Understanding Segmental Bridge Defects and Effective Repair Solutions

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The previous article in this series (see the Winter 2022 issue of *ASPIRE*®) introduced the topic of preservation of concrete segmental bridges in the United States. It discussed the performance challenges for these unique structures and the lessons learned over the last several decades. Better understanding of investigation and inspection techniques—nondestructive and exploratory—and implementation of the holistic analysis methodology described in the article provide the industry with the tools and confidence to ensure that rehabilitation and service-life extension are achievable for concrete segmental bridges. This article explores defects that may be found in concrete segmental bridges and outlines some of the engineering implications. It presents repair solutions and processes, including project delivery methods conducive to optimizing outcomes.

Defects

Spalling and Reinforcement Corrosion

Segmental bridges experience concrete deterioration mechanisms similar to traditional bridges, albeit at a much-reduced pace due to the benefits of prestressed concrete elements and high-quality concrete materials.

Reinforcing steel corrosion is a primary cause of concrete deterioration. Corrosion is an electrochemical process requiring an anode, a cathode, and an electrolyte. These elements combine to form a corrosion cell. The corrosion process causes the steel to rust, creating expansive forces that ultimately lead to the delamination and spalling of concrete (**Fig. 1**).

Reinforcing steel in concrete is typically protected by a passivating layer formed on the steel in an environment with a high pH level, which is found within concrete. Disruptions to passivation can be caused by chlorides or by carbonation of the surrounding concrete.

Exposure to chlorides dissolved in water, such as saltwater spray in coastal environments or highway deicing salts, accelerates the corrosion process. Cracks and joints may allow water and contaminants to reach embedded metals more quickly.

Carbonation is a process where carbon dioxide in the air is absorbed into the concrete and lowers the concrete's pH. A pH below 10 promotes corrosion. Carbonation is typically a slow-moving process that occurs in environments where structures experience wetting and drying cycles.

Grouting Issues and Post-Tensioning Tendon Deterioration

Over the past 20 years, corrosion of post-tensioning strands in segmental bridge construction has been investigated, the causes determined, and solutions developed. Corrosion and potential failure of tendons is an ongoing concern. It is important to understand the causes of corrosion before developing repair and strengthening solutions, should it be determined that repairs are necessary.

Corrosion of segmental bridge tendons in the United States was first discovered in the early 2000s. A variety of issues

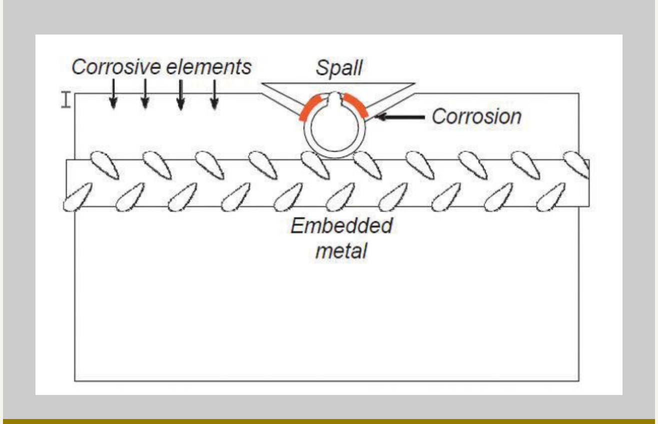

Figure 1. Corrosion is an electrochemical process requiring an anode, a cathode, and an electrolyte. If all of these elements are present, they can combine to form a corrosion cell that causes the steel to rust, creating expansive forces that ultimately lead to the delamination and spalling of concrete. Figure: Structural Technologies.

primarily involving the materials, detailing, and installation techniques related to tendon grouting were determined to be the root causes. The earliest post-tensioning tendon grouts consisted of cement and water as the basic constituents, which at times were augmented with grouting aids such as expansive admixtures. Grout was injected into galvanized, spirally wound metal ducts, which were found to provide poor protection in a corrosive environment in some situations.

Grout-related issues uncovered in these early bridges include segregation of grout materials; voids in grouted ducts; porous, soft grout that remained pasty and permeable; poorly protected tendon anchorage systems; and poor detailing at closure pours (**Fig. 2** and **3**). These issues are discussed in more detail in the previous article in the Winter 2022 issue of *ASPIRE*.

To remedy these issues, the industry made several advancements in grouting details and technology, which are also discussed in detail in the Winter 2022 article, as well as articles in the Winter 2017 and Summer 2019 issues of *ASPIRE*.

Figure 2. Corrosion of individual post-tensioning strands in an external tendon at a location where the duct was not completely grouted, leaving strands unprotected. Photo: Structural Technologies.

Figure 3. Corrosion of an external post-tensioned tendon at a location of soft, moist grout. Photo: Structural Technologies.

Engineering Considerations

Long-Term Post-Tensioning Losses

Our body of knowledge on creep and shrinkage of concrete has been enhanced over the years. Early methods often just applied a factor to the initial forces to account for these phenomena. This approach does not capture the redistribution of the imposed deformations from creep and shrinkage and sometimes provides an inaccurate representation of the actual variation in stresses with time in these bridges and can lead to premature cracking. Modern codes such as the *fib* (International Federation for Structural Concrete) *Model Code for Concrete Structures 2010*,[1] as well as modern software, have greatly improved the accuracy of predictions about creep and shrinkage behavior. Modern design approaches also ensure that predictions of creep and shrinkage are sufficiently bracketed by considering high and low predictions to better account for long-term effects.

Live-Loading Changes

Since the advent of complex post-tensioned bridges, live loading has progressed well beyond the original HS20-44 design truck developed in 1944. Truck sizes and traffic volumes have increased significantly. The HL-93 notional loading reflects these contemporary demands and is a significant increase over the original HS20 highway loading, particularly for spans greater than 150 ft. The loads for spans of that size were found to be underestimated by the older method, which is unfortunate because spans greater than 150 ft are where post-tensioned girders begin to be considered. Older bridges, and older segmental bridges in particular, are subjected to more live-load demand than they were originally designed for, which may lead to structural cracking and potential deterioration.

Principal Stresses

Early design codes did not require designers to check principal shear stresses. This stress check, which is required in current design codes, is particularly critical for webs to ensure that web shear cracking does not initiate under service-load conditions. Earlier design codes placed some limits on the concrete contribution for shear under factored loads, but no checks were required at the service limit state. In addition, critical detail areas such as anchor blocks and diaphragms may be subject to large tensile stresses from restraint and stress concentrations such as reentrant corners that were not considered in the original simplified analysis and may result in cracking. Today, finite element analysis software can analyze these critical areas and identify the need for additional reinforcement for high principal stresses. Earlier bridge designs did not benefit from modern analysis methods, and thus locations of high principal stresses are sometimes subject to cracking and spalling.

Casting Geometry

In the casting yard, proper match casting of segments is critical to ensure that the compressive stresses due to post-tensioning can be transferred across the segment joints through uniform bearing. The bearing surface can be interrupted by several different issues. Improper repairs made to segments before erection may result in localized bearing "hot spots" that cause an internal redistribution of stress across the joint. Improper shimming of segment joints can also create the same effect. Over the service life of the structure, these localized hot spots create stress concentrations that can lead to cracking and/or spalling and may lead to the beginning of local deterioration in the segment. Older segmental bridges with dry joints (no epoxy) are particularly sensitive to localized bearing points. Epoxy-coated joints help provide a uniform bearing surface to compensate for shims, repairs, and any irregularities.

Cracking

Issues that cause unintended stresses may eventually lead to cracks in segmental bridges. Although prestressed concrete is designed to limit concrete service stresses in the precompressed tensile zone, unintended concrete tensile stresses can lead to cracks in segmental concrete bridges. Given that service-level design stresses are based on the full design section contribution, cracking may create a local section loss within the concrete cross section. Over time, this section loss can be progressive and result in higher localized tensile stresses and changes in the flow of stress around these local section-loss regions, which may contribute to additional unintended tensile stresses.

Repair Solutions

Segmental bridges are durable structures by design. With careful monitoring, inspection, repair, and rehabilitation, the intended function of these bridges can be maintained to provide the full, if not extended, service life.

The successful repair of corrosion-damaged concrete requires a clear understanding of the causes of the deterioration and the careful selection of repair materials and application techniques.

Material Selection

Selection of concrete repair material is focused on ensuring that the material is appropriate for environmental and structural loads and is compatible with the substrate material. The following are important properties to consider when selecting materials:

- Compressive strength similar to the underlying substrate.
- Low drying shrinkage of repair materials—suppliers should be asked to provide shrinkage data. Drying shrinkage can be controlled by minimizing water demand (low cement content consistent with design strength and maximum aggregate distribution), water-reducing admixtures, and proper curing.
- Compatibility with placement techniques (pumping, pouring, and pressure placement into forms) to ensure proper filling of the repair cavity.

Repair Process

The following procedures are necessary for the successful repair and extended service life of concrete members:

- Ensure the safety and stability of the structure by removing loads and/or shoring and bracing as determined by a licensed design professional.
- Remove corrosion. This is critical to the long-term success of surface repairs. Repairs have failed because reinforcing steel corrosion was not properly removed.
- Remove concrete around a corroded reinforcing bar that has lost bond with the existing concrete. This removal is critical for the repair to be successful and will allow the new material to fully encapsulate the

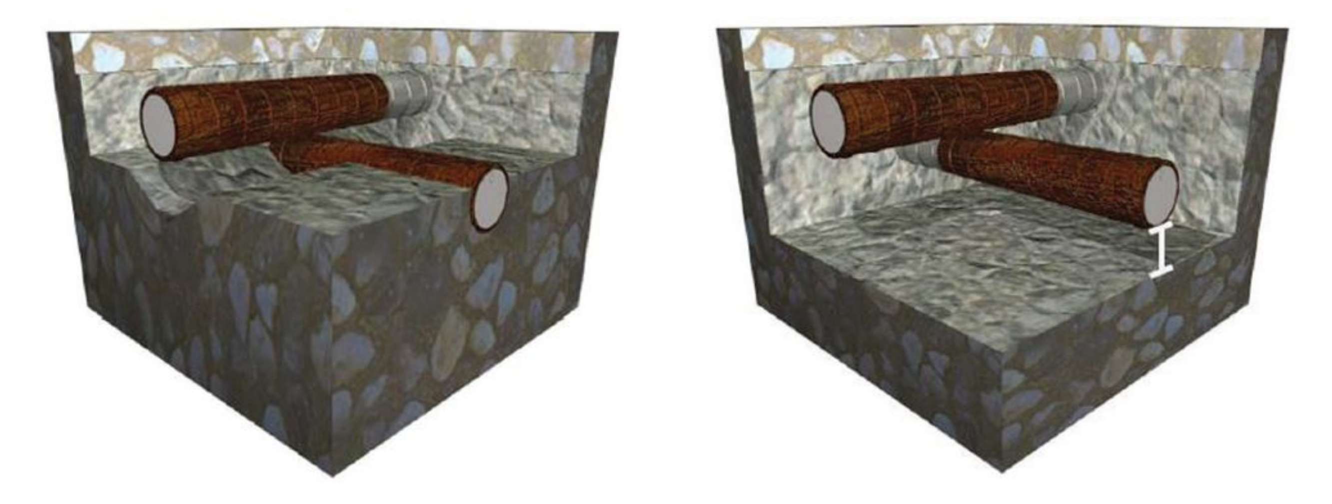

Figure 4. When multiple reinforcing bars are corroded, concrete must be removed around the bar and where the bar has lost bond with the existing concrete, as shown in the right image. This ensures future protection of the bar. Figure: Structural Technologies.

bar to provide a protective, high-pH environment (**Fig. 4**).
- Apply the appropriate repair geometry (rectangular areas without reentrant corners). Sawcut edges to ensure a surface with no feathered edges.
- Repair or replace reinforcing bars as required.
- Clean the surface of concrete and reinforcing steel by abrasive blasting, high-pressure water, or mechanical methods to ensure that corrosion is removed from reinforcing steel and concrete pores are open (that is, there is no dust or debris that might inhibit bond).
- Moisture condition the substrate to accept new repair material.
- Use application techniques that create an intimate bond of the new material to the substrate (pumping pressure, vibration, hand and/or mechanical pressure).
- Maintain surface moisture and/or apply curing compound after repair is completed.

Consistent implementation of these requirements will significantly extend life of the concrete members.

Crack Repair by Adhesive Injection

Concrete cracks can be repaired to restore load transfer or for waterproofing purposes by using adhesive (generally epoxy) injection. To ensure crack repair efficacy, it is important to understand the cause of the crack as well as the amount of movement to be expected. Cracks with excessive movement will reopen in the same or an adjacent location. If cracks are caused by reinforcing bar corrosion, they cannot be repaired by injection because the corrosion process will continue after treatment. Concrete removal, thorough cleaning of the reinforcement to remove all existing corrosion, and replacement of the concrete is the proper solution for cracks caused by reinforcement corrosion.

Crack repair by adhesive injection is accomplished by pressure injection of a low-viscosity fluid into ports along a surface-sealed crack (**Fig. 5**). The injection proceeds in a port-to-port basis (ports spaced approximately the width of the element) until the crack is filled. The efficacy of this method is verified by core removal or nondestructive testing techniques.

Strengthening Methods

Composites

One effective repair method for strengthening concrete bridges involves using externally bonded composite material such as carbon-fiber-reinforced polymer (CFRP). Favorable characteristics of CFRP materials include their tensile strength-to-weight ratio and noncorrosive nature. This strengthening technique provides an alternative load path for the structure and is effective for restoring flexural or shear capacity to various types of concrete bridge elements. On segmental bridges, CFRP sheets can be applied to either the inside or outside faces of web walls and slabs of box girders, as well as around columns or on pier components (**Fig. 6**). The workability of the material facilitates its effective use in a diverse range of geometric configurations. When encountering time-dependent effects such as creep and shrinkage, externally bonded CFRP can help stabilize a structure by slowing the spread of cracking at distressed locations.

Proper design and detailing of a CFRP strengthening system are crucial, and a solid understanding of the structure's stiffness and CFRP material properties is necessary for proper application of this solution. Sound workmanship and adherence to proper quality assurance and quality control practices are also imperative to ensure effective bonding and long-term performance. Top-coat finish options are also available for ultraviolet protection and the desired aesthetic. (See the Concrete Bridge Preservation article on externally applied fiber-reinforced-polymer composites in the Winter 2021 issue of *ASPIRE*.)

Figure 5. A cracked concrete element being prepared for repair with epoxy injection by installing grout ports and sealing the surface. Photo: Structural Technologies.

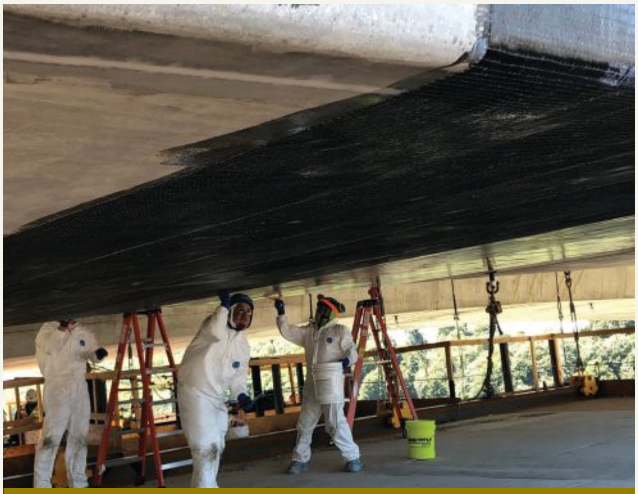

Figure 6. Carbon-fiber-reinforced polymer (CFRP) being installed to strengthen a concrete segmental bridge. Proper design, detailing, and installation is required for a CFRP strengthening system. Photo: Structural Technologies.

Post-tensioning

Post-tensioning is a strengthening technique used to counteract tensile stresses and deflections due to damage and deterioration to the structure, or from increased load demand. Unlike mild steel reinforcement, post-tensioning provides active reinforcement, which is accomplished by introducing a prescribed magnitude and distribution of internal forces using bar or strand systems.

Information related to loads, geometry, boundary conditions, mild reinforcement, and material properties of the existing structure should be gathered before starting analysis and design of the post-tensioning strengthening system. The two primary engineering considerations are strength and serviceability. While sufficient post-tensioning should be provided to strengthen the member for factored load combinations, care should be taken not to overstress the member at the service limit state, including the combination of post-tensioning and dead load only.

The design should ensure an effective connection between the structure and the post-tensioning system. Jacking forces can be large and can generate critical bearing, tensile, and bursting stresses within the existing concrete member and/or new concrete anchorage block. Deflections, crack control, and reinforcing steel stresses at service loads should be checked for both the strengthened member(s) and any other affected members to provide the expected serviceability.

External post-tensioning—such as placing the tendons within the void of the segment—has been successfully used on numerous segmental structures (**Fig. 7**). New tendons are added and tensioned at discrete locations along the length of the existing members. Fabricated steel or concrete deviators are typically placed at midspan, third points, or quarter points along the span to create a draped tendon profile.

Protection is required for all post-tensioning systems. Multiple strand tendons are typically encapsulated in corrosion-resistant, high-density polyethylene ducts. Low-bleed cementitious grout or flexible filler is used to further encapsulate and protect the strands.

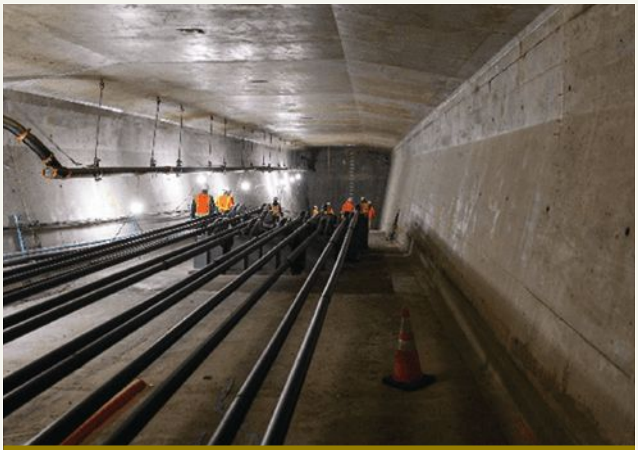

Figure 7. External post-tensioning tendons being installed to strengthen an existing concrete segmental bridge. Photo: Seattle Department of Transportation.

Project Delivery Options

Specialized experience and efficiency in the project delivery process are often of particular importance when it comes to structural assessment, solution development, and rehabilitation of segmental bridges. To successfully navigate the challenges that we have described, and to fully leverage the important lessons that have been learned, two things are crucial: establishing a strong team and facilitating effective collaboration within that team.

Project delivery models that have proven effective at bringing together all key project partners (owner, designer, construction engineering and inspection, and contractor) to achieve shared project goals include construction manager/general contractor, construction manager at risk, and progressive design-build. In our opinion, these contracting methods are most effective at delivering the greatest value to owners for the types of repair projects discussed here. These project delivery options involve the right people earlier in the process, which facilitates:

- identifying and understanding true root issues,
- generating the best solution,
- collaborative budget and schedule development, and
- risk mitigation.

Conclusion

Concrete bridges in general, and particularly those with segmental construction, can and should be preserved to fulfill and possibly exceed service-life expectations. A sound approach to obtaining successful results includes understanding root causes of deterioration, developing a holistic assessment and repair strategy, and adhering to best practices using a qualified and effective project team while making the repairs. Experience gained by the industry over the past few decades is summarized in this article and the article in the Winter 2022 issue of *ASPIRE*. These lessons should be implemented to efficiently and effectively maintain these bridges, which make up some of our nation's most critical transportation infrastructure. The concluding article in this series will demonstrate the effective implementation of these concepts through case studies.

Reference

1. *fib* (International Federation for Structural Concrete). 2013. fib *Model Code for Concrete Structures 2010*. Berlin, Germany: Ernst & Sohn.

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