# Segmental Bridges: Case Studies and Lessons Learned

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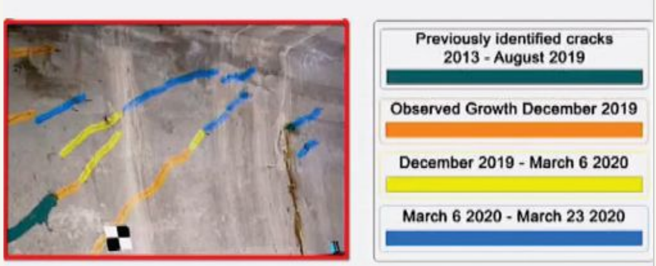
Segmental bridges are durable and have a long history in the U.S. bridge inventory. With the oldest of these bridges approaching the end of their initial design life cycles, owners are seeking to extend their useful lives. Most segmental bridges have performed well and can have extended service lives if detailing issues and maintenance concerns are addressed, as discussed in this series of articles on segmental bridge rehabilitation (for the previous articles, see the Winter 2022 and Spring 2022 issues of *ASPIRE*®). This last article in the series focuses on case studies and lessons learned from completed and ongoing rehabilitation projects. There is a lot of value in learning from bridge rehabilitation projects, as most of the solutions come from out-of-the-box thought processes that frequently lead to ideas for durable repairs that can be implemented economically. The following three case studies will present the issues, probable causes, solutions, and lessons learned for these unique challenges.

## Case Study: West Seattle High-Rise Bridge Emergency Repairs

The West Seattle High-Rise Bridge was designed as a concrete cantilevered, segmental box-girder bridge rising 140 ft above the Duwamish Waterway and extending 1340 ft across three spans. Construction commenced in 1981 and the bridge opened to traffic on July 14, 1984. It serves as a link for more than 100,000 vehicles per day between the neighborhood of West Seattle and the rest of Seattle, Wash.



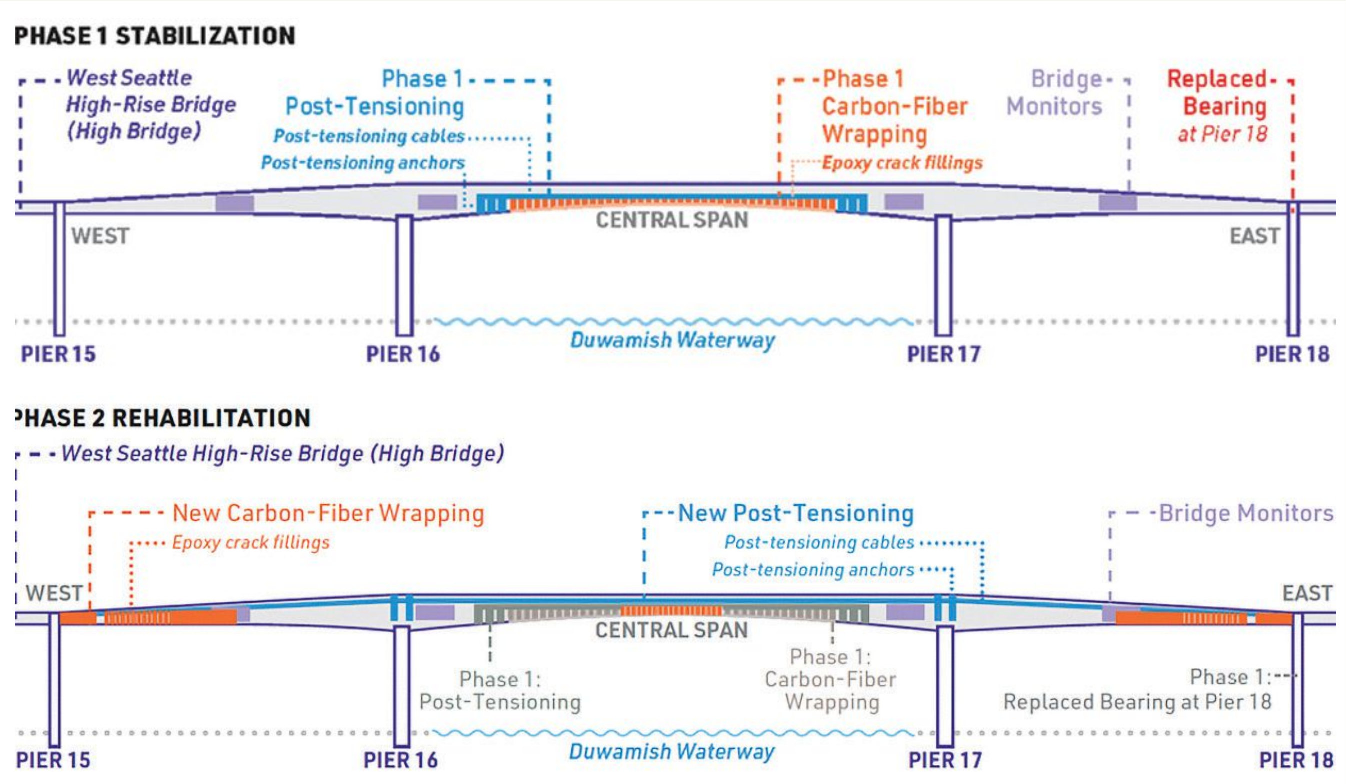

Tracking crack growth at one location on the West Seattle High-Rise Bridge from 2013 through the bridge's closure on March 23, 2020. Photo: WestSideSeattle.com.

### Issues

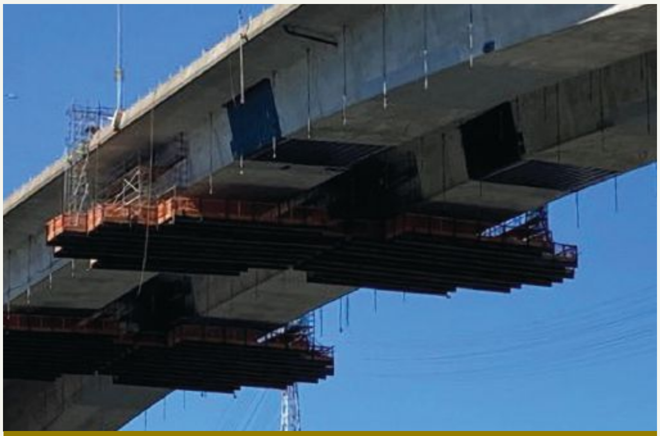
During a 2013 routine inspection, cracks averaging 0.01 in. in width were identified at four locations near post-tensioning tendon anchorages. A recommendation was made to seal the cracks with epoxy, install eight electronic crack monitors, and conduct frequent observations to monitor cracks that could expand or penetrate the girder walls. During a subsequent 2014 inspection, inspectors reported that several cracks appeared larger than previously recorded and that indeed some cracks now appeared to penetrate the 12-in.-thick box-girder walls.

In late 2018, specialists found that cracking had proliferated beyond the previously identified locations and a recommendation was made to install 32 additional crack monitors. Follow-up inspections in May and November of 2019 found that existing cracks had not appeared to widen; however, significant additional cracking was noted in both the slab and webs of the girders,

Electronic crack monitors and epoxy injection repairs in December 2020 on the West Seattle High-Rise Bridge. This photo shows four of the previously installed crack monitoring devices and electronic data cables along with one of numerous cameras (visible in the upper left corner of the photo), installed throughout the bridge to allow visual monitoring of cracking. Photo: Pullman Services.




Schematic elevation views of the West Seattle High-Rise Bridge showing activities and locations for Phase 1 stabilization and Phase 2 rehabilitation projects. Figure: Seattle Department of Transportation.



Access platforms for initial repairs to the exterior of the West Seattle High-Rise Bridge. Photo: WestSideSeattle.com.

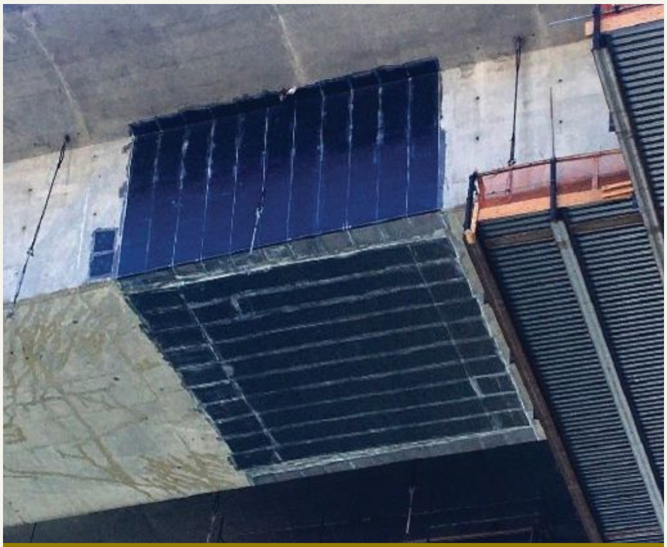
including extensive diagonal cracking in the walls of the main span. Although some cracks were found to extend the full depth of the concrete, the vast majority of the cracks encountered did not appear to extend the full depth of the girder slabs and walls. In those cases where cracking did extend the full depth of the concrete, the crack widths at the exterior surfaces were "hairline" in nature. Work orders were issued to perform additional epoxy injections to mitigate moisture intrusion.

In February 2020, engineering studies revealed significant concerns regarding load capacity. It was suggested that daily observations be conducted, and plans developed to reduce the number of traffic lanes. On March 19, the accelerating rates of crack growth led to a recommendation to close the bridge and to begin developing plans to inhibit potential collapse. On March 23, the Seattle Department of Transportation ordered an immediate closure to all traffic.

## Cause

Numerous factors, including heavier truck and bus traffic, the addition of a seventh traffic lane, and a 2001 seismic event, have been theorized to be contributors to the documented

One aspect of the rehabilitation of the West Seattle High-Rise Bridge was the installation of new external post-tensioning tendons and anchorages inside the bridge. Photo: Pullman Services.



As part of the rehabilitation of the West Seattle High-Rise Bridge, carbon-fiber-reinforced polymer was installed at selected locations. Epoxy-injected cracks are visible on the bottom slab of the box girder. Photo: WestSideSeattle.com.

deterioration. In addition, it was also suggested that the superstructure may have gradually weakened over time due to long-term creep of the concrete within the box girders. If that theory were true, where the bottom slab anchorage blisters were originally within the negative moment envelope with the concrete in compression, the anchorages would now be within the positive moment envelope with the concrete in tension.

However, it has since been determined that the primary cause of the cracking was that the bottom continuity post-tensioning anchorages were not adequately distributed within the spans, which created local and global tensile stress issues. Therefore, the root causes of the observed cracking were the local effects of concentrated anchorages of the bottom continuity post-tensioning tendons, inadequate detailing of the bottom slab reinforcement at those anchorages, and limited understanding or sophisticated tools to predict time-dependent effects.

### Solutions

Following the 2020 bridge closure, a two-phase approach to stabilization and repair was developed. Phase 1 focused on stabilizing the main span to mitigate concerns regarding potential collapse, whereas Phase 2 would complete repairs necessary to fully reopen the bridge to traffic.

Phase 1 repairs commenced in late 2020 and required the use of custom platforms to access the bridge's exterior. To stabilize the structure and to allow subsequent Phase 2 repairs to be performed, the project team implemented a repair scope that included epoxy injection at crack locations, installation of an external longitudinal post-tensioning system within the concrete box girders, and the installation of carbon-fiber-reinforced polymer (CFRP) at selected locations along the superstructure.

Phase 2 commenced early in 2022 and again included CFRP and external longitudinal post-tensioning, as well as more comprehensive epoxy injection at the remaining cracks located throughout the superstructure. The West Seattle High-Rise Bridge is currently expected to be reopened to traffic in July 2022.

## Case Study: Roosevelt Bridge

The Roosevelt Bridge in Stuart, Fla., is a twin, precast concrete, post-tensioned segmental box-girder bridge constructed using the balanced-cantilever method. The two parallel structures each have 41 spans and a total length of approximately 4600 ft. The bridge's post-tensioning system consists of internal grouted tendons in galvanized corrugated metal ducts.

### Issue

In June 2020, the Florida Department of Transportation (FDOT) closed portions of the bridge to address emergent repair needs identified during a routine inspection. Cracking was discovered in the bottom slab of southbound span 1 over Dixie Highway, and out of an abundance of caution, both bridges and Dixie Highway were immediately closed to traffic.

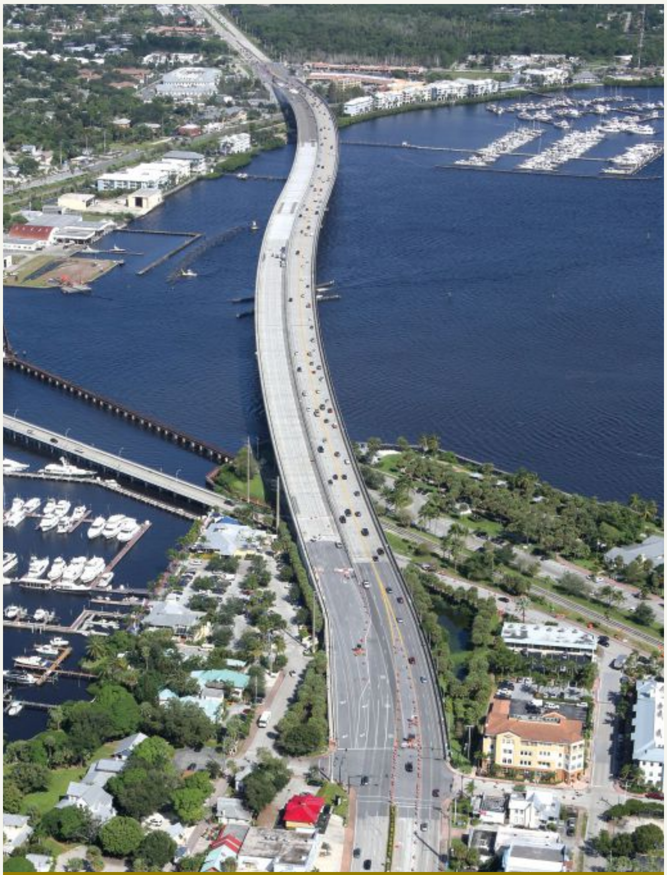
### Cause

FDOT quickly assembled a team of consultants to determine the extent of the issue because it could compromise the life safety of the traveling public. They determined that the crack was caused by five post-tensioning tendons that had failed in the bottom slab due to excessive corrosion. The corrosion was attributed to water that migrated from the bridge deck through segment joints and bottom slab tendons, and leakage through fiberglass storm drainage pipe joints inside the bridge. The consultants further determined that the immediate issue was isolated to the southbound structure, and the northbound structure could be reopened to traffic. As the northbound bridge was being reconfigured to accept both north- and southbound traffic, an emergency shoring system was installed beneath southbound span 1, which would allow the reopening of Dixie Highway.

### Contracting and Construction

The initial crack was discovered on June 16, 2020; emergency shoring was in place by June 26; and the northbound bridge reopened to traffic on June 27. Dixie Highway was reopened on July 3 after being realigned to clear the emergency shoring system.

FDOT began the design for the repair of the bridge and initiated an emergency contracting process for the repairs. For the first time in FDOT history, the agency selected the construction manager/general contractor (CMGC) method of project delivery. This contracting method leverages early contractor involvement to assist with design and repair methods, expediting project completion and reopening of the structure.



North- and southbound traffic on the northbound Roosevelt Bridge during repairs to the southbound bridge. Photo: Florida Department of Transportation and Cardno.

On June 30, four contractors were solicited for the work with a preliminary repair scheme and request for quote. Selection was made on July 17; contracts were executed on July 20; and the notice to proceed was issued on July 21 for an immediate start. The preconstruction phase allowed 30 days for collaborative development of repair plans and mutually agreeable lump-sum construction pricing.

Once the construction phase began, supplemental shoring was added to southbound span 1. The emergency shoring was adequate in capacity; however, it could not be moved to facilitate the support and adjustment of each precast concrete bridge segment during repairs. During the construction phase, the remaining bottom slab continuity tendons on southbound span 1 had to be detensioned, and their associated concrete anchorage blocks had to be removed from inside the box section to clear the way for the installation of the new post-tensioning system. The supported segments of southbound span 1 also needed to be raised and lowered during the repair process to avoid cracking in the webs as existing tendons were detensioned and to reinstate the original geometry and ride quality of the bridge deck.

### Solution

An innovative repair solution was implemented, involving the installation of external multistrand post-tensioning tendons inside the box to replace the failed and corroded existing internal tendons. The tendons were installed above the bottom slab using new cast-in-place concrete deviation blocks to anchor the tendons. Existing concrete anchorages were demolished and removed. This solution protects against corrosion while also allowing FDOT to remove and replace the tendons in the future, if necessary. This solution also maintains the aesthetics of the bridge, as the repair did not alter the outward appearance of the structure. In addition to adding external post-tensioning to southbound span 1, multistrand tendons were also installed in 17 other expansion joint spans to strengthen the structures to meet updated design specifications, based on the load rating analysis. In total, 48 new external post-tensioning tendons were installed in the two bridges.

During the repair work, FDOT personnel performed thorough inspections of the bridge deck and internal tendons. Hundreds of core samples were taken to assess concrete and strand condition across all areas of both bridge structures. These inspections determined that minor cracking in the bridge deck surface and cracks between precast concrete segment joints, or between segment joints and the original closure pours, could allow water to migrate through the concrete and into the post-tensioning tendons. Water from the highly corrosive coastal environment could carry and deposit chlorides within the concrete and grouted post-tensioning tendons. To protect their investment and extend the structures' service lives, FDOT decided to prevent water recharge within the concrete and post-tensioning tendons by having the CMGC perform epoxy injections, externally seal bridge segment joints, and install an epoxy deck overlay on both bridges.

## Case Study: Channel Five Bridges in the Florida Keys

The Channel Five segmental bridge is located in one of the most beautiful, and harshest, environments for a bridge structure. The precast concrete segmental substructure of this critical bridge has endured daily exposure to saltwater from tidal, wave action, and seawater spray for more than 40 years.

### Issue and Cause

Chloride had penetrated to the outer layers of the substructure's reinforcement and had infiltrated defects in the segment joints and post-tensioning bar blockout pourbacks, which initiated corrosion in the mild reinforcement and vertical post-tensioning bars, leading to spalling of the exterior concrete cover on the precast concrete segmental box piers. An engineering evaluation of the bridge in its current state was performed, and the substructure load demands that are imposed on the bridge as it sits today were determined. It is critical to understand where this bridge is relative to the imposed deformations from creep and shrinkage, which will have largely already occurred at this time. The theoretical calculations can be generally confirmed from observations of the bearing deformations after correction for thermal movement. However, after more than 40 years, the structure has already experienced the long-term movements, and this process is far from an exact science.

To facilitate repairs on the southbound span 1 of the Roosevelt Bridge, additional 100-kip-per-leg shoring towers were added around the initial emergency shoring. In the upper right of the photo, a vertical crack is evident in the outside web of the box girder. Photo: Structural Technologies.

### Developing Solutions

As with any rehabilitation program, the challenge is to determine the currently available capacity, how much capacity can be restored through a rehabilitation scheme, and the inevitable benefit-to-cost ratio evaluation. This evaluation generally assesses how much additional useful life expectancy can be achieved and how much extending the life of the current structure would cost compared with replacement. One benefit of segmental bridge construction is that, in most cases, the substructure capacity is based on temporary construction requirements, which can be much higher than the service-level design forces. This is particularly true for substructures, as in this case, because the span-by-span construction technique used for this bridge required larger pier column dimensions to support the temporary erection truss that was used to support the span segments. The construction demands, coupled with the relatively high axial force from the self-weight of the robust concrete box girder, yields a significant amount of capacity available for service-level loads where creep- and shrinkage-imposed deformations have already occurred. The net result or benefit of this substructure design was that the aforementioned section loss of vertical post-tensioning bars did not create a concerning loss of capacity. These evaluations are still ongoing, and solutions are being developed to restore the capacity required to address design loads, including the higher wind loadings that are required by today's specifications. (See the article in the Winter 2017 issue of *ASPIRE* about a similar situation where a solution to replace piers under a segmental concrete box-girder bridge was developed, allowing the bridge to remain in service.)

## Lessons Learned

Some of the key lessons learned on these projects are the following:

- The level of effort needed to evaluate an existing structure cannot be understated, particularly for structures with extensive deterioration.
- Parametric studies help assess the remaining capacity where there is some uncertainty regarding the amount and location of section loss and/or deterioration.
- Constructability must be a primary consideration in evaluating rehabilitation options, particularly if the structure's reduced capacity due to deterioration could preclude some rehabilitation alternatives.
- It is crucial to fully vet repair materials, particularly for their suitability for use on the project site. Because field installation is performed on deteriorated concrete under less than optimum conditions, materials may not achieve the same strength or durability exhibited in laboratory results.

## Conclusion

These three case studies demonstrate that the industry is fully capable of effectively rehabilitating and preserving existing segmental concrete bridges if they encounter performance challenges. The projects highlighted represent the power of leveraging the cumulative knowledge gained over the past several decades. A holistic approach that identifies the root causes for issues observed in a structure and carefully considers the most appropriate repair strategies can lead to extended service life and optimal performance results. Great things are

A typical segmental box pier of the Channel Five Bridges in the Florida Keys has experienced daily exposure to saltwater from tidal, wave action, and seawater spray for more than 40 years. This had led to spalling of the exterior concrete cover. Photo: COWI.

possible when experienced and qualified teams work together methodically to assess the performance challenges, properly understand defects, and implement well-conceived solutions. Keys to success for the case studies presented here included not only innovative technical considerations but also new and unconventional approaches to problem-solving and project delivery. True collaboration and open communication among all project team members is vital for collective success.

This article is intended to take the principles and concepts from the two preceding articles in the series and show how they can be practically applied. These examples, and others like them, can also provide us with confidence in the continued use of segmental concrete bridge design and construction methods for new bridges in the future. Practitioners in the industry can, and will, carry forward the lessons learned into the design and construction of new projects.

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EDITOR'S NOTE

*COWI acquired FINLEY Engineering Group in April 2022.*

The Virginia Route 33 Bridge over the Mattaponi River has post-tensioned lightweight concrete spliced girders with a lightweight concrete deck to achieve two units with spans of 200-240-240-200 ft. Photo: *Kenneth S. Harmon*

## Structural Lightweight Concrete Contributes to **Sustainable Solutions**

To address global climate change, designers are now examining designs to reduce energy consumption and the release of greenhouse gases in the construction materials being used. Even though high temperatures and significant energy is required to expand lightweight aggregate, an article in the spring 2022 issue of *Lightweight Design eNews* (https://www.escsi.org/e-newsletter/engineers-corner-myths-and-misconceptions-6/) demonstrates that embodied energy and emissions in the construction materials used for a lightweight concrete building can be reduced compared to an equivalent building constructed using normalweight concrete because the quantities of materials are reduced for the lightweight concrete building. The article includes tables of embodied energies and emissions for each construction material that are multiplied by the mass of that material used in the building. The sum of these quantities provides an estimate of the total embodied energy (or emissions produced) in the materials used to construct the building.

The same tables of embodied energy and emissions can be used for bridges. While a bridge example is not currently available, it is likely that a bridge designed to fully utilize the benefits of lightweight concrete would have a reduced impact on the environment compared to an equivalent design using normal weight concrete, similar to the improved results shown for the building. To obtain a more complete understanding of the environmental impact of a structure, transportation and construction activities, as well as waste generation and water use, should also be considered.

The members of ESCSI, who produce rotary kiln expanded shale, clay, and slate lightweight aggregate, have been working to reduce the energy and emissions intensities for their materials for many years. The industry is confident that lightweight concrete will be more widely used as more designs are required to consider the total impact of a project on the environment.

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ESCSI
Expanded Shale, Clay and Slate Institute
Rotary Kiln Structural Lightweight Aggregate