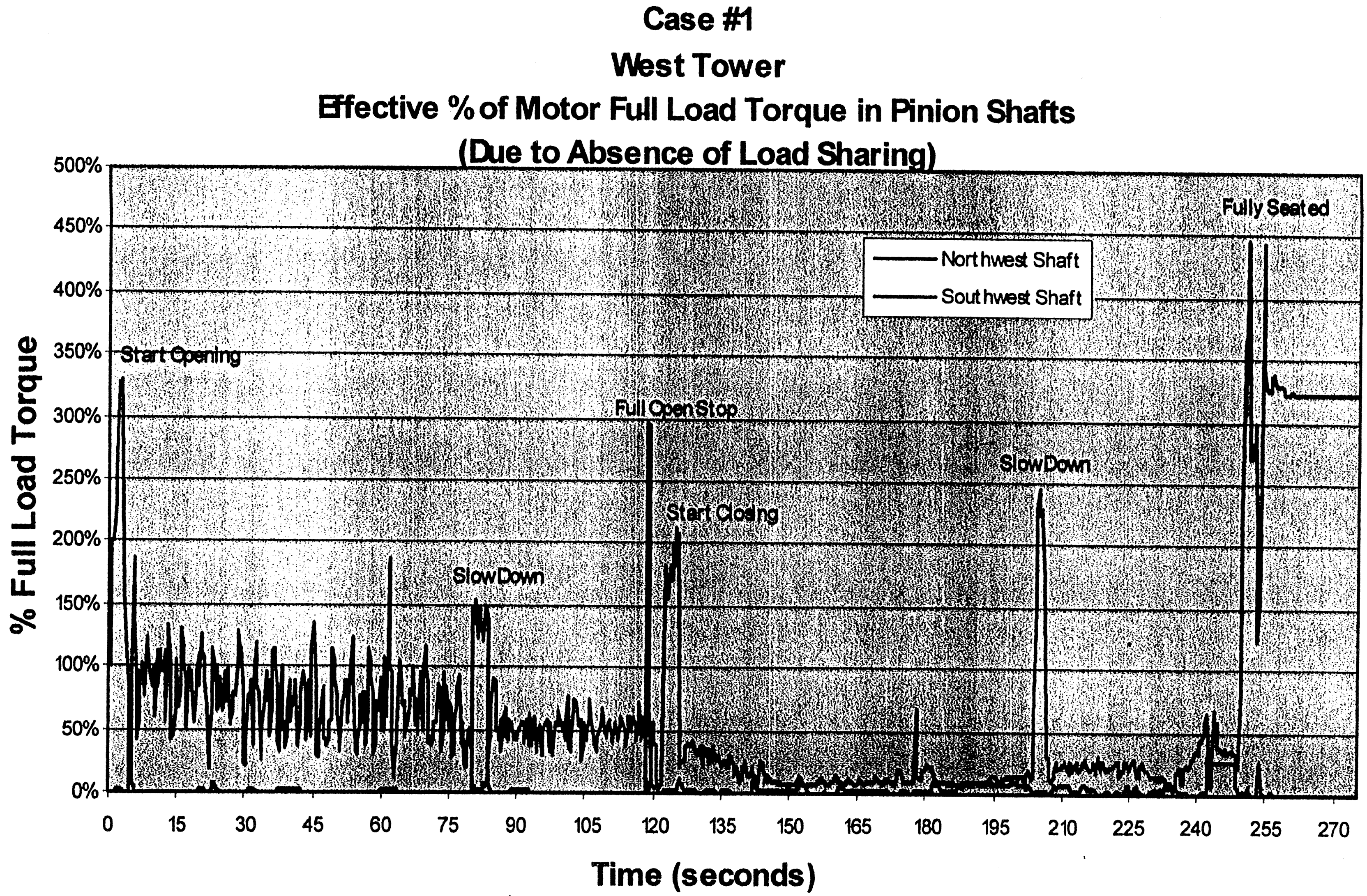

FIGURE 4 - EFFECTIVE %FULL LOAD TORQUE TO EACH PINION SHAFT

PHOTOGRAPHS

BRIDGE: **CASE 1**

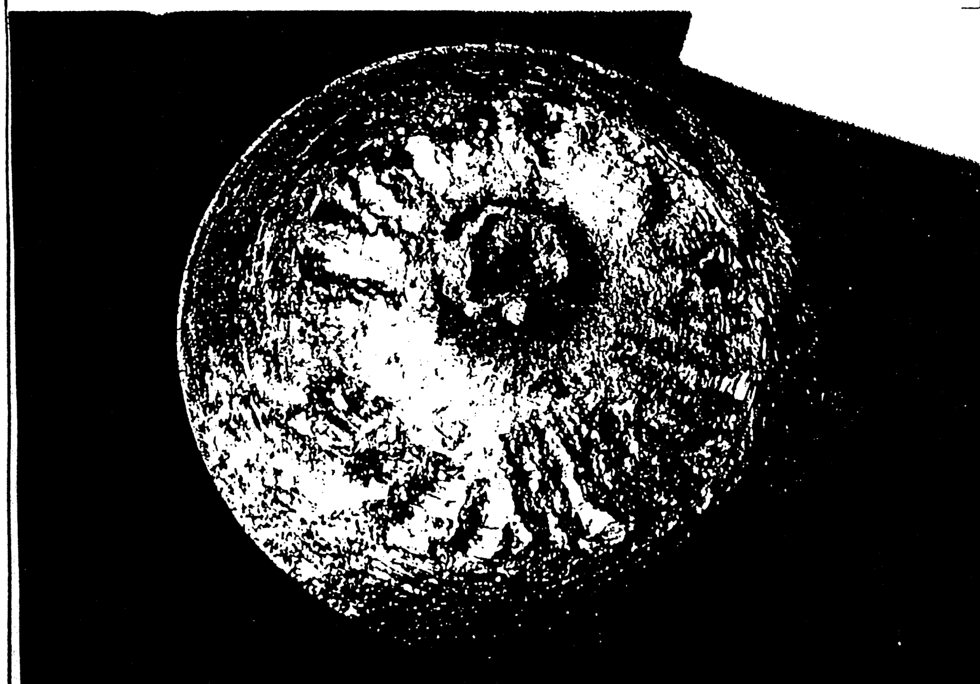

PHOTO NO. 1

Northwest pinion shaft fatigue failure. Indicates classic bending fatigue failure of a rotating shaft.

PHOTO NO. 2

Southwest pinion shaft fatigue cracks emanating from keyslots at approximately 45 degree angles. This is indicative of torsional shear fatigue.

PHOTOGRAPHS

BRIDGE: **CASE 1**

PHOTO NO. 3

Southwest pinion shaft keyway distortion from torsional yielding.

PHOTO NO. 4

Pinions were realigned using new bearings and new pinion shafts. The frozen adjustment clutches were removed and new floating shafts installed using keyless locking assemblies for future indexing.