Investigation of Rack and Pinion Alignment of the Cass Street Movable Bridge in Joliet, Illinois

Christopher Hahin, P.E.
Engineer of Bridge Investigations

Physical Research Report No.129

July, 1998

Limited Distribution Document

Distribution of this report is limited to all DOTs and other transportation officials and consultants in its present form, and copies may be obtained upon written permission of District One of the Illinois Department of Transportation.

Illinois Department of Transportation
Bureau of Materials and Physical Research
126 East Ash Street / Springfield, Illinois / 62704-4766

Technical Report Documentation Page

1. Report No. FHWA/IL/PRR-129	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle INVESTIGATION OF RACK AND PINION ALIGNMENT OF THE CASS ST. MOVABLE BRIDGE IN JOLIET, ILLINOIS		5. Report Date June, 1998
		6. Performing Organization Code
7. Author(s) Christopher Hahin, PE		8. Performing Organization Report No. PRR-129
9. Performing Organization Name and Address Illinois Department of Transportation Bureau of Materials & Physical Research 126 E. Ash St. Springfield, IL 62704		10. Work Unit (TRAIS)
		11. Contract or Grant No. HR-25-104-98-1
12. Sponsoring Agency Name and Address Illinois Department of Transportation Bureau of Materials & Physical Research Springfield, IL 62704		13. Type of Report and Period Covered Final Report, November, 1997 to May, 1998
		14. Sponsoring Agency Code

15. Supplementary Notes
This report is prepared in cooperation with District One, Illinois Department of Transportation.

16. Abstract

EXECUTIVE SUMMARY

The Cass St. Bridge is a rolling lift bascule bridge that spans the DesPlaines River, which divides the City of Joliet. The bridge has an average daily traffic (ADT) of 15,500 vehicles/day, and experiences approximately 2,000 lifts per year for commercial barges and casino boats. The racks and pinions, which are essential elements of the drive mechanism for lifting and closure of the bridge, have experienced severe wear in recent months due to misalignment. Wear is ascribed to minor track non-parallelism, insufficient pinion bearing collar bolting, and high rack and pinion tooth loadings. Rack tooth loadings at bridge opening are twice the AASHTO allowable tooth loadings.

This report describes the non-standard stub teeth used in the original 1931 design and the retrofit of 1986, the verification of rack and track alignment by survey and gravity methods, and recommendations for realignment. Recommendations include: (1) exchanging unused rearward rack elements with worn forward elements; (2) leveling rack elements; (3) repositioning pinion bearing collars; (4) determining clearances and alignment reference marks and dimensions for final positioning and future monitoring; (5) future modification to shrink-fit the pinion gear bearing to the existing built-up structural plates instead of reliance on a small bolted collar; and (6) increasing rack face width.

17. Key Words Bridges; Movable Bridges; Bascule Bridges; Rack and Pinion; Misalignment; Wear; Involute Stub Tooth; 20° Pressure Angle	18. Distribution Statement *Limited to all DOTs and other transportation officials and consultants upon written request.*

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	*Unclassified*		

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

TABLE OF CONTENTS

FOREWORD

This report can be of interest to engineers, consultants, designers, planners, inspectors and other technical personnel who are concerned with the performance, durability and maintenance of movable bridges.

NOTICES

The contents of this report reflect the views of the author who is responsible for the analysis of facts and data presented herein. The contents do not necessarily reflect the official views or policy of the Illinois Department of Transportation (IDOT). This report does not constitute a standard, specification, or regulation.

The State of Illinois does not endorse products or manufacturers. Trade or manufacturer names appear herein solely because they are considered essential to the object of this report.

ACKNOWLEDGMENTS

The author gratefully acknowledges the support of IDOT District One and the technical assistance of Edward Kramarz, James Tabor and Sara Wilson of the Bureau of Maintenance, and Michael Schechtman and Rodney Richgruber of the Bureau of Land Acquisition, and the review by Jeffrey South of IDOT Bureau of Materials and Physical Research. The advice of John Ehret, consulting mechanical engineer, and Gary Bish of Horsburgh & Scott, is also appreciated.

LIST OF FIGURES AND TABLES

BACKGROUND

The Cass St. Bridge is rolling-lift bascule that spans 174 ft over the DesPlaines River, which divides the City of Joliet. The Cass St. Bridge is a significant bridge, acting as a central artery conveying traffic from the east side of the DesPlaines River to the western portion of Joliet. The bridge has an ADT of 15,500 vehicles per day and an estimated ADTT of 1500 vehicles per day. The bridge must have the capability to open upon short notice by radio due to the heavy barge traffic and the movement of casino boats, and experiences approximately 2,000 lifts per year.

a. General Design. The design of the Cass St. Bridge is similar to the other rolling-lift bascule bridges over the DesPlaines River in Joliet, consisting of a span and counterweight rolling on the supporting tracks resting on the bridge abutments. The counterweight is attached to a semi-circular tread plate structure, and virtually balances the span. ***Figures 1*** and ***2*** are elevation views of the bridge. ***Figure 3*** shows the relative locations of racks, tracks and anchorages.

b. Drive Mechanism. In the center of this semicircle are the pinion gears, driven by gear trains and two 50 hp motors. Each motor operates at 460V / 3 phase at 870 rpm. Since the center of a cylinder rolling on a flat plane translates along a straight line, the stationary rack teeth serve as anchor points for the pinion gears to force the nearly-balanced span to lift. Each rack consists of 4 segments. Rear and forward segments have 17 teeth; the two middle segments have 16 teeth each. Because the bridge is span-heavy by 2% or less, minimal force is required to close the bridge.

c. Repairs. The racks and pinions of this bridge have previously experienced wear problems and misalignment. In 1963, the main pinion shafts and bearings were replaced by American Bridge. In 1985-6, all racks and pinions and shafting were replaced, along with all gears, brakes and tracks. Segmental tread castings were replaced by a single socketed tread plate. By 1997, movement in the main pinion collar bearings was noted on all sides of the bridge. The collars were welded into place on the west side of the bridge, which exhibited the least amount of misalignment. The northeast rack segment particularly sustained severe wear after bolts were retightened.

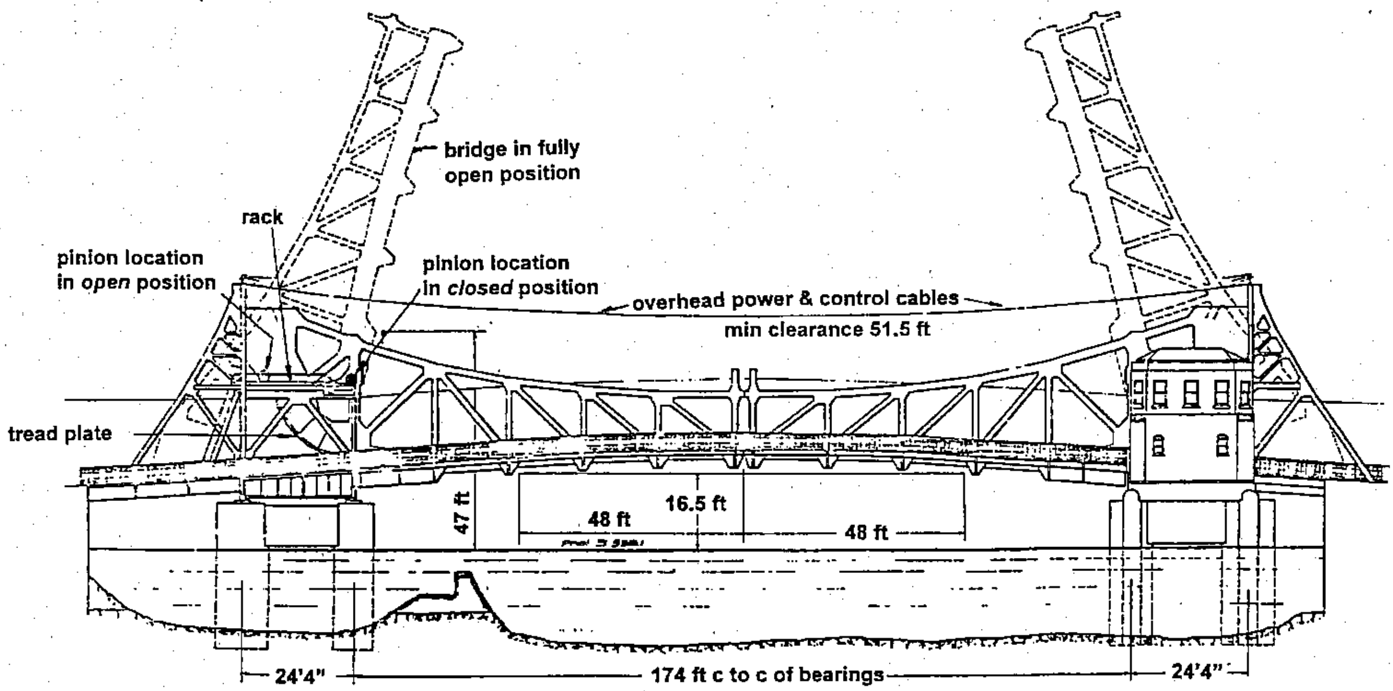


Figure 1. Elevation view of the Cass St. Bridge over the DesPlaines River, Joliet, Illinois, showing general lift span dimensions and overall geometry. Locations of the pinion on the fixed rack in the open and closed positions are shown. Adapted from original 1931 plans.

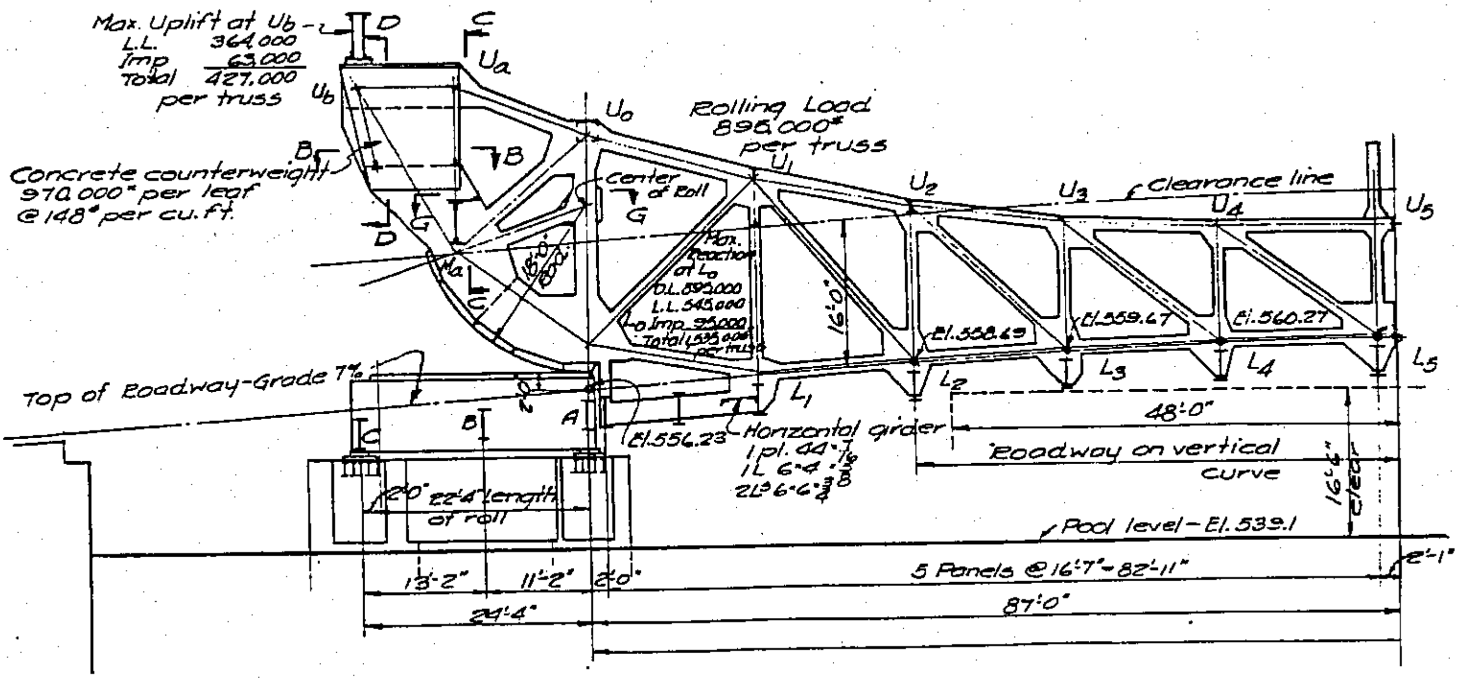


Figure 2. Sectional view of the Cass St. Bridge rolling lift bridge, showing counterweight, tracks, tread and 1/2 span. Adapted from original 1931 plans.

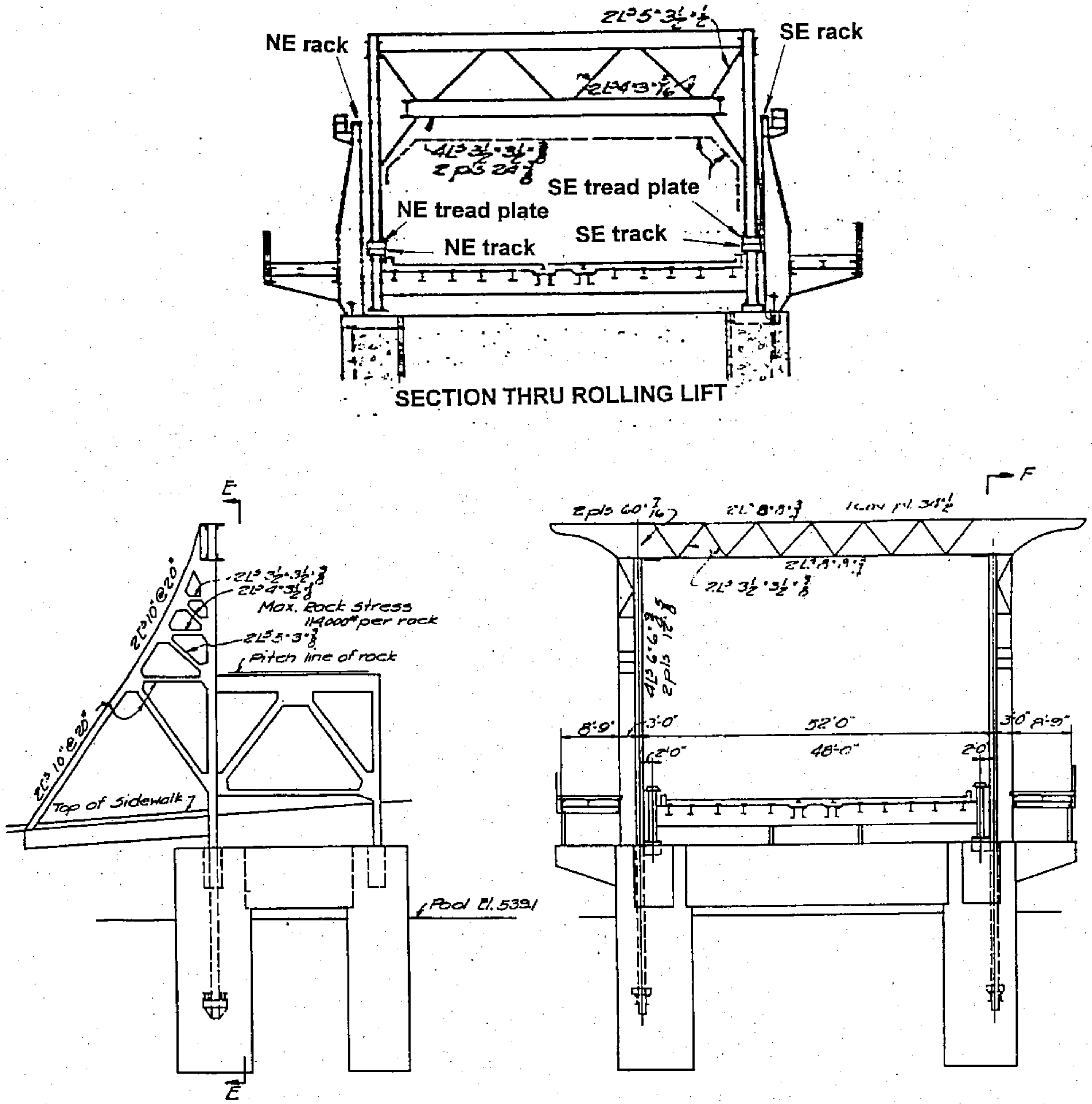


Figure 3. Rack and track supports and anchorages, and respective locations of tread plates, racks and tracks on the abutment end of the Cass St. Bridge. Adapted from 1931 plans.

GENERAL CONDITIONS

Based on the wear pattern as shown in *Figure 4*, the pinion is not correctly aligned with respect to the rack. Pinion orientation changed after the shims used in the retrofit of 1985-6 had fallen out, because the bolt holes had enlarged and bolt preload had disssipated. The steel shims were C-shaped, and were not passively captured by use of any epoxy or silicone rubber sealants. The collar was bolted to a series of rough, hot-rolled structural plates. These plates were not machined flat, nor were they spot-faced (made flat only in area of contact), nor was the bearing collar apparently reworked during the 1986 retrofit. Coincident with the 1997 rack and pinion problems were center lock misfit problems. Subsequent work in late 1997 apparently corrected the center lock interference problem, but the rack wear problem still remains.

a. Abnormal Wear on Rack Teeth. The racks, particularly in the northeast corner of the bridge, have experienced abnormal wear after the pinion bushing collar bolts were replaced due to hole expansion and incidental bolt breakage in 1997. The west side collars were welded into place with capture plates. The west side racks have not experienced significant wear damage like the east side. Broken collar bolts on the east side were removed, replaced and tightened in late 1997. Afterwards, the northeast rack developed a grooved wear pattern developed on the forward rack elements within a few weeks, as shown in *Figure 4*.

b. Survey of Track Parallelism. The original structural plans of 1931 and the retrofit plans of 1984 call for tread plate sockets to be oversized in diameter by 0.250" to accommodate grease and debris on the tracks. This means that the tread plate could deviate from a straight line by ±0.250". Grinding marks from tread plate sockets against several track button teeth confirm this deviated travel of the tread plate.

Several surveys of the parallelism of the NE and SE tracks were performed by District 1 surveyors. The first survey used a very accurate transit and several fixed USGS monuments located nearby the bridge as references. The transit used was a Geodometer Model 600 (manufactured by Geotronics AB, Danderyd, Sweden), which

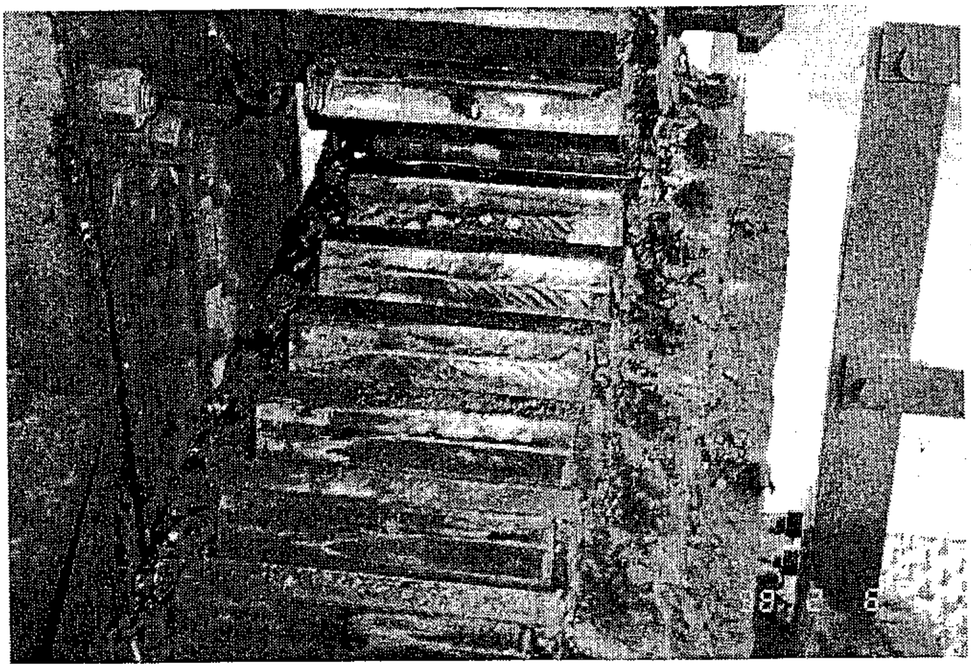


Figure 4. Wear pattern on the northeast forward (river side) rack segment which sustained the greatest wear pattern. Pattern indicates poor tooth contact and pinion misalignment.

has an angular accuracy of ±1 second (±0.0003°). Initial readings indicated significant deviations in the placement of the track alignment buttons, but the survey measurements were often impeded by structural details associated with the inherent design of the bridge. Because of the distance of these monuments from the tracks, these measurements were considered as doubtful and unreliable.

A second and more direct survey of the eastern tracks revealed several anomalies. The Geodometer Model 600 instrument was placed on its tripod and centered directly over the center of the SE corner track bolt. Track button teeth are tapered cylinders set in bored holes and anchored down with a 1"-8UNC center bolt. From this corner position, the direct linearity and spacing of the track buttons could be measured, as well as SE and NE track parallelism. After measurements were made on the SE track, the transit was placed over the NE corner bolt where specific angles were measured for the SE track buttons. See *Figure 5* for transit placement on the bridge tracks and how angles were turned.

c. Survey Results. Key results are summarized in *Table 1.* The track survey indicates that the buttons were set in a straight line, with their centers deviating from linearity by no more than 2 mm. Spacing between each button center hole should be 16.75"; however, measurable variances in spacing were found. The range of spacing error for the NE track was +0.032" to -0.089"; for the SE track, +0.031" to +0.119". The maximum amount of shift of 0.121" can be accommodated by the 0.250" oversizing of the tread plate sockets.

Although individual track linearity and button spacings were satisfactory, track lines were not parallel and buttons lacked proper correspondence. The NE button line was shifted toward the river by 0.659". This was confirmed by setting the SE track button line as a reference, and then turning the transit sight by 90.000°. It was found that the opposite button was not at 90°, but off by approximately 0.06°. Although 0.06° appears to be insignificant, this angle is over a distance of 576", resulting in a riverside displacement of 0.659", which exceeds the oversized socket hole accommodation of 0.250". Moreover, it skews the entire leaf span slightly, partially accounting for the center lock misfit.

Table 1

Spacing Errors in Track Buttons

track button number	required angle, degrees	required distance, inches	actual angle SE track	actual distance SE track	spacing error SE track	actual angle NE track	actual distance NE track	spacing error NE track
1	0.0000	0.00"	0.0000	0.000"	---	0.0656	0.659	+0.659
2	1.6657	16.75	1.6705	16.798	+0.048	1.7239	17.336	-0.074
3	3.3286	33.50	3.3369	33.584	+0.084	3.3892	34.112	-0.054
4	4.9858	50.25	4.9966	50.359	+0.109	5.0486	50.886	-0.033
5	6.6348	67.00	6.6378	67.031	+0.031	6.6989	67.653	-0.019
6	8.2728	83.75	8.2816	83.840	+0.090	8.3358	84.397	-0.031
7	9.8973	100.50	9.9055	100.585	+0.085	9.9664	101.216	+0.032
8	11.5059	117.25	11.5133	117.328	+0.078	11.5023	117.213	-0.037
9	13.0963	134.00	13.1075	134.119	+0.119	13.0879	133.911	-0.089
10	14.6664	150.75	14.6758	150.851	+0.101	14.6615	150.697	-0.053

Lastly, a 100 ft tape in 0.01' increments was stretched across both ends of the NE and SE tracks. The width dimension should be 48' = 576"; however, the riverside dimension was 576.12" and the shoreside was 576.48". Dimensional variations from design geometry are shown in ***Figure 6.***

The oversized tread socket holes generate an inherent misalignment of 0.051°, based on 0.250" lateral deviation over 280.5" of rack length. The difference in width of 0.36" from 576.12" to 576.48" adds another potential 0.074° of misalignment along the rack's long axis (the Z-axis). These dimensional variations could cause a cumulative potential misalignment of 0.125° along the Z-axis.

The riverside displacement of the track buttons by 0.659" results in misalignment along the long axis of the pinion (the X-axis). Over 576" of track width, this can cause a misalignment of 0.066°. At the NE rack, a cumulative angular misalignment of [0.051° + 0.074° + 0.066°] = 0.191° is theoretically possible, but 0.164° misalignment is more probable because of tread socket oversize. Even when mating spur gears of significant size and coarse pitch, such misalignment is clearly undesirable. These inherent design and construction misalignments must be rectified in future track and rack modifications.

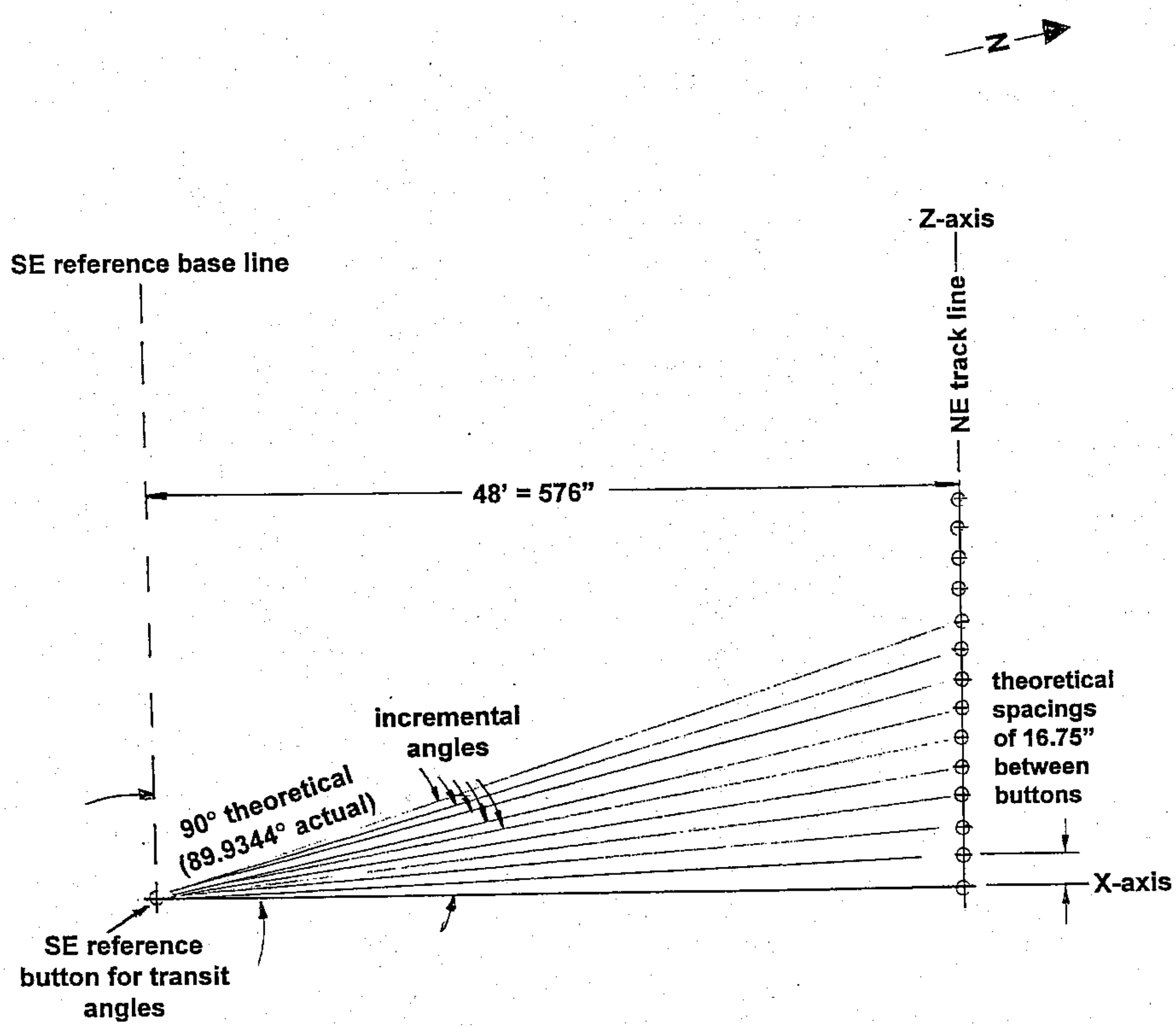


Figure 5. A Geodometer Model 600 transit accurate to 1 second was centered over the SE corner button tooth bolt and angles turned for respective buttons on the opposite track. Procedure was reversed on the NE corner bolt. Linearity of SE and NE bolt lines was also measured. Average deviation from a straight line was approximately 2 mm.

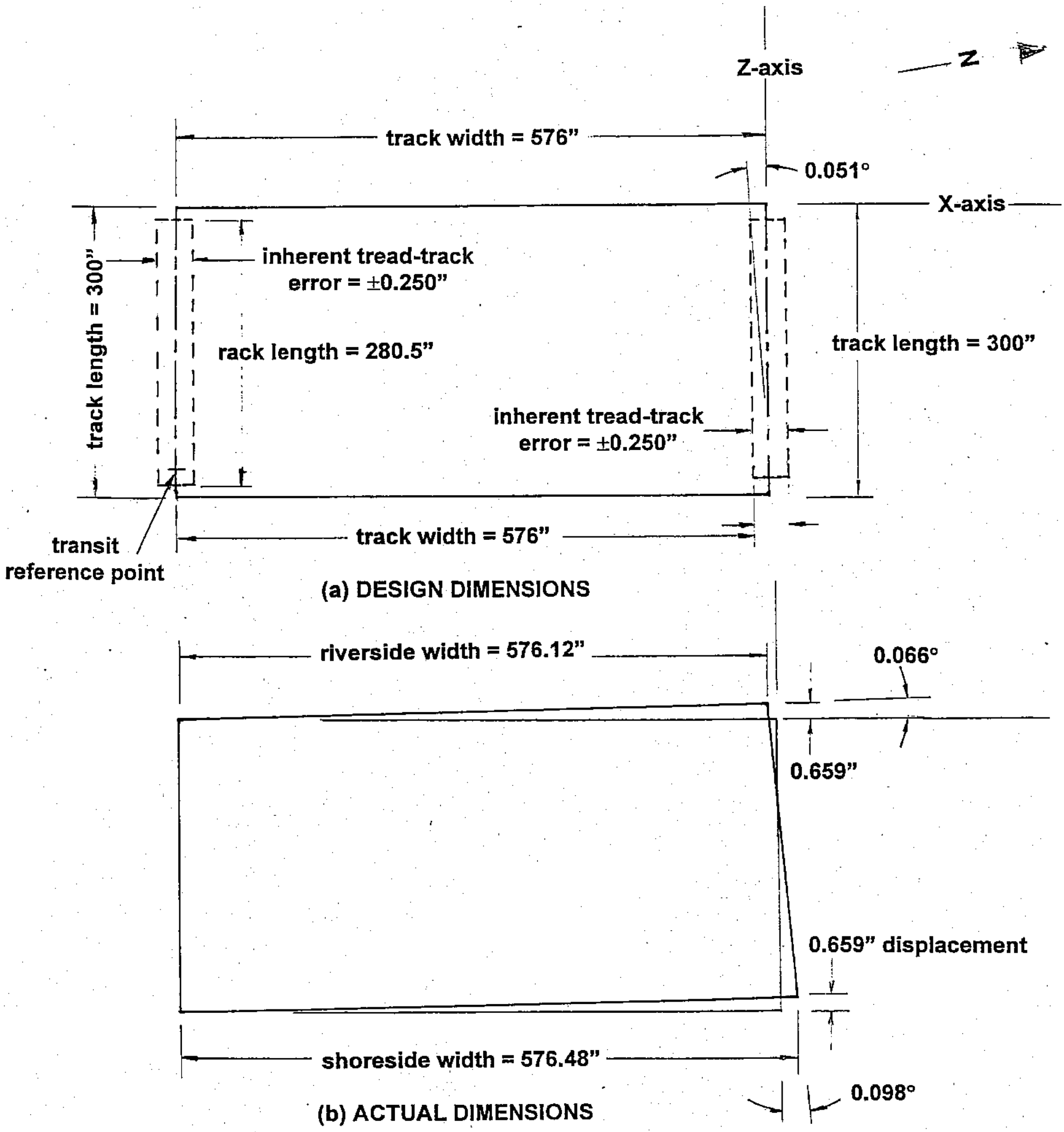
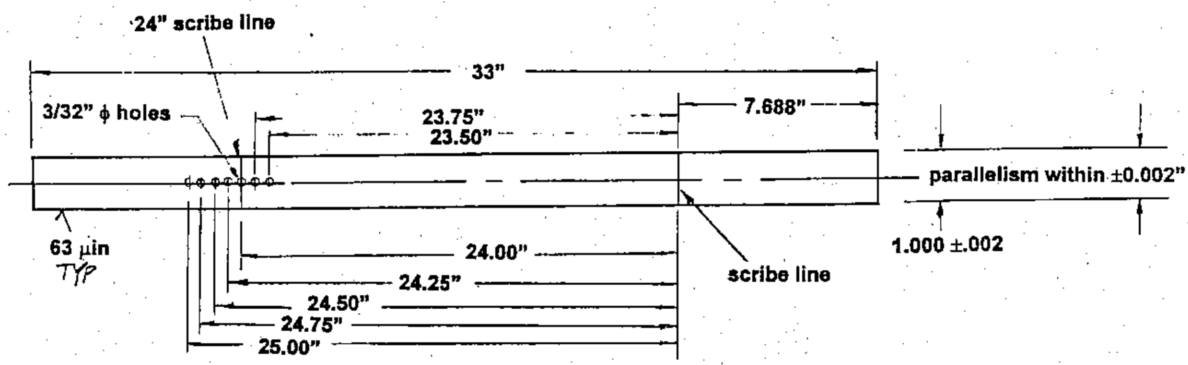


Figure 6. Design dimensions for the track (a) are compared with actual dimensions as measured by direct survey (b). Scale of distortion in (b) is greatly magnified for effect. Because of the oversize of the tread sockets by 0.250", the tread can deviate from true linearity by ±0.250".

d. Parallelism of Racks and Tracks. A third survey was performed to check the parallelism of the track with respect to the upper rack. Measurements were made by use of a flat, calibrated bar with a small hole drilled exactly 24.00" from the center line of the rack plate, as shown in ***Figure 7.*** With this offset, the bar was clamped to the rack base plate, and aligned with the rack center line. A line was then sent through the drilled hole which held a heavy plumb bob. The accuracy of a plumb line in still air is approximately ±0.015". The measurements indicated that the eastern side track was offset 24.00" ±0.125" from the rack center line. Plumb bob measurements on the rearward portions of the northeast and southeast tracks were within 0.125" of the center line of the track plate.

However, measurements of the 24" offset on the river side of the track proved to be difficult. First, there was no means of attaching the calibrated bar to the rack, since the supporting base plate for the rack terminates flush with the forward rack element. Even after clamping the offset bar to the rack, structural elements on the bascule span interfered with the drop of the plumb line. In addition, traffic must be halted to obtain this measurement. Because the riverside measurement was not made, an extension bar should fastened to the track to make this measurement in the future.

e. Levelness of Rack. Several rack elements were checked for levelness with a standard 24" construction spirit level. Common construction levels do not have the defined accuracies associated with master precision levels, but they do give relative indications of general construction tolerances. Measurements on the NE rack indicated a slight upward tilt of the rack toward the river, which accounts for variations in the clearance dimension between the rack bottom land and the pinion tooth during its travel.



PLUMB LINE OFFSET BAR

Material: **AISI 12L14 cold drawn 1" square bar**

Figure 7. Dimensions of the calibrated offset bar used in the gravity method to verify the required rack-to-track offset of 24 inches.

PINION BEARING COLLAR STRESSES

The pinion bearing collar is fastened to a series of built-up plates with 1 1/8" nominal diameter turned bolts. The magnitude of stresses in the collar holes, bolts and bolt holes are significant determinants of rack and pinion durability for the Cass St. Bridge.

a. **Bolt Preload and Stresses.** The abnormal wear on the rack began when the pinion bearing collar bolts lost a portion of their preload. Afterwards both shear and tensile forces displaced and fatigued the bolts. The failure of the collars to remain in rigid plate contact is caused by (1) bolt eccentricity; (2) plate and casting roughness; (3) no apparent torque specification; (4) use of built-up plates; and (5) the massive size of the pinion shaft, bearing and bushing compared to the collar and bolts. As the collar and structural plate begin to separate, bending moments and shear forces are transferred through bolts instead of directly through the collar to the structural plates.

Maintenance of bolt preload on a series of built-up plates is often difficult, particularly if the plates are not entirely flat. A 12.75" ID x 23.5" OD bushing with a collar has a moment of inertia of 13,674 in^4. In contrast, a bolt circle consisting of six 1.125" diameter bolts has a moment of inertia that is only 5% of the bushing collar. The maintenance of bolt preload and an excellent mating surface between the collar and plates is critical to structural integrity of the connection. Adding non-captive shims further compounded the problem.

b. Maximum Pinion and Rack Tooth Loadings. According to the calculations of Donohue Engineers in 1984, a maximum applied moment of 167,000 ft-lbs is required to raise the bridge, which occurs when the bridge is fully closed. This is because the bridge is span-heavy so it will naturally close without benefit of power. In turn, this causes the highest pinion and rack teeth loadings to be sustained by the first rack segment when opening the bridge.

The pinion pitch circle has a diameter of 18.94", which results in a torque radius of 9.47" (0.789 ft). The approximate force required to raise each bascule leaf is 211,660 lbs. Assuming this force to be equally distributed by two pinions, this results in 105,830 lbs of load shared per pinion. The original 1931 plans cited a maximum tooth loading of 114,000 lbs per pinion. The 1984 retrofit reduced maximum loadings by only 7%.

c. Nominal Shear Stresses on Bolts. The unconcentrated shear stresses on six collar bolts are substantial, but are within AASHTO allowable stresses for high strength bolts per Table 10.32.3B of AASHTO *Standard Specifications for Highway Bridges* [Reference 5]. Six 1.125" diameter bolts have a total area of 5.964 in^2. When these six bolts sustain 105,830 lbs of force, this results in a distributed shear stress of 17,700 psi. The allowable shear stress for ASTM A325 bolts in a shear plane is 19,000 psi.

d. Tensile Stresses on Bolt Holes. When a perforated cylinder rim is subjected to internal pressure, the bearing collar bolt holes surrounding the larger central hole are subjected to distortions and stress concentrations. The shear and bending forces on the pinion shaft bearing provide an analogous internal pressure. The bolts in the collar and the steel plate are lathe-turned-and-fitted to provide an ANSI B4.1 LC6 locational clearance fit. This close fit causes collar distortions to be primarily transferred to the first and second layer of structural plates, with distortion progressively decreasing in influence on the successive plates.

Stress concentrations in a perforated flange with internal pressure have been studied by Kraus (as summarized by Peterson) [Reference 6]. The graphical solution for the Cass St. Bridge conditions is shown in ***Figure 8***. For the Cass St. Bridge, the bolt hole radius r is 0.565", and the bolt circle radius R is 10.50", resulting in an r/R ratio of 0.54. For six bolts, the stress concentration factor K_t is about 2.5 in the collar bolt holes.

Uniformly distributing 105,830 lbs of force among six bolt holes results in 17,638 lbs/hole. If this force exerts pressure on one side of a 1.125" diameter hole of 1.5" depth, 23,455 psi bearing pressure results. Because of stress concentrations, peak stresses can potentially rise to 58,600 psi, which exceeds the probable yield strength of 35,000 psi for the casting and plates. Holes on the castings and plates for both Cass St.

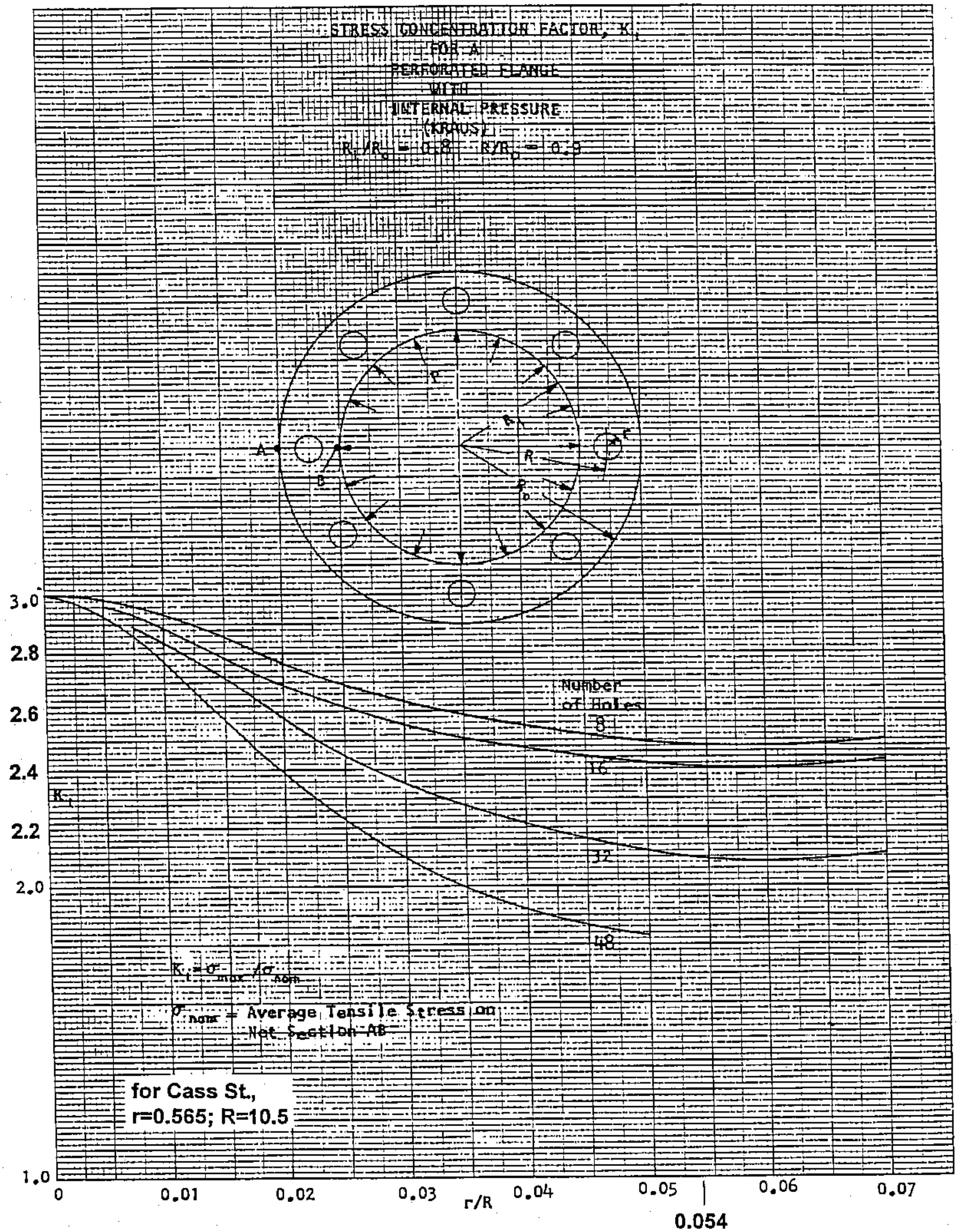


Figure 8. The graphical solution of Kraus for stress concentrations in a perforated flange with internal pressure. In the Cass St. Bridge pinion bearing, the shear and bending forces on the shaft provide the internal pressure. The K_t for 6 bolt holes was estimated as 2.5; and for 11 bolt holes, $K_t \cong 2.4$. Source: R. Petersen, *Stress Concentration Factors,* Wiley-Interscience, New York, 1974, p 192.

and Jefferson St. Bridges exhibited elongation when reworked in 1985-6. These holes were redrilled from their original diameters of 1.063" to 1.125" at that time. If the number of collar bolts were increased to 11 bolts, nominal bearing stress decreases to 12,800 psi. Stress concentration factor K_t drops slightly to 2.4. Peak bolt hole stresses also decline to 30,100 psi, which is slightly less than the probable casting or plate yield strength of 35,000 psi.

e. **Bending Stresses on Bolts.** The offset of the pinion gear as it mates with the rack causes a bending moment on the pinion shaft and the bearing collar. When the bearing collar is properly preloaded by bolting to the structural plates, nominal collar stresses are only 1,200 psi because of the high moment of inertia of the pinion bearing & bushing. However, when bolt preload dissipates, bolts start to absorb load transfer. The 21" bolt circle has a radius of 10.5", and with six 1.125" bolts, it has a moment of inertia of 658 in^4 by the parallel-axis theorem. The 105,830 lbs lifting force causes bending stresses of 25,300 psi in the bolts. Prying forces on the collar add an additional 21.5% of stress. Combined bending and prying stresses are 30,800 psi, which is well within the proof stress of 74,000 psi for an ASTM A325 bolt.

f. **Bolt Fatigue Life.** For bolts in tension to sustain 500,000 or more stress cycles, AASHTO *Standard Specifications for Highway Bridges* (Section 10.32.3.4) require that stress levels not exceed 27,000 psi. Based on 2,000 lifts per year, approximately 24,000 lifts (48,000 stress cycles) were sustained since 1986. Estimated stress range is about 30 ksi, with the mean stress depending on the preload present in the bolt. The estimated fatigue life available for a bolt subjected to a 30 ksi stress range from service load and prying action is between 20,000 to 500,000 cycles. Since only about 50,000 cycles were sustained before failure, it appears that concentrated stresses are present, and that force distribution is not uniform.

If the number of collar bolts is increased from 6 to 11, bending and prying forces decrease to safer levels. With 11 bolts, cyclic tensile stresses are estimated to be 16,900 psi, which is substantially less than the 27,500 psi AASHTO limitation for 500,000 or more cycles of available fatigue life under normal conditions.

GEAR MESH

Proper mesh of the rack with the pinion is a function of alignment and positioning, and of the inherent compatibility of the tooth forms. The correct meshing of the pinion with the rack is essential to the solution of the problem, since an abnormal mesh will result in poor load transfer, clashing and premature wear due to point load concentrations and high tooth contact stresses. With the lower yield strength materials as called for in the Earle Industries and Donohue Engineers plans submitted in 1984, high Hertzian contact stresses resulted in grooving, galling and minor pitting. The wear problem was not abated with the liberal application of greases containing molybdenum disulfide.

a. Tooth Contact. Tooth contact between the face of the pinion gear and the rack was not proper. The pinion gear shaft was skewed, and was not perfectly level. This condition apparently developed after the C-shaped shims lost their preload and fell out after bolt loosening or breakage.

The orientation of the X, Y and Z axes for the rack and pinion are shown in ***Figure 9.*** The observed wear pattern appears to indicate that the pinion shafting axis is tilted with respect to the X-axis, and is also rotated a few degrees, placing the pinion's transverse plane out of alignment with respect to the Z-axis.

The pinion alignment may have been reasonably close after the retrofit work of 1986. However, continual lifting and closure of the bridge has resulted in a change in load transfer pathways. Proper load transfer should be from the collar to the structural plate. Due to loss of bolt preload and hole expansion, load transfer has shifted from the collar bolts to the structural plates they bear against. Because of lack of spot-facing on the bearing collar, there is a high probability that the bolts were eccentrically loaded. Spot-facing is a machining procedure to locally flatten the areas of direct contact, such as at collar, bolt, washer or nut contact surfaces. Moreover, the 1984 plans had no burr relief specified for the bolt holes in the structural plates. Burr relief attenuates localized stress concentrations under a tightened bolt head.

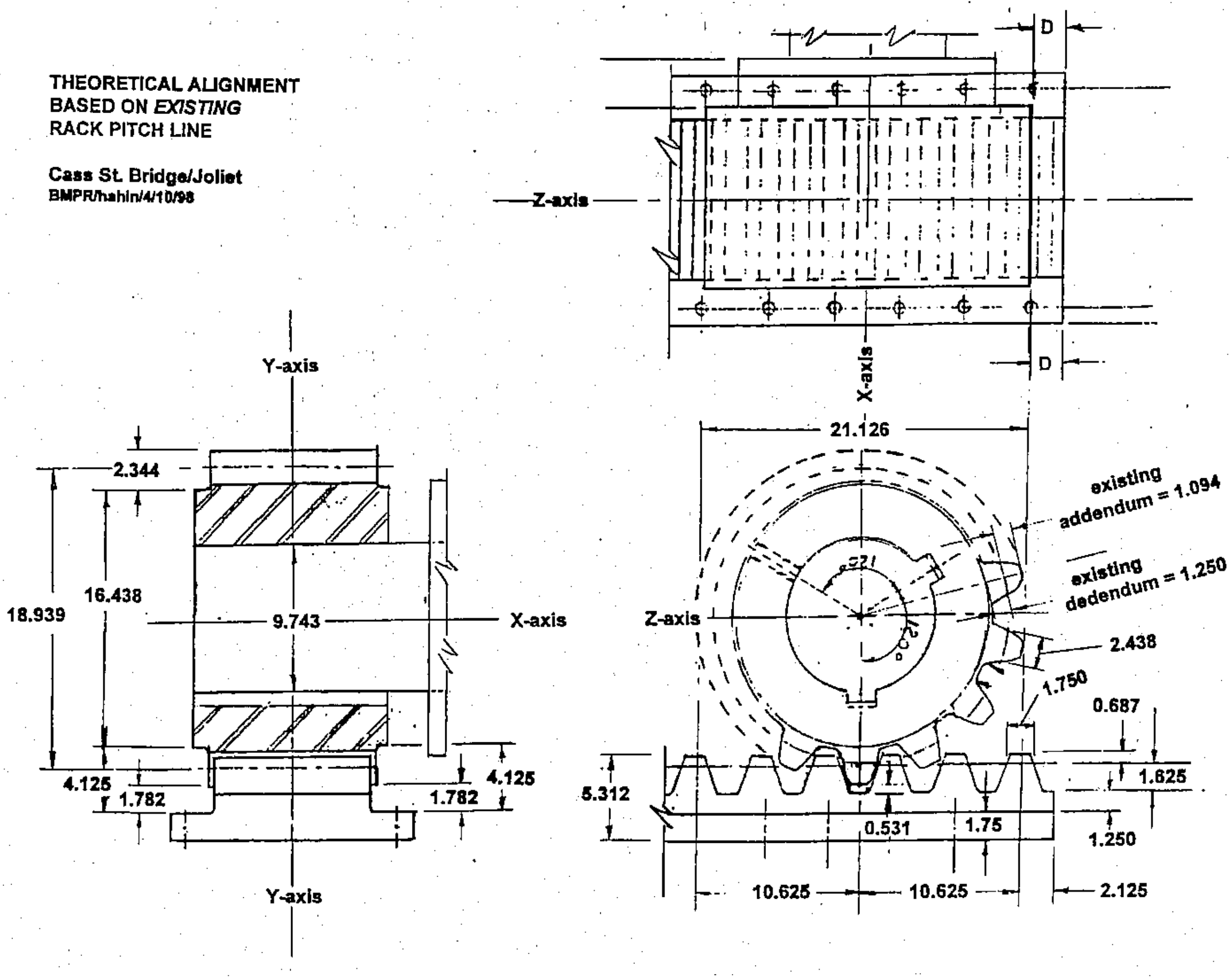


Figure 9. Orientation of the X, Y and Z-axes for alignment of the pinion and levelness of the rack, and other general dimensions. Reference dimensions are the clearance between the rack and pinion teeth; rack pitch line and pinion pitch line alignment; levelness of the pinion, and "D" distance equality on both sides of the rack and pinion.

The 9.75" diameter pinion shaft is so massive in comparison to the collar bolts that they cannot effectively transfer loads if misalignment is present. After the alignment shims fell out, replacement bolts were refitted in 1997. However, the pinion was seriously out of alignment and abnormal wear resulted in a short period of time.

b. Non-Standard Tooth Geometry. Establishing a pinion alignment procedure was complicated by the non-standard nature of the rack system. This investigator discussed the rack & pinion tooth dimensions with Mr. John Ehret, a mechanical engineering consultant, and with Mr. Gary Bish, Manager of Gear Engineering, Horsburgh and Scott, the manufacturer of the gears replaced in 1986. The rack and pinion at Cass St. is a variant of the 20° involute stub tooth system. The pinion teeth were presumably increased in thickness to compensate for wear, since a pinion typically undergoes far more revolutions than individual segments of a rack. However, the greatest amount of pinion gear travel on this bridge is largely confined to the first three rack segments. The greatest forces are applied to the first rack segment. The rack teeth on this bridge also have thinner dimensions at the pitch line, increasing the probability of tooth damage, seizure or breakage at overload.

Current plans indicate that the rack & pinion is a "special" 20° involute stub tooth, as were the original 1931 plans. When compared with the American Gear Manufacturer's Association (AGMA) formula dimensions for a standard 20° involute stub tooth system, the pitch lines and addendums for a 4.25" circular pitch obtained from the Earle Industries and Donohue Engineers drawings are definitely non-standard. Comparisons between standard teeth and the "special" 20° involute stub teeth shown on drawings are summarized in ***Table 2.*** The retrofit of 1986 simply duplicated the 1931 shift of a standard pitch line location upwards to compensate for the oversized pinion teeth, which are 0.313" thicker at the addendum. Normally, both rack and pinion stub teeth would be 2.065" to 2.095" thick at the pitch line.

The 14-tooth pinion gear also has a very low tooth contact ratio of 1.12 with the rack because of its coarse diametral pitch of 0.735. The normal contact ratio for this gear should be 1.3 to 1.4 per recommendations of *Machinery's Handbook*. No change was made was to increase the 10" face of the rack or helical gears, which would have decreased overall tooth contact stresses when the rack and pinion are properly meshed.

Table 2

AGMA Standard Stub Tooth Dimensions
Compared to Cass St. Bridge Rack & Pinion Drawing Dimensions*

Dimension Description	AGMA Standard Formula	Standard Dimension	Pinion Dimension	Rack Dimension
addendum	a = 0.2546 p	1.082	1.094	0.688
dedendum, min	b = 0.3183 p	1.353	1.250	1.625
working depth	h_k = 0.5052 p	2.164	2.344	2.313
basic tooth thickness at pitch line**	t = 0.500 p	2.125**	2.438	1.750
clearance, min	c = 0.0637 p	0.271	-------	0.531
backlash, AGMA range	per AGMA tables	0.040-0.060	oversized	0.062

*This table compares the AGMA 20° Involute Stub Tooth System for a 4.25" Circular Pitch with the Cass St. Bridge rack and pinion dimensions cited from Earle Industries and Donohue Engineers drawings.
**Does not include backlash.
p = circular pitch.

c. Comparison with Standard Involute Stub Tooth Geometry. Because the Cass St. Bridge racks and pinions have a non-standard involute tooth form, the actual gear manufacturer, Horsburgh and Scott, of Cleveland, Ohio, was contacted for their advice on gear form and intermesh of the rack and pinion. Simultaneously, actual tooth thicknesses were measured with a tooth thickness vernier accurate to 0.001" (Benson Vernier, Model 10-1 DP, of Bradford, UK). Comparisons of thickness obtained from the Horsburgh & Scott computerized gear program dimensions with the actual pinion and rack dimensions are made in ***Table 3***.

As shown in ***Table 3***, the actual tooth dimensions compared with a standard 20° involute show a decrease in thickness at the tips of both rack and pinion teeth. This is beneficial because the actual pressure angle of the rack is 21.43°, resulting in a progressive widening of rack teeth toward its dedendum.

Table 3

20° Involute Stub Teeth per Horsburgh & Scott Form vs. Actual Dimensions

depth from tip of tooth	Horsburgh & Scott calculated tooth thickness	actual mean tooth dimensions*	difference between actual vs. calculated dimensions
rack			
0.00	1.247	1.188	-0.059
0.20	1.393	1.365	-0.028
0.40	1.538	1.529	-0.009
0.60	1.684	1.679	-0.005
0.687 (addendum)	1.750	1.743	-0.007
0.80	1.829	1.825	-0.004
1.00	1.975	1.973	-0.002
1.10	2.048	2.052	+0.004
pinion			
0.00	1.546	1.513	-0.033
0.20	1.761	1.709	-0.052
0.40	1.953	1.897	-0.056
0.60	2.123	2.065	-0.058
0.80	2.268	2.215	-0.053
1.00	2.388	2.390	-0.047
1.094 (addendum)	2.437	2.390	-0.047
1.20	2.480	2.441	-0.039

*Based on measurements on different teeth from two racks and two pinions. Measurements varied by ±0.004".

The actual gear mesh at the pitch line, and at other locations below the rack's pitch line, along with actual tooth thicknesses, are shown in ***Figure 10.*** ***Table 4*** lists the estimated backlash of a pinion addendum with tooth thickness at 2.390" mated with the rack at or below the indicated rack pitch line of 0.687". ***Table 4*** shows that having a pinion tooth addendum dipping down to 0.765" will result in a backlash of 0.060", which is right at the outer limit of the 0.030-0.060" range of backlash for these gears per *Machinery's Handbook.* There is adequate tooth tip relief and ample backlash. If the pinion tooth addendum extends below the rack pitch line by as much as 0.060" to 0.063", there should be about 0.070" backlash still available, as shown in ***Figure 11.***

Table 4
Estimated Backlash Between Pinion Teeth and Rack Teeth*

location on rack tooth	pinion tooth thickness	rack tooth thickness at location	combined rack & pinion thickness	backlash
0.687 depth (at rack pitch line)	2.390	1.743	4.133	0.117
0.750 depth (0.063 below)	2.390	1.789	4.179	0.071
0.765 depth (0.079 below)	2.390	1.800	4.190	0.060
0.800 depth (0.113 below)	2.390	1.825	4.215	0.035

*This table is based on a circular pitch of 4.250", and the pinion addendum extending downward below the marked pitch line at 0.687". Backlash range recommended per *Machinery's Handbook* is 0.030" to 0.060" for most coarse pitch gears.

d. Pinion Materials. The pinion material is an AASHTO M102 Class D forging and is suitably matched in terms of nominal mechanical properties with the AASHTO M103 Grade 70-36 (ASTM A27) casting used for the rack. An AASHTO M102 Class D forged pinion has a wide permissible range of hardness (149 to 207 Brinell Hardness Number [BHN]), whereas an AASHTO M103 casting has no specified BHN range. There is no specification as to whether test bars should be taken from casting risers or runners, or if they should be separately cast test bars. The materials selected for the pinion and rack have hardnesses that are somewhat lower in comparison to most gears that operate at higher speeds and greater contact pressures. However, the forged pinion should have considerable toughness at lower temperatures, although quenched & tempered alloys with higher hardness could have been selected. Wear patterns developed in the rack are consistent with the softer character of an ASTM A27 Grade 70-36 casting.

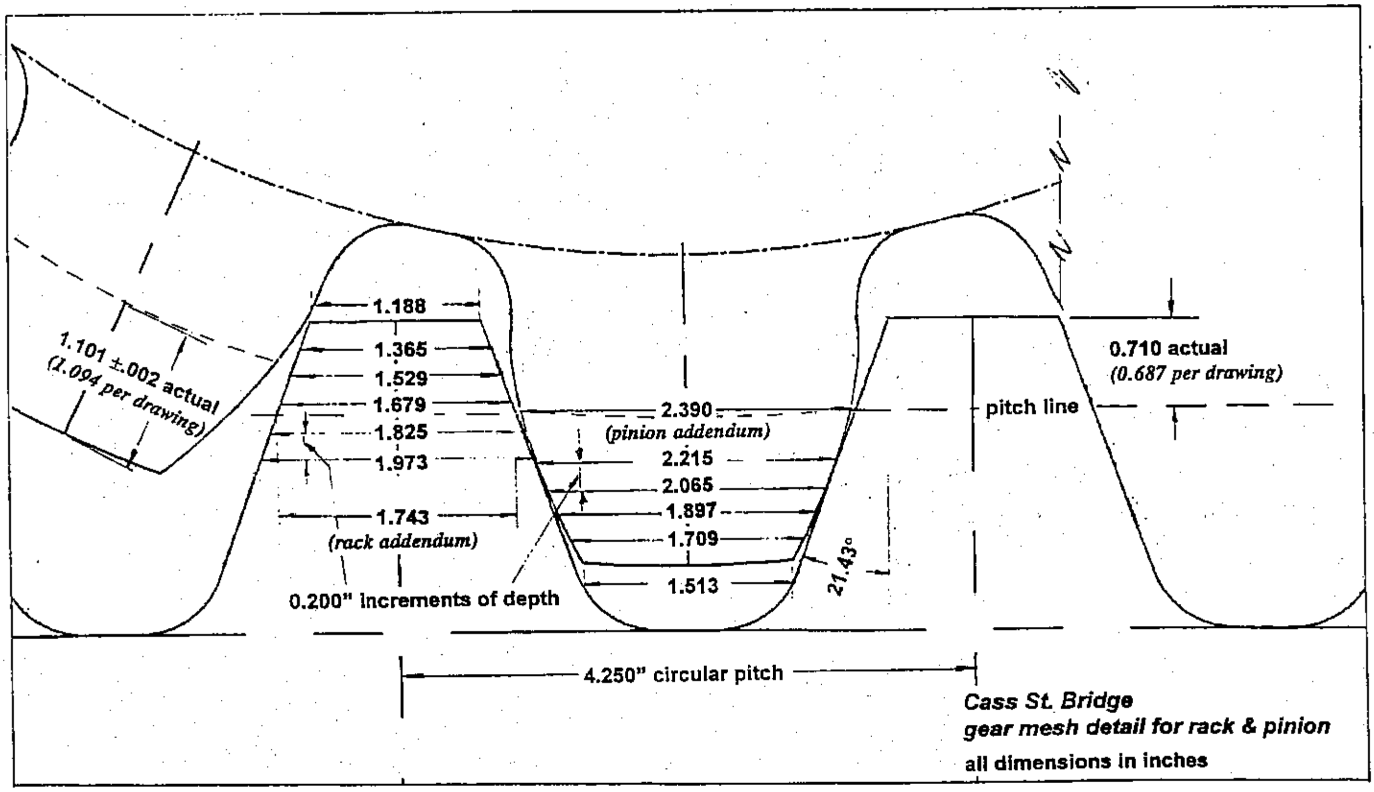


Figure 10. Actual gear mesh at the original design pitch line, showing actual dimensions taken by a tooth thickness vernier of the racks and pinions retrofitted in 1986 at various depths.

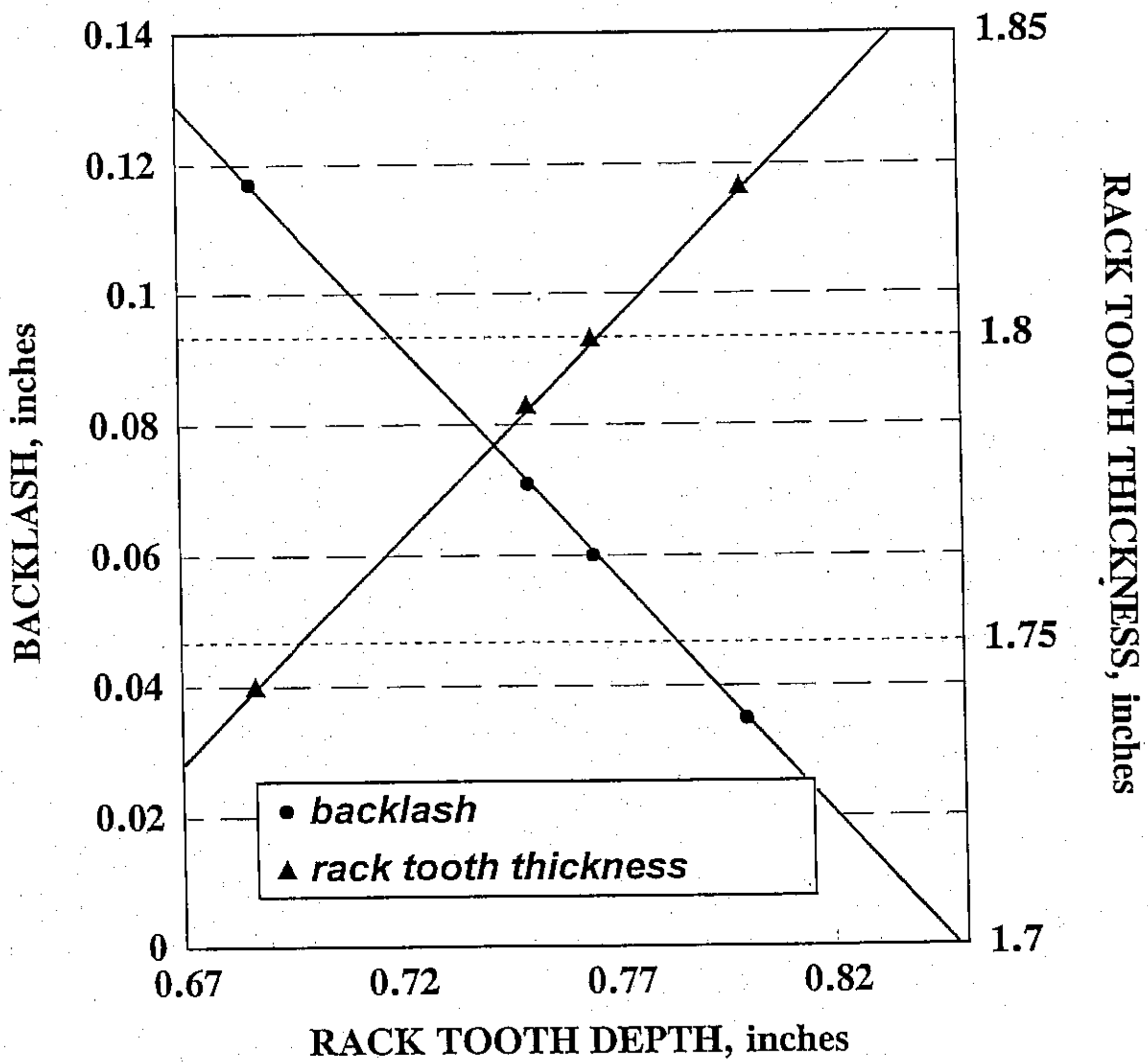


Figure 11. Plot of the amount of backlash available as the pinion addendum progressively moves downward below the rack pitch line. This graph assumes that the thickness of the pinion addendum is 2.390", the actual mean dimension obtained from field measurements with a geartooth thickness vernier.

e. Gear Tooth Stresses. Tooth stresses were evaluated by use of the AASHTO allowable tooth load formula as referenced in Section 2.6.12, Strength of Gear Teeth, *Standard Specifications for Movable Highway Bridges* [Reference 4]. The AASHTO formula is a modified form of the basic Lewis equation and takes dynamic conditions into account. For spur gears with involute stub teeth, the following tooth strength relationship applies:

$$W = f\,[s]\,[p]\,[0.178 - \frac{1.033}{n}]\,(\frac{600}{600 + V})$$

where
W = allowable tooth load, lbs
p = circular pitch, inches
s = allowable stress, psi
f = effective tooth face width, inches
n = number of teeth in pinion
V = velocity of pitch circle, ft/min

For the Cass St. Bridge, the 14-tooth pinion gear has a circular pitch of 4.25" and an effective face width of 10", based on its interface with a 10" wide rack. A typical bridge opening takes about one minute. The pinion gear travels about 280.5" in one minute, which translates to a pitch circle velocity of 23.38 ft/min.

The pinion gear is an ASTM A668 Class D forging, which has an allowable stress of 22,500 psi per AASHTO specifications. The rack is an ASTM A27 steel casting with an AASHTO allowable stress of 16,000 psi. AASHTO allowable stresses for cast steel are appreciably lower than allowables for forgings due to the higher incidence of defects in castings. Moreover, the pinion gear is not in a common structural frame with the rack, which is securely fastened to a separate structural frame. The allowable stress for the rack must be decreased by 20% from 16,000 psi to 12,800 psi because of the potential for misalignment, which apparently was not considered in the 1984 repair plans.

The Cass St. Bridge pinion gear teeth are rated at 95,670 lbs per the AASHTO formula. Although this load capacity is substantial, the pinion teeth are slightly undersized to carry the 105,830 lbs at bridge opening. The forward rack segments are seriously deficient with an AASHTO allowable tooth load of 54,426 lbs, which is only 51% of the maximum load required to open the bridge. Coincidentally, the rack teeth have suffered the greatest amount of wear damage.

INTERIM PINION ALIGNMENT

The pinion gear is located precisely at the center of a semi-circle that rolls back and forth, and is attached to the counterweight structure which is mounted on a semi-circular tread plate. The tread plate is socketed, and rolls on tracks. The supporting tracks are flat plates attached to the bridge abutments and foundation, whereas the racks are fixed but offset to permit movement of the bridge. The locations of the tracks, tread plates, and racks on the bridge are shown in ***Figure 1, Figure 2*** and ***Figure 3.*** The bridge is so well-balanced by a counterweight, usually within 1-2% of the span weight, that only minor torque effort is required to raise the span. The track tread supports the entire span and counterweight structure when lifted. The counterweight structure provides a frame for the entire system of drive gears for lifting and closure of the bridge. The track tread aligns the structure by use of a series of tread sockets, which are 0.250" larger in diameter than the fixed button heads bolted to the track.

a. Rack and Track Parallelism. The alignment of the pinion is predicated upon parallelism of the rack with the track below. A calibrated offset measurement was made on the rearward portions of the NE and SE tracks with their respective racks using a machined bar and the heaviest plumb bob available. The dimensions of the calibration bar are shown in ***Figure 4.*** The calibration bar was physically clamped to the rear of the rack, with the bar center line marks aligned with the center line of the rack. The plumb bob indicated that the track center was offset from the rack center line by 24.13" ± 0.02" on both tracks.

b. Sources of Misalignment. The structure could potentially shift as much as 0.250" as the span is lifted, lowered and then closed. However, the amount of pinion-to-rack mismatch created by a slight deviation of the track of 0.250" from parallelism with the fixed rack over 280.5" inches of travel is only 0.051°. This translates to the pinion potentially being placed at angles of 89.95° with respect to the rack's longitudinal axis, assuming that the pinion was 90.00° at some starting point. As the track button heads and tread sockets wear away, this minor misorientation of 0.051° will inevitably increase in the future.

Added to this inherent design misalignment are the construction variations in design dimensions of track button displacement and track parallelism. These factors add an additional amount of error, which could potentially amount to 0.164° of pinion misalignment.

Even if we assume that this potential for misalignment will increase due to the inherent design of the bridge, it is evident that the pinion collar bearing is not properly aligned, and exceeds the inherent design misalignment of 0.051° because of shim loss, bolt breakage and bearing collar movement. Due to excessive and premature wear of the rack which occurred over only 1,000 lift-and-closure cycles or less, the NE pinion should be immediately realigned.

c. Interim Alignment Procedure. The proposed alignment procedure in this report assumes that the rack is a reasonably proper reference base for the alignment of the pinion until more permanent changes to the track can be made, including changing button diameters to 8.44" and re-centering & reboring button holes. ***Figure 9*** is the reference drawing for interim pinion alignment.

1. Shift rearward rack element forward.

Exchange the essentially unused rearward 17-tooth rack segment with the worn forward (river side) rack segment. Place the forward rack segment to the rear, with worn teeth at the end of the rack.

2. Level racks; realign racks only if necessary.

Use an engineer's master precision level with a sensitivity of at least 0.0005" per ft, such as a Starrett No. 199Z or an MSC Industrial Supply No. 06530125 or an approved equal, to level the first rack segment in the X and Y axes. Insert stainless steel or brass shims as necessary. Realign the other rack segments if necessary by removal of non-level segments. Expand holes in plates below the rack by reaming to permit repositioning of each segment, but use the same diameter bolts. Use ASTM A490 or SAE Grade 8 coarse thread bolts with hardened washers to maintain high preloads. Rack realignment is necessary only if the rack face has shifted 0.250" beyond the face of the pinion gear.

3. Determine alignment of pinion gear with rack.

Determine pinion alignment by use of the following reference measurements:

(a) *X-axis* alignment shall be determined by clearance between the pinion tooth and the rack bottom land. Clearance should be 0.531" ±0.010" on both sides of the rack. At a clearance of 0.531", the pitch lines of both rack and pinion should be within ±0.010" of each other.

(b) *Y-axis* pinion tilt should be determined by the levelness of the pinion. The pinion should be level within ±0.010".

(c) *Z-axis* and *X-axis* pinion inclination is determined by the "D" distance shown in *Figure 9.* Distance "D" should equal be on both sides of the rack within ±0.004" when the face of a precision 90° angle plate is affixed parallel to the rack teeth.

4. Alignment of the pinion bearing collar.

(a) Drill set screw tap holes and tap threads into the pinion bearing collar per *Figure 12.* Loosen the pinion collar bolts to permit gear adjustment. Position the bearing collar with the set screws until the pinion gear is properly aligned with rack in the X, Y and Z axes.

(b) Remove the bearing collar bolts one by one, spot face the collar holes, and insert new bolts with spherical washers. Insert shims at each position as required. Drill five (5) new 1.125" diameter holes per *Figure 12.* Permanent shims should be 3" x 1.38" brass or stainless steel sheet with a center hole, with sheet thicknesses varying from 0.002" to 0.010". Do not use C-shaped shims, except for temporary adjustment.

(c) Tighten new ASTM A325 or SAE Grade 5 coarse thread bolts to achieve the proper fit with the existing vertical bridge plates. Torque well-oiled, clean-threaded 1.125" diameter bolts to 350-375 ft-lbs. Turned bolts are required per AASHTO specifications.

5. Verify new alignment.

The new alignment should be verified by several full openings and closures of the bridge, carefully observing the pinion mesh with the remaining rack elements. The collar and bridge plates should be scribed with reference marks for any perceptible collar or bolt movement which could be noted in future inspections.

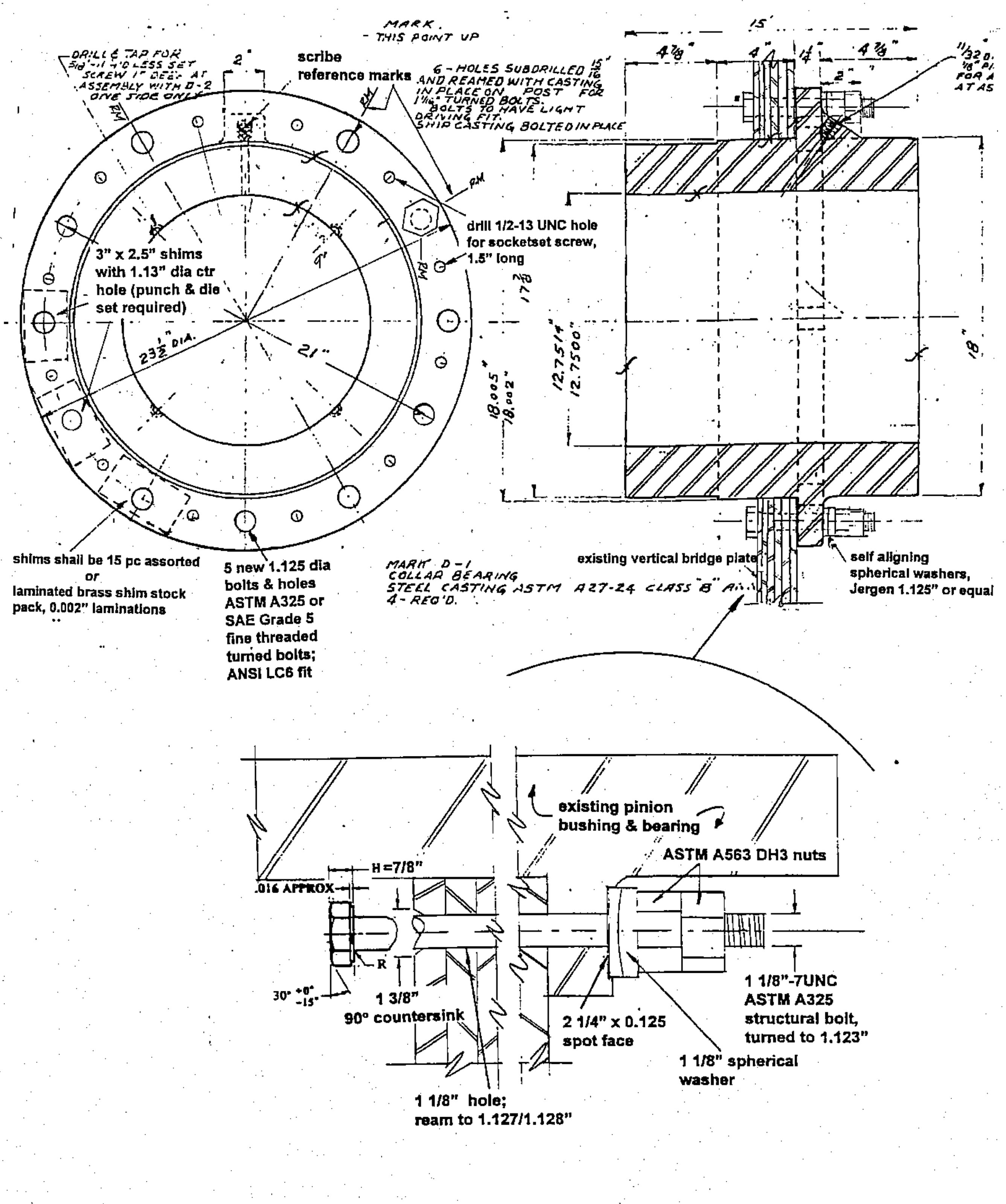


Figure 12. Modification of the original (existing) pinion bearing collar for alignment, showing set screws for alignment, insertion of center-hole brass or stainless steel shims, spherical washers, and five (5) additional bolts.

SPARES

The SE, NW and SW racks and pinions will eventually require replacement, especially if the bridge sustains a major barge or boat impact which causes any misalignment of the structure. Since there is no imminent plan to replace the racks and pinions with standard gear tooth forms of integral diametral pitch, the acquisition of a spare pinion and a 17-tooth rack element is strongly recommended.

Quotations for these machine elements were obtained from reputable sources throughout the United States, and are summarized in ***Table 4***. Quotations vary widely, depending on the manufacturer's tooling and set up costs. The least cost quotation for a single pinion gear was $6,400, whereas the least cost estimate for a rack was $7,672. Cost estimates are based on the use of annealed AISI 8620 or AISI 4140 steel forgings for the pinion, and ASTM A516 or A572 or AISI 8620 steel plate for the rack.

Table 4

Cost Quotations for Single Rack Element and Pinion Gear*

source	location	rack element	pinion
Horsburgh & Scott	Cleveland, OH	$14,417	$6,400
Industrial Sprockets	Santa Fe Springs, CA	18,600	9,870
Machinery Maintenance	LaSalle, IL	7,672	11,958
Xtek	Cincinnati, OH	12,795	8,665

*Quotations are based on acquisition of only one rack and one pinion. Xtek provided quotations for multiple units; $5,780 each for 4 pinions total; and for 8 rack elements, $7,475 each.

SUMMARY

1. The Cass St. Bridge racks sustained premature wear due to pinion and track misalignment.

2. The racks and tracks are reasonably parallel, but are slightly out of tolerance, with a deviation from parallelism by at least 0.36". The track has an inherent design parallelism tolerance of ±0.250". Additionally, the NE and SE tracks exhibit a significant displacement in track button correspondence by 0.656".

3. Cumulative misalignment from the present track layout could theoretically amount to 0.164° misalignment, with 0.098° from slight non-parallelism of the NE and SE tracks, and 0.066° from NE track button displacement. Additional rack misalignment could arise from improper positioning of the pinion collar bearing. Misalignment and its effects on racks and pinions have been a continuing problem for several rolling lift bascule bridges over the Des Plaines River.

4. Abnormal wear on the racks and pinions began after collar bolts lost their preloads due to (a) bolt eccentricity, (b) plate and casting roughness, (c) no apparent bolt torque specifications, and (d) a massive pinion shaft and bearing fastened to built-up hot-rolled plates by a thin bushing collar and only six bolts.

5. Bolt stresses at bridge opening are in excess of AASHTO allowable stresses required for an extended fatigue life of more than 500,000 cycles.

6. Tooth loadings on the rack at bridge opening are almost twice the AASHTO allowable loadings for movable bridges, and the pinion tooth loadings are borderline.

RECOMMENDATIONS

1. An ***interim pinion alignment*** procedure was developed for a short-term fix which applies to the eastern side of the bridge. The proposed interim alignment procedure does not apply to the western side, since plates which capture the pinion bearing collar were welded into place in 1997:

a. The worn river side 17-tooth rack element should be exchanged with the virtually unused rearward rack element on the NE corner of the bridge.

b. The newly-exchanged forward rack element should be leveled with a master precision level and serve as the reference platform for the pinion gear alignment.

c. Insert leveling/alignment set screws into the pinion bearing collar. Loosen the collar bolts to realign/level the pinion, using established reference marks and dimensions on the rack and pinion. Assure that the pinion pitch line is at or slightly below the rack pitch line. Some variation is permitted in the levelness of the other rack segments, as long as the clearance between the pinion teeth and rack bottom land is between 0.453" to 0.531".

d. Insert captive brass or stainless steel shims to provide an integral contact between the pinion bearing collar and structural plate. Do not use C-shaped shims for permanent installation. Insert new, well-oiled ASTM A325 or SAE Grade 5 turned bolts to specified torque. Machine bolt diameters to provide an ANSI LC6 fit.

e. Lift and close the bridge. Place reference scribe marks on bolts and collars and structural plate. Note any other apparent misalignment or loss of bolt preload or collar movement after several months.

f. Obtain a spare AISI 4140 pinion and a spare AISI 8620 17-tooth rack segment for any future emergency.

2. In the future, specific actions should be taken to provide ***permanent realignment of the tracks, pinions and racks*** to eliminate the root causes of the misalignment problem:

a. Reposition NE track buttons so that they are precisely 90.000° ±0.0015° opposite their SE counterparts, and that the bolt hole center lines are truly parallel and linear. Establish a precise track button center with a very accurate transit. Rebore each button cylinder hole to relocate the button to its proper center. Expand the track button base diameter to 8.440"±0.005", maintaining the existing conical slope. This will place the track within the AGMA backlash tolerances of the rack and pinion.

b. Remove the existing pinion bearing collar and install a new structural plate. The new plate should be either spot-faced by field machining, or by specially positioning and field welding a very flat plate to the existing plates. The flat plate must be thermally stress-relieved before machining, and preheated to avoid distortion.

c. The rack face should be increased in width. The holes in the structural plate below the rack should be expanded to permit some rack segment adjustment. The rack should be machined from tough, quenched-and-tempered alloy steel plate, and satisfy AASHTO allowables for tooth loading. A standard 20° involute stub tooth rack and pinion system should be used.

d. Machine a new, single-piece aluminum bronze pinion bearing, and use a shrink-fit connection with the existing bolts and spot-faced structural plates. This shrink fit can be obtained by boring out the existing structural plates, and using a precisely machined bearing. Do not use the rough 1931 steel casting and internal bronze bearing design that is still in service. A shrink-fit connection would end the sole reliance on bolt preload, and better distribute the forces generated by the massive pinion shafting which are now being transferred to bolts fastened to riveted sections of thin built-up plates.

REFERENCES

1. Cass St. Bridge Plans, approved by I. Erdal and C. Hazelet, Scherzer Rolling Lift Bridge Co., October, 1931; and W. Smith, Division of Waterways, State of Illinois, November, 1931.

2. Cass St. Bridge Rehabilitation, approved by A. Landini, Donohue Engineers & Architects, April, 1984; and H. Monroney, Illinois Dept. of Transportation, May, 1984.

3. E. Oberg, F. Jones and H. Horton, *Machinery's Handbook*, 22nd Edition, Industrial Press, New York, 1984, pp 613-693.

4. *Standard Specifications for Movable Highway Bridges,* American Association of Highway & Transportation Officials (AASHTO), Washington, DC, 1988.

5. *Standard Specifications for Highway Bridges, 15th Edition,* AASHTO, Washington, DC, 1992.

6. H. Kraus, "Stress Concentration Factors for Perforated Annular Bodies Loaded in Their Plane", *Stress Concentration Factors,* R. Petersen, ed., Wiley-Interscience, New York, 1994, p192.