Dr Conway

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EXAMINATION OF BROKEN SHAFT FROM PRETORIA AVENUE BRIDGE OTTAWA, ONTARIO

by

D. E. PARSONS

PHYSICAL METALLURGY DIVISION

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SUMMARY OF RESULTS

Metallurgical examination of a broken 4 in. shaft from the lifting mechanism at one corner of the Pretoria Avenue bridge showed that a crack had propagated in a helical path until a fragment broke from the shaft and jammed the mechanism.

Failure was attributed to alternating torsion stresses, applied over a long period of time, to the low yield strength of the material and to the design of the component. Design of the shaft provided stress raisers in the form of grease grooves on the circumference of the shaft at forty-five degrees to the shaft axis. Another stress raiser was also present at the intersection of the radial grease holes with the grease grooves on the outside surface of the shaft. The presence of these stress raisers and the tendency for the climbing gear and rack to skip teeth under some circumstances were probably contributing factors.

Magnetic particle examination of the three remaining shafts revealed the presence of cracks in an early stage of propagation. These cracks had lengths of about 3/8 in. and started at the intersection of the radial grease hole with the surface grooves.

Recommendations were made pertaining to replacement of the four shafts using quenched and tempered high strength alloy steel shafting.

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* Senior Scientific Officer, Ferrous Metals Section, Physical Metallurgy Division, Mines Branch, Department of Mines and Technical Surveys, Ottawa, Canada.

INTRODUCTION

On January 30, 1963, Mr. W.W. Gruber of the Marine Works Branch, Canals Division, Department of Transport, submitted a broken shaft from the Pretoria Avenue, Ottawa, Ontario, lift bridge to the Physical Metallurgy Division, Mines Branch, Department of Mines and Technical Surveys for metallurgical examination. The remaining three lifting shafts were also removed and were submitted for magnetic particle examination on February 13, 1963. (These three shafts had not failed but did contain cracks starting at the intersection of a transverse grease hole with grease grooves located on the surface and at 45 deg to the shaft axis. The cracks had a length of about 3/8 in., and followed a helical path along the grooves).

The covering letter, File No. 4056-233 (Canals) January 30, 1963, from Mr. J.N. Ballinger, Chief Canals Division, Marine Works Branch, Department of Transport, requested information about the probable cause of failure and asked for recommendations concerning replacement of the shafts.

The appearance of the broken shaft is shown in Figure 1. The shaft contains an axial bore hole that connects via three transverse (radial) holes to three pairs of "X-shaped" grease grooves. The shaft operates in the horizontal position and is driven from the side shown at the left of Figure 1. Approximately 6 in. of the shaft, shown at the extreme right, Figure 1, is exposed to the weather and is slightly pitted.

In operation, this shaft is driven by a pinion at the left side causing rotation of a climbing gear that travels up a fixed rack, thereby raising one leg of the bridge. There are four lift mechanisms, one for each corner of the bridge, connected through a long and flexible linkage to the power source, so that the four shafts operate simultaneously moving each of the four climbing gears up the racks. Under some conditions it is possible for the climbing gear to skip a tooth in the rack, thereby jamming, and causing the supporting leg of the bridge to spring away from the rack.

The shaft illustrated in Figure 1 had been in service from 1919 until June 1962, when a triangular fragment broke out of the shaft allowing one corner of the bridge to drop about two feet and causing jamming of the lift mechanism.

In normal service the loads on this shaft are intended to be of the order of about two tons and except for this load the weight of the bridge is counterbalanced.

Since 1919, changes in bridge weight have been matched by changes in the counterbalance weight so that excessive loads should not occur in one leg providing the climbing gears and racks remain in proper contact.

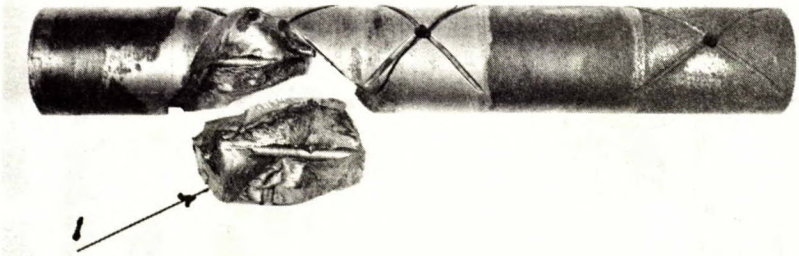
The mechanism for each leg is contained in a concrete pit so that stiffening of the post members is difficult or impossible (and may not be desirable); however, improved contact between the gear teeth and the rack is being achieved by use of shims.

APPEARANCE OF BROKEN SHAFT

The appearance of the broken shaft containing a helical crack at 45 deg to the axis of the shaft is illustrated in Figures 1 and 2. Figure 3 illustrates the appearance of the crack surfaces at the end of the helix remote from the drive end. Part of this crack was open and exposed to oxidation prior to the final rupture. Figure 4 illustrates a helical fracture described (1), as characteristic of fractures due to alternating torsion.

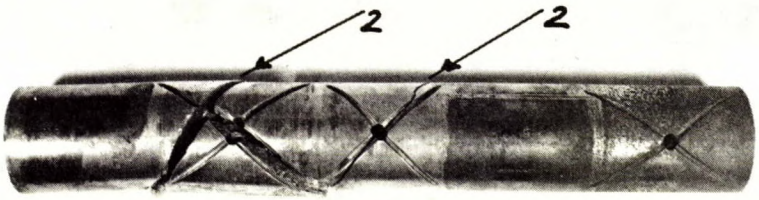
The fracture, illustrated in Figure 1, appears to have commenced at the corners of the radial grease holes and to have propagated in both directions along a helical path towards the ends of the shaft.

drive end



(a) X1/8

drive end



(b) X1/8

Figure 1. Broken Shaft from Lift Mechanism of Pretoria Avenue Bridge. The view shown in Figure 1 (a) illustrates the helical fracture, bore-hole, radial holes, grease grooves and the fragment that caused failure of the mechanism in June 1962. Figure 1 (b) illustrates the appearance of the broken shaft with the fragment fitted in position. The fragment (arrow 1) and the path of the helical crack (arrows 2) are marked.

The appearance of the fracture surfaces is shown in Figure 2. The tip of the open helical crack was examined by cutting a 3/4 in. transverse slice at position A, Figure 2. The appearance of the fracture surfaces exposed by sectioning is illustrated in Figure 3. The oxidized (black) and bright parts of the fracture indicate that part of the crack was present prior to failure in June 1962.

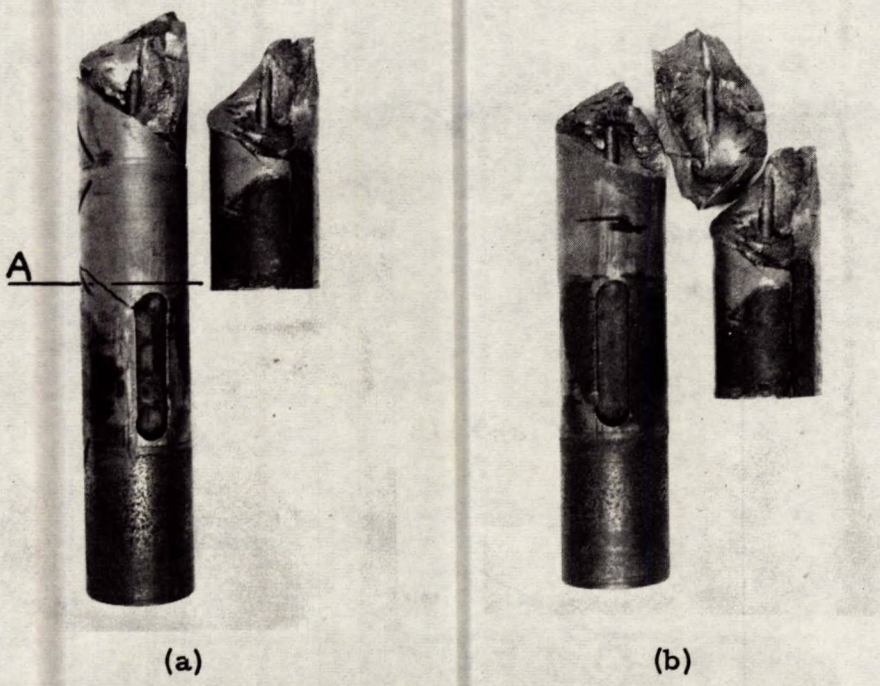


Figure 2. Same Shaft as Figure 1, with Fracture Surfaces Exposed. A transverse slice, 3/4 in. thick, was cut at position A for inspection of the crack adjacent to the tip of the helix.

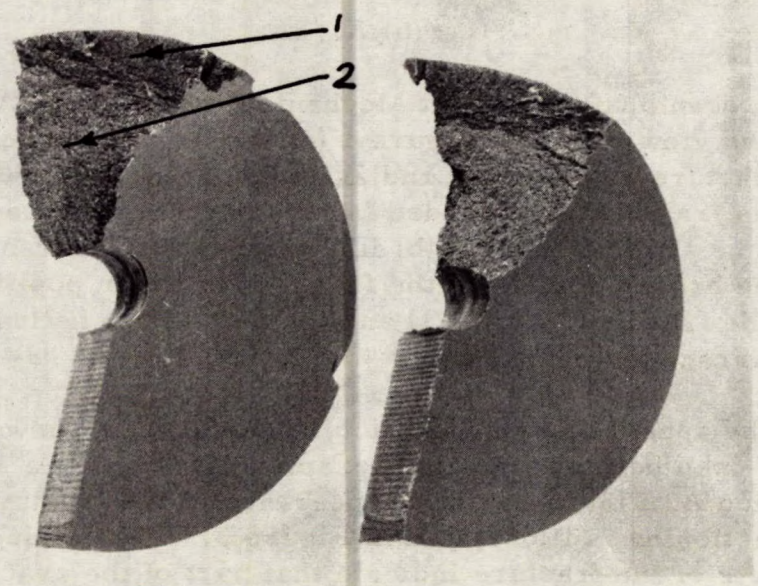


Figure 3. Transverse Section at Position A (Fig. 2) with Fracture Surfaces Exposed.
A dark (oxidized) area (arrow 1) and a bright area (arrow 2) are visible on the fracture surface indicating the presence of a crack in this region prior to the final rupture.

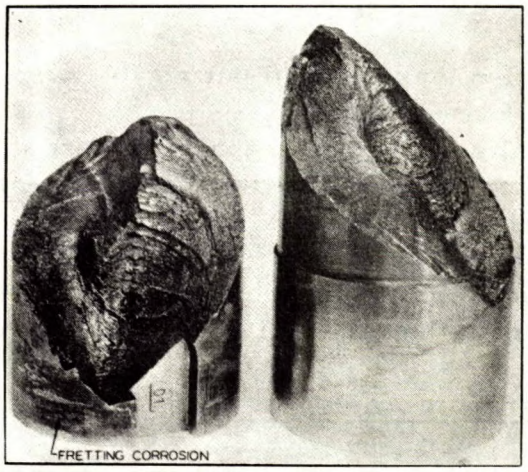


Figure 4. Textbook Fracture. Typical fracture due to alternating torsion as illustrated by M. Hetényi. (See also references 2 and 3).

Part of the text, by Hetényi, pertaining to alternating torsion and to the fracture illustrated in Figure 4, was as follows:- "A fatigue crack generally follows a path dictated by the normal stress field, hence one would expect alternating torsion cracks to follow a path 45 deg to the axis. It is almost a certainty that a crack of approximately 45 deg helix found in service is due mainly to alternating torsion. Although there are cases where torsion produces other results, it can be said that bending or axial stresses do not, in practice, produce the diagonal crack which is uniquely characteristic of torsion failure.

A mathematical analysis has indicated that, with failure starting at a small localized stress concentration, a helical crack is to be expected as a result of alternating torsion. This is completely confirmed in all cases of torsion tests of a shaft with a transverse hole, regardless of material.

In torsion fatigue tests of 14 S-T aluminum, J.A. Sauer noted that relatively highly stressed specimens (short life) tended to crack axially and circumferentially, while specimens stressed at a lower level (long life) tended to crack in a helical manner."

METALLURGICAL EXAMINATION

Metallurgical examination was carried out as follows:-

(1) Chemical and Spectrographic Analyses.
(2) Mechanical Tests: tensile, Charpy V-notch impact bars and hardness tests.
(3) Metallurgical Examination.
(4) Magnetic Particle Inspection of Three Unbroken Shafts from the other Lifting Positions.

Chemical and Spectrographic Analyses

The results of chemical and spectrographic analyses made on the broken shaft are shown in Table 1.

TABLE 1

Chemical and Quantitative Spectrographic* Analyses (Per Cent)

Sample	C	Mn	Si	S	P	Ni*	Cu*	Cr*	Mo*	V*	Al*
Broken Shaft	0.35	0.41	0.19	0.033	0.014	0.02	0.029	<0.1	<0.005	ND	0.003
AISI-C-1034	0.32/ 0.38	0.50/ 0.80		0.050 max	0.040 max						

ND - Not detected

The chemical composition of the broken shaft conforms to the chemical requirements of AISI-C-1034 except for the slightly low quantity of manganese. The silicon content 0.19% classifies the steel as a "killed" grade. The steel has a relatively coarse grain size, which is consistent with the absence of grain refining additions, with the 4 in. section size and the probability that the bar is in the as-rolled condition.

Mechanical Tests

The results of tensile tests made on two 0.505 in. diameter longitudinal test bars are shown in Table 2.

TABLE 2

Tensile Test Results

Bar No.	UTS (kpsi)	YS-0.2% Offset (kpsi)	% El. in 2 in.	R.A. %	Brinell Hardness 3000 kg load
1	75.2	33.2	30.0	46.2	180
2	74.8	33.0	29.0	47.0	180

The hardness and tensile properties indicate that the bar was used in the as-rolled condition.

The results of Charpy V-notch impact tests are listed in Table 3.

TABLE 3

Charpy V-Notch Impact Results (ft-lb)

Sample	95°C (200°F)	25°C (75°F)	5°C (40°F)	-18°C (0°F)	-40°C (-40°F)
Bar 1	50	10	6	3	2
Bar 2	44	11	4	2	2
Bar 3	46	16	6	2	2

Except for the bars broken at 95°C (200°F), the impact bars showed little deformation and were characterized by coarse-grained cleavage fractures.

Metallographic Examination

Sections were cut adjacent to the tip of the helical crack and were examined under the microscope. The structure consisted of ferrite and pearlite and was typical for hot rolled mild steel shafting. Figure 5 illustrates the general microstructure of the bar consisting of fine pearlite and pro-eutectoid ferrite. The grain size is relatively coarse, indicating that the bar is in the hot-rolled condition.

Figure 6 illustrates an area through the helical crack adjacent to the tip. The crack follows a path that is neither intergranular nor transgranular. There is evidence of deformation in excess of the yield point of metal as shown by the presence of ruptured ferrite grains and twinning (Neumann bands) in some ferrite grains adjacent to the crack. Possibly this severe deformation occurred at the time of final failure. The location of the tip of the crack (at the end remote from the drive end) and the presence of numerous secondary cracks are consistent with a history of slow crack propagation culminating in rupture and application of a final shock load.

The appearance of an area containing ruptured ferrite grains in Figure 7 shows that stresses in excess of the yield point have been present in metal adjacent to the main crack.

X100 - etched 2% nital solution

Figure 5. Typical Microstructure Observed in Broken Shaft. The structure consists of pro-eutectoid ferrite and fine pearlite and is typical of hot-rolled AISI-C-1034 steel in a 4 in. section.

X100 - etched 2% nital solution

Figure 6. Transverse Section Through the Tip of the Helical Crack Remote from the Drive End of the Shaft.
Secondary crack and ruptures are associated with the main crack.

X500 - etched 2% nital solution.

Figure 7. Small Cracks (Ruptures) which Extend Through One or Several Grains and Indicate Stresses in Excess of the Yield Point.
Small ruptures are present in numerous regions adjacent to to secondary cracks indicating overstressing and severe metal damage adjacent to the tip of the helical crack.

Magnetic Particle Inspection of Three Shafts

Magnetic particle inspection was carried out, using fluorescent particles and black light for inspection, on the three unbroken shafts used for lifting the other corners of the bridge. Fatigue cracks were detected in two of these shafts. The cracks started at the intersection of radial grease holes with the circumferential grease grooves and extended in a helical direction for about 3/8 in. from each side of the hole. The presence and direction of these cracks indicated that failure was a consequence of the application of alternating torsion stresses which coincided with the grease grooves in the region of the shaft subjected to maximum torsion. The helical path and the appearance of these cracks was consistent with the opinion that crack propagation was relatively slow and that the grease grooves acted as stress raisers.

SUMMARY AND DISCUSSION

The appearance of the broken shaft and the results of magnetic particle examination of the three remaining unbroken shafts (containing short cracks) indicate that failure starts at the shoulder of the radial grease holes in the region of maximum torsion stress and that the cracks propagate in a helical direction, sometimes following the circumferential grease grooves.

The yield strength and Charpy V-notch impact strength are relatively low in comparison with similar properties obtainable in modern medium alloy steels, for example, in AISI-4340 or AISI-8740 oil quenched and tempered. Data published by Atlas Steels Limited(4), show izod impact values of 74 ft-lb at a yield strength of 86,000 psi and Brinell hardness of 241 for SPS-245 steel oil quenched and tempered at 650°C (1200°F) in 4 in. sections. Similar results for Ultimo-4 steel show impact values of 71 ft-lb combined with a yield strength of 117,000 psi at a Brinell hardness of 277 in the oil quenched, tempered 650°C (1200°F) condition for 4 in. sections.

CONCLUSIONS

1. Failure occurred by application of an unusual load to a shaft containing a prexisting helical crack. Failure of this component is due to alternating torsion stresses.

2. The torsion stress is localized by the presence of helical grease grooves on the shaft circumference. Cracks appear to start at the shoulder between the radial grease holes and the helical grease grooves.

3. The steel used in this old shafting had very low yield and impact strength in comparison to alternate materials now available.

4. The final shock load probably resulted from disengagement of the climbing gear and rack together with subsequent jamming of the broken fragment of shaft.

RECOMMENDATIONS

1. Replace the shafting with oil quenched and tempered steels having equivalent properties to those shown for SPS-245 or Ultimo-4 steels having yield strengths of 86,000 psi and 117,000 psi, respectively, combined with Izod impact strengths of the order of 70 ft-lb. These properties are obtained by oil quenching and tempering at 650°C (1200°F) in 4 in. sections.

2. Chamfer or countersink the intersection of the transverse grease hole and grease grooves.

3. The grease grooves should preferably have their long axis parallel to the longitudinal direction of the bar, rather than in the transverse or 45 deg helical positions, thereby minimizing the stress-raising effect of the grease grooves.

REFERENCES

1. M. Hetényi - "Handbook of Experimental Stress Analysis" - John Wiley and Sons, Inc., New York, p. 605 (1950).

2. V.M. Faires - "Design of Machine Elements" - The MacMillan Company, New York, Pp 107-114, 284, 304-320 (1949).

3. F. B. Seely - "Resistance of Materials" - Third Ed., John Wiley and Sons, Inc., New York, Pp 67-88 (1947).

4. Atlas Steels Limited, Technical Data (Tool Steels), Pp 92-93.

DEP:ac

APPENDIX

Extract from Reference (2), p. 306

"If the material is purchased according to physical specifications, the design shear stress is the smaller of the following values:

S_s = (0.3) (elastic limit in tension)

S_s = (0.18 (ultimate tensile strength)

The design compressive or tensile stress is to be the smaller of the following values (to be used when the shaft is in bending only):

S = (0.6) (elastic limit in tension)

S = (0.36) (ultimate tensile strength).

It is assumed that steel is elastically half as strong in shear as in tension, the factor of safety in these stresses appears low; but it should be observed that the factors K_t and K_m should make adequate allowance for peak stresses due to variations in the loading. When there is a keyway in the section being designed, the design stress = 3/4 (design stress without a keyway)."

Extract from Reference (4)

Average Mechanical Properties

	UTS (kpsi)	Yield Point (kpsi)	% El.	R.A. %	Izod Impact (ft-lb)	Brinell Hardness
SPS-245 (4 in.), Oil Quenched Tempered 1200°F	117.0	86.0	24.0	58.0	74.0	241
Ultimo-4 (4 in.) Oil Quenched Tempered 1200°F	136.5	117.0	19.0	60.0	71.0	277
Broken Pretoria Bridge 4 in. Shaft	75.0	33.1	29.5	46.6	12 (Charpy V-notch)	180