HEAVY MOVABLE STRUCTURES, INC.
SEVENTEENTH BIENNIAL SYMPOSIUM

October 22-25, 2018

Mitigation of Cracks in Sheave Trunnions for the Burlington Bristol Bridge

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Abstract

Cracks discovered in sheave trunnions of the Burlington Bristol Bridge during inspections in 2014 prompted a follow-up inspection of the reported areas of distress. The presence of additional crack initiations was revealed, and the initially reported cracks were verified. An attempt to eliminate the cracks failed in much of the affected region to remove the full depth of the cracks. A subsequent retrofit effort was successful, as verified by nondestructive examinations, in elimination of all indications of cracks in these journals.

The following biennial inspection of 2017 included all trunnion journals in the bridge. Cracks were detected at locations where none were reported previously. After approximately two years of service, however, no new initiations were evident within the regions of crack mitigations of 2015.

Development of cracks in the transitional region of the trunnions indicates susceptibility to service related distress. While restoring the trunnions to their original condition is not possible, the useful life of the trunnions may be extended through implementation of appropriate mitigation procedures, and ongoing monitoring of the trunnion condition.

Introduction

The Burlington Bristol Bridge, shown in Figure 1, is a movable bridge with a span-driven vertical lift span crossing the Delaware River between Burlington, New Jersey, and Bristol, Pennsylvania. Opened to service in 1931, the bridge supports a two lane road deck. Counterweight towers at each end of the lift span support the four sheave trunnions that are seated in plane half-bearings. Lifting of the movable span induces cyclic stress reversals in the trunnions as they rotate, with the greatest stress concentrations experienced within the transitional fillet region between the journal bearing surface and the trunnion thrust face. It is in this region that cracks were initially discovered in two of the trunnion journals.

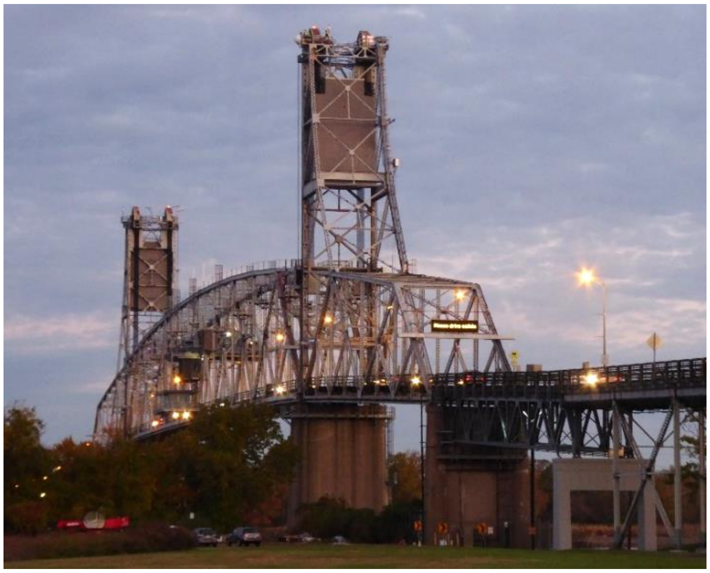

FIGURE 1. The Burlington Bristol Bridge viewed from the New Jersey shore.

Trunnion Design

The drawing in Figure 2 shows the design of the forged steel trunnions used in the Burlington-Bristol Bridge. The journal ends are reduced from the nominal 21-1/2 inch sheave seat diameter to 19 inches, and fitted to the plain half-bearings mounted at tops of the counterweight towers. The journal bearing surface transitions with a 1/2 inch radius fillet to the thrust face. A center-bored hole extends through the full length of the 7 ft-1/4 in. long trunnions.

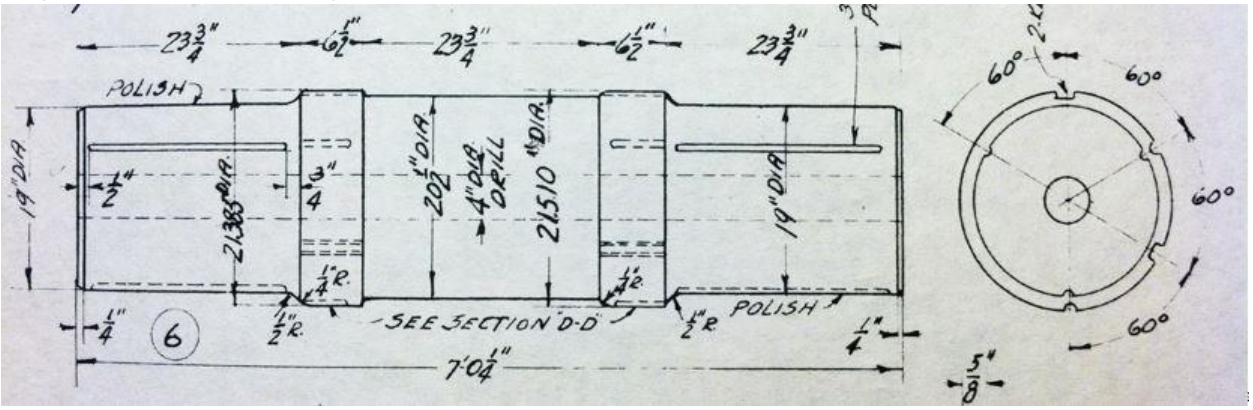

FIGURE 2: An excerpt from drawings shows the overall design, and geometric features of the trunnions.

Examinations of Trunnion Journals

Visual observation allowed general assessments for scoring, gouging, and impact damage, however cracks could not be discerned without the aid of magnetic particle or ultrasonic examination methods. Emphasis of the examinations was directed toward the transitional region of the journals where concentrations of stress are highest, and potential initiation of cracks is greatest. All trunnion journals were subjected to wet fluorescent magnetic particle examination, a practical and effective method for detection of crack initiations. Ultrasonic examinations were used where volumetric examination of the journals, and estimates of crack depth was necessary.

Grease reservoirs mounted on top of the plain half-bearings were removed for access to the transitional region of trunnion journals, shown in Figure 3, for visual and magnetic particle examinations. Access to the full circumference of the journals for examination required lifting of the movable span to re-position the trunnions in approximate one-third increments, allowing inspection overlap and a favorable viewing orientation throughout. End and bore-hole surfaces were used for ultrasonic examinations where needed. The examinations emphasized detection of cracks, and evaluation of conditions that might be detrimental to the service life of the trunnions.

FIGURE 3: A trunnion journal seated in its half-bearing, is shown with the grease reservoir removed.

Development and Detection of Cracks

The cracks detected in the trunnion journals appear to have originated as the result of two primary mechanisms that occur during operations of the movable span. Bending stress reversals are imposed on the journals during rotations of the sheave trunnions, with highest concentrations at regions of the transitional fillet. Cracks that originate from this mechanism, referred to as “fillet-cracks” are typically positioned low to mid-fillet, as shown in Figure 4, within the transitional region of the journal.

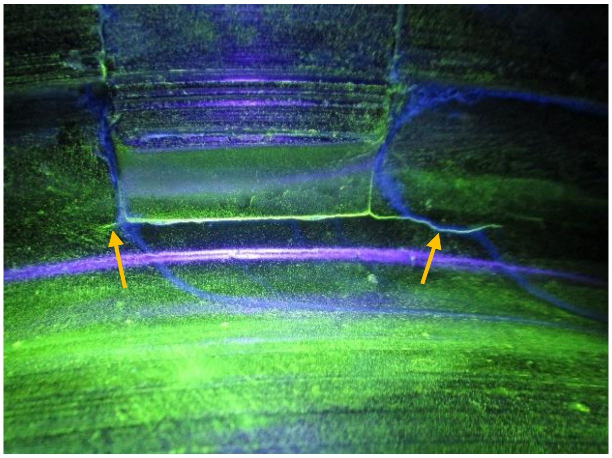

FIGURE 5: Keyway cracks located high in the transitional fillet extend from the keyway.

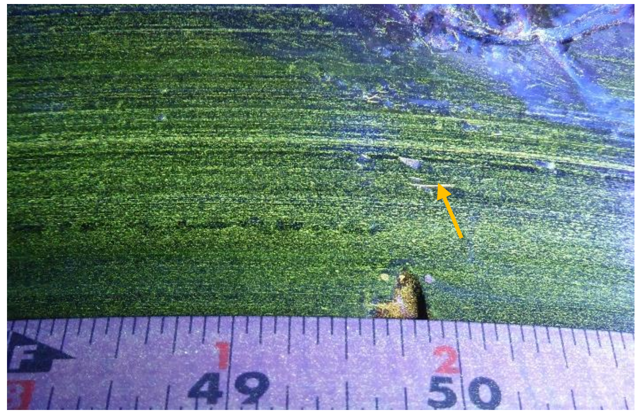

FIGURE 4: Crack initiation (arrow) positioned low in the transitional-fillet.

Cracks extending from the corners of keyways, referred to as “keyway-cracks,” appear to originate due to an impact or prying mechanism that is much different from the initiation and propagation of fillet-cracks. As shown in Figure 5, these cracks originate in the upper portion of the transitional region, and at the bottom surface of the keyway, where the key acts against the sides during rotations of the trunnions.

Crack Detection

Nondestructive examinations were used to aid the detection and characterization of discontinuities, as cracks in journals are typically very fine, and not discernable to the unaided eye. Using a wet fluorescent technique, the magnetic particle method with the enhanced contrast of the inspection medium is highly sensitive to detection of early crack initiations, and is preferred for initial examinations. Where cracks have propagated or coalesced to a continuous length of about one or more inches, ultrasonic examinations using a through bore technique may be useful in estimation of depth. Visual examinations, especially within the transitional regions of the trunnions, might identify conditions that could lead to crack initiations. In general, some of the detrimental surface conditions may be pre-emptively addressed to reduce the potential for development of cracks.

Stress Risers

An apparent site of origination for some cracks in Burlington Bristol Bridge trunnions were nicks or gouges within the transitional region. Several blemishes of this type were in alignment with grease grooves in several trunnion journals, and might have been inscribed to mark the placement of groove locations during manufacture. These blemishes create stress risers with local concentrations when subject to tension that is associated with bending. Cracks extending circumferentially in both directions from one of these nicks, as shown in Figure 6, were revealed when subjected to wet fluorescent magnetic particle examination.

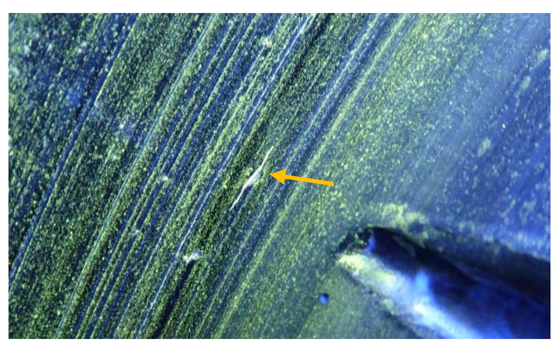

FIGURE 6: Crack initiations extend in two directions from a blemish (arrow) in the transitional region of a journal.

Cracks may occur when the stress range is high, and when a threshold that is a function of design, load, and number of operational cycles is exceeded. The change of section from the trunnion sheave seat to the journal surface is an inherent region of stress concentration that is distributed within the radius of the transitional fillet. Although often initiated by local stress risers that were established at sites of either intentional or unintentional nicks, some cracks have originated in areas that appear to be blemish free. The presence of blemishes, near surface discontinuities, and tiny crack initiations, however, all act to concentrate stresses and accelerate the process of fatigue cracking.

At early stages, crack initiations are typically shallow and short in length; but immediately establish local stress risers that are prone to extension. When multiple initiations develop in close proximity, individual segments tend to coalesce, creating a longer and deeper crack-tip, a more severe stress riser, and greater challenge for possible mitigation.

Fillet-Cracks

Fillet-cracks were detected in two journals during examinations of 2014 and 2015, but in additional journals as well, during the biennial examinations of 2017. Cracks have not, however, been detected in all of the trunnion journals. Coalescence of the fillet-cracks shown in Figure 7 had exceeded a length of 1-1/2 inches by 2015, however, the response from ultrasonic examinations indicated that the depth was relatively shallow, and that mitigation by excavation could be accomplished.

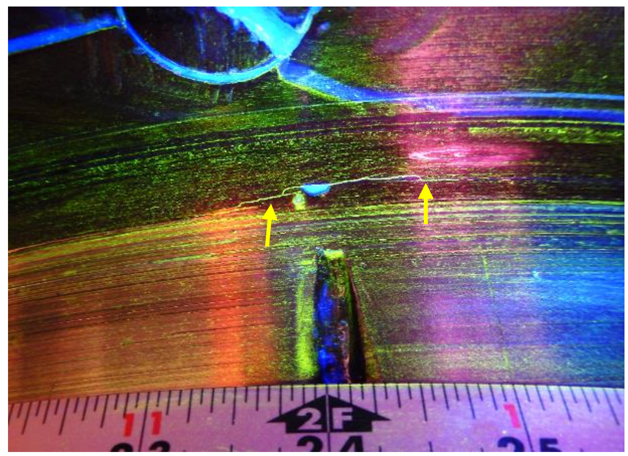

FIGURE 7: Multiple low to mid-fillet cracks (arrows) have coalesced and extended.

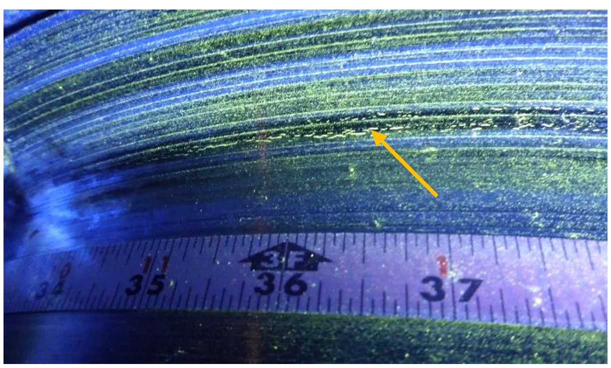

FIGURE 8: Multiple crack initiations, beginning to coalesce were detected in one journal.

A concentration of fillet-cracks, shown in Figure 8, was detected in the 2017 examinations, distributed over a circumferential area of about five inches. Fillet crack initiations detected at other locations were typically short and scattered, as shown in Figure 9. With crack initiations that originate within the regions of highest stress concentrations, and propagation that is transverse to the axis of the trunnion, all fillet cracks threaten the integrity of the trunnions, and should be mitigated if possible.

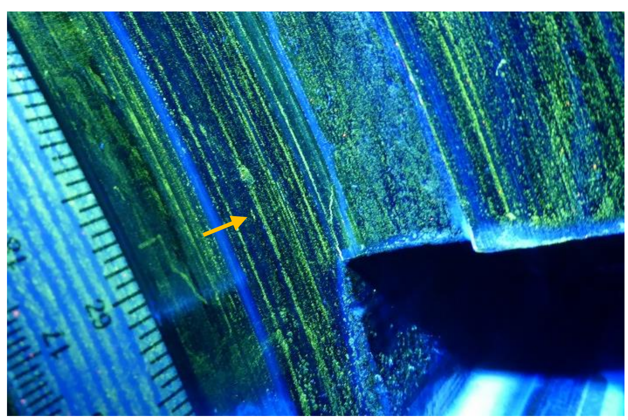

FIGURE 9: Most new crack initiations in 2017 (arrow) were short and isolated.

Keyway-Cracks

Keyway-cracks have typically propagated with an approximate lateral extension from corners of the keyways. These cracks may be more prominent and dramatic in appearance than some of the fillet cracks, but the apparent mode of propagation does not immediately threaten the integrity of the trunnion. With an apparent "pealing" effect, the cracked region remains contained within the sheave. These cracks are not transverse to the axis of the trunnion, but the ultimate path of propagation is not certain, therefore, regular examination is needed to monitor progress.

Excavations/Mitigations

The fillet-cracks identified in 2014 and early 2015 were excavated in November 2015, as shown in Figure 10, for mitigation of the affected regions. Feasibility for remediation was established prior to the start of mitigation efforts, where depths of about 0.15 inches were estimated for most cracks that were identified in nondestructive examinations.

FIGURE 10: Excavations for mitigations of cracks sometimes undercut the plane of the journal.

The mitigation excavations were governed mainly by the fillet-crack depth, and generally followed the original contour to produce a gradual transition to the surrounding trunnion surface. Excavations required for the deeper cracks sometimes undercut the plane of the journal surface, as well as the trunnion thrust-face. The extent of material removed was kept to the minimum necessary for complete removal of the crack-tip, while maintaining the appropriate transition.

Excavations of the cracked areas were accomplished using carbide cutting burrs, driven by a hand held die-grinder. Initial attempts using aluminum carbide abrasive wheels proved to be a poor choice due to the low rate of material removal, roughness of the excavated surface, and rapid wear of the tool. Selection of appropriate and efficient tools enhanced the quality of the excavation, and accelerated the process in what is often (due to limited bridge opening periods) a time constrained work period.

In crack mitigations, shallow, incremental excavations were followed by magnetic particle examinations in an ongoing sequence to monitor the crack elimination progress. The direction of working for excavations within the journal transitional region was parallel to the trunnion axis, avoiding circumferential grooves that might concentrate bending stress, or create background interference in magnetic particle examinations. Fine grit sanding flap-wheels were used to complete the contour blending and surface finish of the excavations, as shown in Figure 11. During excavations, the trunnion bearing was protected from removed material that might adversely affect wear. A final magnetic particle examination verified complete removal of the crack-tip within completed areas of mitigation excavations.

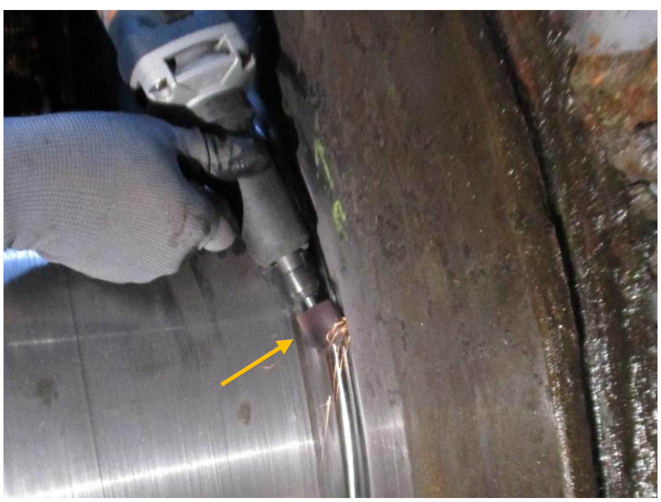

FIGURE 11: Excavations surfaces were completed by polishing with a sanding flap-wheel (arrow).

With expectation based on ultrasonic examinations that removal of the crack-tip would be achieved in relatively shallow excavations, a limit for material removal was not precisely defined. The extent of material excavated from the trunnion journal, however, was monitored at representative locations using a dial gage fitted to a specially designed fixture, as shown in Figure 12, to measure the relative depth of mitigation excavations. Gradual transitions were maintained in all excavations, therefore, a three-point measuring protocol (high, mid, and low) created a satisfactory approximation of the mitigated fillet region profile.

FIGURE 12: A dial gage was fitted to a fixture for post mitigation measurement of the fillet region profile.

A maximum excavated depth of approximately 0.35 inches was required to eliminate the tip of the deepest fillet crack. This depth, however, was limited to less than one half inch circumferential area, and was reduced to 0.25 inch depth on either side just one inch away, and to 0.10 inch depth or less within two inches on either side. Excavations of 0.05 to 0.10 inch depth, generally consistent with the ultrasonic estimates of depth, were sufficient for elimination of most crack-tips. Table 1 presents a summary of excavated depths within the transitional region for the two mitigated journals. The measurements outlined in red required the most extensive mitigation excavations.

Table 1.

Trunnion Journal	Transitional Fillet Profile Measurement							KEY: NM Not Measured
	Circumferential Orientation	Initial Measurement Fillet Position			Post Mitigation Measurement Fillet Position			Comment
		Low	Mid	High	Low	Mid	High	
NW Inboard	16 inch	NM	NM	NM	- 0.010	- 0.020	0.010	Area of gouge – blended by shallow excavation
	17 inch	NM	NM	NM	- 0.020	- 0.035	0.010	Area of gouge – blended by shallow excavation
	18 inch	NM	NM	NM	- 0.030	- 0.050	0.010	Area of gouge – blended by shallow excavation
	19 inch	NM	NM	NM	- 0.030	- 0.045	0.010	Area of gouge – blended by shallow excavation
	20 inch	NM	NM	NM	- 0.030	- 0.055	0.010	Area of gouge – blended by shallow excavation
	21 inch	NM	NM	NM	- 0.005	- 0.005	- 0.005	
SE Outboard	1 inch	NM	NM	NM	0.00	0.00	0.00	
	2 inch	NM	NM	NM	0.00	0.00	0.00	
	3 inch	NM	NM	NM	- 0.010	- 0.020	- 0.010	Left side of journal lubrication groove
	5 inch	NM	NM	NM	- 0.150	- 0.200	- 0.090	Right side of journal lubrication groove Area of crack mitigation
	6 inch	- 0.050	- 0.050	- 0.050	- 0.085	- 0.110	- 0.100	Area of crack mitigation
	8 inch	NM	NM	NM	- 0.005	- 0.050	- 0.025	Area of crack mitigation
	10 inch	NM	NM	NM	- 0.030	- 0.040	- 0.005	Area of crack mitigation
	11 inch	0.00	- 0.005	- 0.005	NM	NM	NM	
	12 inch	NM	NM	NM	- 0.005	- 0.015	0.00	Area of crack mitigation
	13 inch	-0.010	- 0.050	- 0.065	- 0.030	- 0.035	- 0.040	Vicinity of keyway Area of crack mitigation
	14 inch	NM	NM	NM	- 0.085	- 0.050	- 0.025	Vicinity of keyway Area of crack mitigation
	15 inch	- 0.005	- 0.045	- 0.060	- 0.085	- 0.115	- 0.095	Vicinity of keyway Area of crack mitigation
	16 inch	NM	NM	NM	- 0.085	- 0.105	- 0.070	Area of crack mitigation
	18 inch	NM	NM	NM	0.00	- 0.005	0.00	
	20 inch	- 0.030	- 0.020	0.00	- 0.010	- 0.015	0.00	
	22 inch	NM	NM	NM	- 0.110	- 0.090	- 0.040	Area of crack mitigation
	23 inch	- 0.120	- 0.120	- 0.030	- 0.190	- 0.240	- 0.160	Area of crack mitigation
	24 inch	NM	NM	NM	- 0.250	- 0.345	- 0.230	Left side of journal lubrication groove Area of crack mitigation
	25 inch	- 0.100	- 0.110	- 0.040	- 0.175	- 0.255	- 0.190	Right side of journal lubrication groove Area of crack mitigation
	26 inch	NM	NM	NM	- 0.075	- 0.100	- 0.060	Area of crack mitigation
	29 inch	0.00	0.00	0.00	0.00	0.00	0.00	

The development of cracks is complex, and depths may vary along the length. Recognizing that the identified cracks were relatively shallow, those with depths somewhat greater than anticipated were excavated rather than allowing crack-tips to remain within the highly stressed fillet region. The most extensive excavation, shown in Figure 13, undercuts the journal and the thrust face, but generally follows the contour of the original fillet. Detection and mitigation at an early stage may be expected to reduce the extent of material removal, and the potential for propagation or initiation of new cracks.

FIGURE 13: The deepest mitigation excavation undercut the plane of the journal surfaces, but followed the contour of the original fillet.

EXPECTED OUTCOME

Following mitigations of fillet-cracks, an extension of service life for the trunnions is expected, however, the many unknown factors defy an estimate that is definitive of time. With elimination of the crack tip, appropriate contouring, and polishing of the surface, the high concentrations of stress are more uniformly distributed within the transitional region, and the potential for initiation of cracks is significantly reduced.

Mitigations involve removal of material from the trunnion fillet region that may reduce resistance to bending stress; however the polished finish exceeds the smoothness of the original journal fillet, enhancing resistance to crack initiations. In consideration of uncertainties, susceptibility to cracking, and potential new initiations, continued examinations and appropriate remediation at regular intervals will assure of the integrity of the trunnions. Completion of mitigations allows the Bridge Authority time to plan for a non-emergency replacement of the trunnions, however, the trunnions may perform without further distress for several years to come.

SUMMARY AND CONCLUSIONS

Detection of cracks within several journals confirms the susceptibility of the trunnions to crack initiations, however, the absence of new crack initiations after two years of service within excavations for the 2015 crack mitigations suggests that procedures to eliminate developing cracks may extend the functional service life of the affected trunnions. The viability of mitigation should be established with estimates of crack depth prior to attempts for excavation. Effective crack mitigations require complete elimination of the crack tip, and polishing of the adjacent surfaces. It is imperative, therefore, that excavations are not interrupted prematurely, and that wet fluorescent magnetic particle examination is used to verify complete elimination of the cracks.

Regular monitoring examination of the trunnions is required to confirm an absence of cracks, and or to limit the extent of required excavation for possible cracks, with detection of potential fillet-crack initiations at an early stage. Excavations of fillet-cracks that may develop at a future date are expected to achieve a similar mitigation benefit. The need to implement plans for replacement of the trunnions will be prompted in continuing development of fillet-cracks, especially within the regions of mitigated cracks.