January 18, 2019

To: Matthew Donahue - SDOT
From: Brett Commander - BDI
CC: Jamie O'Day - SDOT, Kyle Ramer - BDI
Re:

Dear Mr. Donahue,

As you are aware, in December 2018, BDI performed a brief inspection of the current monitoring system at the West Seattle High Bridge, including the interior and exterior portions of cracked box sections. The attached document provides a summary of observations, an assessment of the current condition, recommended actions by SDOT, and recommended options for continued monitoring.

Please contact me with any questions or concerns.

Sincerely,

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Attachments: West Seattle High Bridge Monitoring Summary

INTRODUCTION

BDI performed a brief inspection of the existing monitoring system and the condition of cracked box girder segments at the West Seattle High Bridge. Inspection was limited to the main span and specifically to the regions where crack activity was known to exist. Detailed visual examination of cracks was concentrated on the interior and exterior portions of the main spans in the vicinity of the post tensioning termination in the bottom flange, however a brief visual inspection was performed on the entire main span.

The physical monitoring system is composed of a data logger and 8 crack sensors. There are 2 crack sensors at each box segment experiencing cracks. These segments are located near each end of the main span (10^{th} segment from the piers) and are located on both the north and south girders. While the monitoring components were provided by BDI, the monitoring system was designed by and installed by SDOT, so some level of reconnaissance was required.

The goals of the inspection were:

- Determine if a non-functioning sensor was repairable or needed replacement.
- Determine if additional structural monitoring sensors could be installed inside of the box girder rather than outside (requiring a UBIT).
- Examine crack patterns and provide recommendations for future monitoring.

OBSERVATIONS

MONITORING SYSTEM AND SENSORS

- The signal from a sensor providing faulty readings was examined at the field splice point with a manual readout. No readings were obtained manually indicating the sensor is no longer functional. This sensor either needs to be replaced or removed from the data collection.
- Sensor wire field splices inside the boxes were of poor quality, consisting of twisted wires and wire nuts (Figure 1). These splices, although still functional, should be improved with crimped or soldered splice connections.
- The logger cabinet is at approximately midspan of the north girder. The logger cabinet consists of the following components (Figure 2):
  - CSI CR1000 logger
  - CSI AM16/32 multiplexer
  - Sierra RavenXT modem
  - CSI AVW200 vibrating wire interface
- North girder sensor wires run from the crack meters, located near the middle of the soffit at the cracked segments, to the bottom edge of the segment, and up the girder web to a vent hole near mid girder height. The south girder sensor wires are run to the interior edge, up to the top of the web, across the interior top flange, back down the north web and into the same vent hole as the north sensor wires. Wires enter through the vent hole and continue along the girder interior towards midspan where they are connected to a multiplexer inside the data logger cabinet. Currently 8 channels of the 16-channel multiplexer are being utilized.
  - This means 8 additional sensors can be incorporated into the existing system with no modifications to any components. Expansion cost would be the cost of the sensor, sensor cable, and installation costs.
  - Additional multiplexers could be installed outside of the logger cabinet so larger scale expansion is also an option with relatively minor modifications. Each multiplexer can expand the system channel count by 16 for a relatively low cost considering all other factors.
- The sensors themselves are mounted to the bottom surface of the box girders with 2 sensors on each of the 4 cracked segments. One crack gage crosses perpendicular to the crack and is oriented with the girder axis. The

other crack sensor crosses the same crack at a 45-degree angle (Figure 3). This was presumably done to determine if the crack movement was one directional.

- Crack sensors wires are mounted with concrete screws and small plastic “P clamp” anchors. Many of the plastic anchors have failed so some of the wires are hanging below the box. While not critical, some level of maintenance should be done to replace the plastic “P clamps”. This could be done during a routine inspection or as part of a maintenance effort.

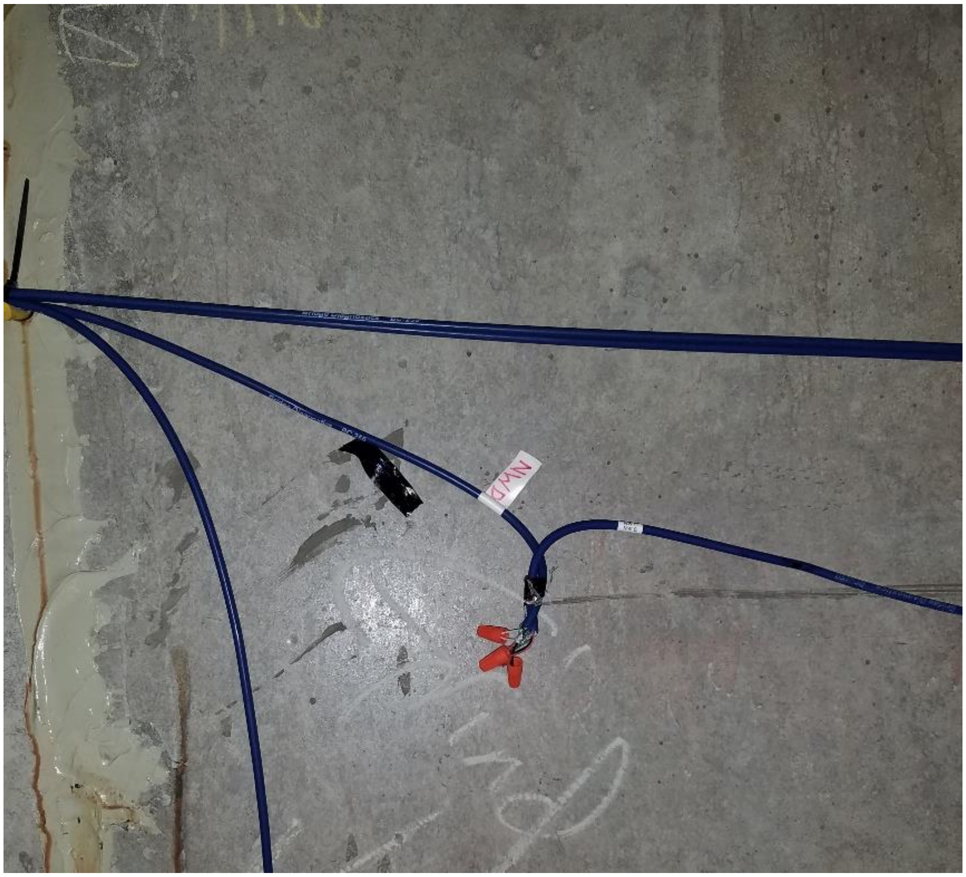

Figure 1 Sensor wire field splices

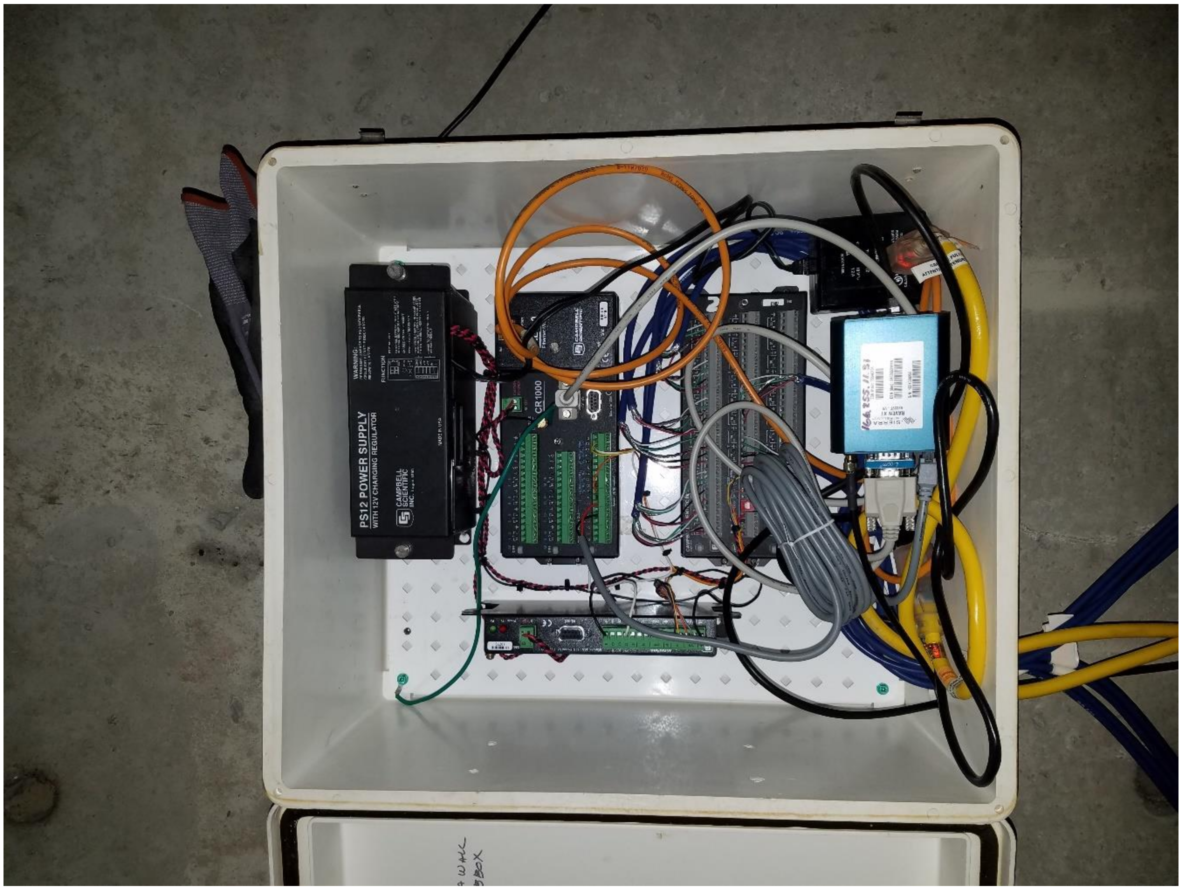

Figure 2 Existing logger cabinet consisting of CR1000 logger, AM16/32 multiplexer, RavenXT modem, AVW200 VW

Figure 3 Typical crack meter installation on soffit of box girders

CRACK FORMATION – GIRDER INTERIOR

Crack formation was examined on the interior faces of both the north and south main-span box girders. Crack formation was found to be in isolated locations and exceptionally consistent and symmetric with respect to the span, the bridge cross-section, and the girder cross-section. The consistency and symmetry of the crack formation throughout is an important clue as to the likely cause and continued propagation of the cracks.

Cracks in the girder floor were observed in the 10th segment from the pier which was the first segment beyond the bottom flange main-span post tensioning. A peculiar observation was that cracks appeared to initiate from the web/flange interface and travel across the bottom flange at a 45-degree angle towards the pier and the center of the box. These cracks originated from both webs and met at the middle of the box which was also the interface with the adjacent segment. In general, bottom flange cracks did not appear to propagate into the adjacent (9th) segment as this was the point of intersection along the two diagonal crack lines. Several parallel lines of cracks existed and were at roughly 12-inch spaces. Figure 4 illustrates the formation of the bottom flange cracks as seen from inside the box.

In addition to the bottom flange, cracks were observed in the box webs in the adjacent segments (11 and 12 from the piers). These cracks appeared to be classic shear cracks as they extended up the webs at a 45-degree angle. These cracks appeared to be extensions of the floor cracks as they originated at the same location along the flange/web interface. Figure 5 illustrate the location and pattern of the web cracks.

Figure 4 Diagonal cracks across box floor originating from floor/web interface just beyond post tensioning anchorage

Figure 5 Diagonal shear cracks on box webs and at floor/web interface

CRACK FORMATION – GIRDER EXTERIOR

Crack formation observed from inside the box were essentially mirrored on the outside surface indicating they were all through cracks. Due to better lighting and a smoother concrete finish, cracks were much easier to see on the outer surfaces. As with the interior, the crack formation on the bottom flange was limited to the segment adjacent to the post-tensioning termination (10th seg from the pier). The web cracks appeared to extend from the bottom flange cracks and travel up the web at a 45-degree angle as shown in Figure 6. The web exterior web cracks were primarily visible in the 11th and 12th segment from the pier as shown in Figure 7.

As was observed in the interior surfaces, the crack formation was very isolated to the same three segments (bottom flange @ Segment 10 and webs of segments 11 and 12) at each end of each box girder. One observation that was easier to detect from the outside, was a shift in orientation of the bottom flange cracks. Figure 8 shows bottom flange cracks which are oriented at a 45-degree angle near the edges of the girder tend to shift to a perpendicular orientation near the center of the box. From the outside, it was apparent that some bottom flange cracks did extend into the adjacent segment (#9 from the pier). Most of these were oriented across the girder indicating positive moment flexural activity (tension in the bottom flange).

Figure 6 Continuation of bottom flange diagonal cracks into web – exterior bottom flange / web interface.

Figure 7 Diagonal shear cracks in exterior face of vertical web.

Figure 8 Bottom flange diagonal cracks shifting to transverse cracks near middle of box girder.

CRACK ASSESSMENT

Based on the observations listed above, a primary hypothesis was generated as to the cause and effect of the existing cracks. The primary clues include:

- Symmetrical diagonal cracks across the bottom flange that extend from both edges of each box and meet near the middle of the box cross-section.
- Diagonal floor cracks shift in orientation near middle of box to perpendicular.
- Diagonal shear cracks in vertical webs that appear to extend from the bottom flange.
- Existing crack monitoring was placed on soffit. No monitoring of web shear cracks.

It seems that the initial discovery of the cracks was at the bottom soffit and that the web cracks begin to appear later. The diagonal cracks across the bottom flange do not correspond with normal gravity loading scenarios and are therefore assumed to be associated with a horizontal shear load or a torsional load on the girder. The fact the cracks are highly symmetrical along the axis of the girder indicates the shear and/or torsion occurred equally in both directions. The consistency of the cracks with respect to both ends of the span and both the north and south girders rules out any sort of settlement issue and highly suggests seismic activity. Therefore, based on the timing and sequence of crack formation, orientation of cracks, and consistency of cracks it is highly probable that the initial formation occurred within the bottom flange as a result of torsional deformation during a significant earthquake.

Web shear cracks are more consistent with gravity loads but were likely initiated from the combination of vertical shear and torsional shear due to seismic loading. The fact that the bottom flange and web cracks appear to be a continuation of the same crack suggests that initiation occurred at the same time.

Records indicate that the cracks are growing in length and that more cracks are developing, although crack monitoring has not shown significant activity in crack width at the instrumented locations. The progression of shear cracks and the rounding of the bottom flange cracks near the middle of the box suggests that while the cracks were initiated due to torsional loads, they are continuing to propagate as a result of gravity loading. Continued crack growth is likely a function of the increased flexibility at the cracked segment. Increased flexibility translates into additional movement and therefore additional cracks. It is therefore highly likely that crack growth in the form of length, width, and density will continue to increase.

Analyses performed by others indicate that the bottom flange cracks are not a structural concern as this segment is near the span inflection point and the structure would function fine with a hinge at that location. This assessment seems reasonable and it is likely that loss of tension stiffness in the bottom flange does not significantly result in a loss of girder load capacity.

What is not known, is if the presence of the diagonal shear cracks has been adequately addressed from a load capacity view point. The shear cracks do have a direct impact on the girders' vertical shear capacity at the influenced segments. While the span can handle flexural moment safely with a hinge at the cracked section, the hinge must be able to withstand all required vertical shear loads.

Regardless if strength and safety are a concern, a serviceability issue does exist as the cracks provide a means for moisture, chlorides, and oxygen to penetrate the concrete and accelerate deterioration of the reinforcing steel.

RECOMMENDATIONS

STRUCTURAL CONDITION AND SAFETY

The primary issue is to determine if the recent structural capacity assessments adequately addressed loss of shear capacity due to web cracks. This is the primary risk with regards to structural strength and potentially a major concern if the shear capacity is deficient. Due to the presence of the cracks including the length, quantity, and spacing shear capacity should be done using a "Strut and Tie" evaluation. A standard vertical shear capacity calculation based on steel shear capacity (Vs) and concrete shear capacity (Vc) would not provide a realistic assessment. If this work has not already been done, it should be a high priority to have it done. This assessment should be a reasonably simple process using results from previous analytical models.

STRUCTURAL CONDITION AND SAFETY

Hopefully the cracks do not present a concern from a load capacity or safety viewpoint, regardless the cracks do pose a threat to the long-term performance as they allow for the ingress of moisture, chlorides, and oxygen which can accelerate corrosion of the reinforcing steel. Therefore, it is recommended that all cracks in the bottom flange and the vertical webs be sealed with epoxy injection.

In addition, stiffening procedures should be considered, as epoxy injection will not significantly reduce the segment flexibility. Increased flexibility resulting from the existing cracks is currently a driving mechanism for continued crack growth. If stiffening procedures are not implemented, epoxy injection may be a re-occurring procedure for the life of the bridge.

To simplify visual inspection of these areas, it is recommended that the webs of the cracked sections be painted with white primer during the epoxy injection process. This will enable inspectors to visually identify crack growth and formation of new cracks.

FUTURE MONITORING

Future monitoring should focus on crack growth in the vertical webs as it is directly related to structural capacity and safety. The extent, urgency, and criticality of the monitoring will be a function of revised analyses and load rating calculations. In all cases, there are essentially eight monitoring locations; vertical webs on both sides of the box girders, on the north and south boxes, at both ends of the span (Segments 11 and 12 from the pier). Additional monitoring of the bottom flange is optional but not as serious of concern since flexural capacity at that location has been identified to not be a strength/safety concern. A range of options are listed below:

1. Expand existing monitoring system to include crack width monitoring on each web. This would include between 8 and 32 additional crack sensors and could be installed at relatively low cost. Ballpark cost estimates for sensors, installation, and implementation into existing monitoring system range from $18,000 to $64,000. The number of sensors would essentially be dependent on whether a single crack per web is to be monitored or several cracks should be monitored at each location. This decision would be a function of the revised load rating results as to whether the situation is a strength/safety concern or strictly a serviceability issue. Installation costs are a function of work windows and therefore only approximate at this time.
2. If resulting shear load Rating Factors do indicate a risk (Rating Factors below 1.0), a more intensive monitoring program may be warranted that not only includes monitoring of existing cracks but also formation of new cracks. This can best be achieved with long displacement sensors to monitor overall shear deformation of the cracked webs and essentially examine the impact of all cracks in the vicinity. Instrumentation of this type can easily be implemented into the existing monitoring system. These sensors could be implemented in combination with, or in lieu of, the crack sensors indicated in Option 1. Eight sensors would be recommended (one at each monitoring location). Cost of sensors, installation, and implementation within existing data logger would be approximately $20,000.
3. In addition to Option 2, Acoustic Emissions (AE) sensors on each web can provide an indication of crack activity and track for changes in daily counts of detectable crack growth and amplitudes of associated energy release. While no direct measure of crack length or width would be obtained, it would provide an indication of activity acceleration. This technology would require additional monitoring equipment beyond the existing onsite data logger. However, results from the AE monitoring equipment can be incorporated into the web-based monitoring system including use of alarm features. A cost estimate for this application is not available at this time as additional research in methodology are required. This option would most likely be implemented only if shear load ratings are found to be deficient.