Extending the Life of Concrete Segmental Bridges

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Concrete segmental bridges were introduced in the United States in the early 1970s and rapidly gained popularity in the 1980s. Today, there are more than 400 concrete segmental box-girder bridges in service throughout the United States, according to data from the American Segmental Bridge Institute (ASBI). A few of the first-generation bridges, which were constructed up to the mid-1990s, are showing signs of distress and need rehabilitation. This article details common causes of observed distress and how to identify them, provides an analysis overview, and discusses repair and rehabilitation methods and how the service life of these structures can be extended.

The design and construction of concrete segmental bridges in the United States have evolved over several decades, including improvements in the following areas:

- Design methodology, software, and American Association of State Highway and Transportation Officials (AASHTO) specifications to account for long-term effects and service life considerations
- Details for post-tensioning that facilitate inspection and improve corrosion protection
- Grouting procedures and grout mixtures
- Post-tensioning systems
- Concrete and reinforcement materials
- Construction methodologies
- Inspection tools and techniques to detect deterioration
- Control of life-cycle costs
- Maintenance techniques

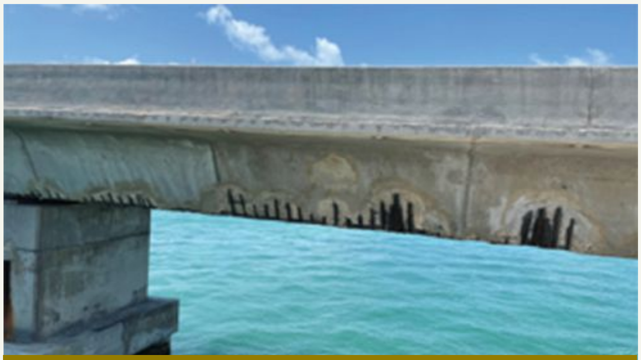
The reality has always been that segmental bridge technology is based on construction methods that have design implications. Therefore, rehabilitation of these bridges must start from this perspective as well.

Segmental Bridge Performance Challenges

Construction Issues

Construction defects can have significant impacts on the long-term service life of segmental bridges. When conditions such as misalignment of segments, damaged shear keys, and geometry control issues are identified during construction, they can be addressed during the construction phase without affecting the service life of the bridge. However, undetected deficiencies such as misplaced reinforcement, damaged epoxy coating of reinforcing bars, incomplete grouting of post-tensioning tendons, poor closure-pour construction, and voids and honeycombs inside the concrete can significantly affect a bridge's operating costs and service life. Undetected defects such as these can manifest into life-safety situations, requiring emergency repairs years after construction has been completed. The recently repaired Roosevelt Bridge in Stuart, Fla., is an example of how construction deficiencies can surface decades later and result in the need for the temporary

A precast concrete segmental bridge with a joint opening extending the full depth of the deck. The spalling is due to a lack of prestressing across the joint and issues with the top-slab dimensional proportions. Photo: Finley Engineering Group.



A precast concrete segmental bridge with loss of concrete cover and reinforcement cross-sectional area due to corrosion of reinforcement after approximately 45 years of service and exposure to a saltwater environment. Photo: Finley Engineering Group.

closure and emergency repair of a vital infrastructure corridor. In this case, the construction of the midspan closure allowed water to get into the tendons, resulting in corrosion and failure of several tendons.

Design Issues

Segmental bridge design best practices have advanced significantly over the past few decades with increased software capabilities, improved knowledge of materials, and advances in design and construction specifications. Early segmental bridges were designed with the latest technology available at the time, but design and construction experience and tools were more limited than they are today. For example, in previous eras, three-dimensional analysis software was not readily available to capture the effects of curvature and superelevation. Determination of these effects relied on the skill of the design engineer to approximate and combine these phenomena, which were not always properly captured. Previous design specifications also did not address some critical design provisions such as web principal stresses and local anchorage zone design. The cracking of the West Seattle Bridge in Washington state is a recent example of a situation where previous design specifications did not anticipate the design issues that occurred many years after the bridge was placed in service. In addition, previously used design details such as dry joints between segments and metal post-tensioning ducts have been largely eliminated from today's standard design practices. Although most older segmental bridges continue to perform well, a few may eventually face challenges from some of the past details and practices that were used in their construction.

Material Issues

The influence of material characteristics and the interaction of adjacent materials can affect the durability and service life of concrete segmental bridges. The materials and their characteristics should be carefully considered for both new construction and repairs. Implementation of a comprehensive strategy for durable concrete as part of the design and construction process may yield the largest improvement in overall durability and service life of segmental bridges. Such an approach takes into account not only the structural design parameters (for example, exposure, stress levels, concrete cover, and reinforcing steel types) but also the constituents of the concrete mixture proportions (such as aggregate quality and size, cement type, water content, and admixtures). It is not uncommon to see designs that include additional costs for epoxy-coated or stainless steel reinforcement but overlook relatively less costly enhancements to the mixture proportions that can significantly improve the overall durability and quality of concrete and extend the service life of the structure.

Grouting Improvements for Post-Tensioning Systems

Throughout the 1980s and 1990s, cement, water, and expansive admixtures were part of the standard formula for post-tensioning grouts. These grouts have proven to be susceptible to bleed water at high points and post-tensioning anchorages, resulting in voids in tendon ducts at critical locations. This situation gained attention in 2000 when several external tendons on the Mid-Bay Bridge in Okaloosa County, Fla., failed.[1] The investigation into this event, as well as others, has led to a better understanding of grout rheology, mixing, placing, and duct system detailing requirements. Subsequent improvements in the grouting process and duct systems have been developed and implemented.

In response to post-tensioning system deficiencies and the improvements required, the Post-Tensioning Institute (PTI) and ASBI worked together to develop specifications for materials, installation, and grouting of multistrand, post-tensioned tendons, as well as training and certification programs. The *Specification for Multistrand and Grouted Post-Tensioning* (PTI/ASBI M50.3-19[2]) and *Specification for Grouting of Post-Tensioned Structures (*PTI M55.1-19[3]) provide detailed product specifications

Comparison of grout column samples. The sample on the right exhibits bleed water segregation; the sample on the left is a nonbleeding, nonsegregating grout. Photo: Structural Technologies.

Post-tensioning system details and procedures, quality assessment, quality control, and technician training and certification requirements have all contributed to more successful and reliable tendon grouting. Photo: Structural Technologies.

and inspection requirements for post-tensioning systems and components such as plastic ducts and anchorages. They specify procedures and details as well as requirements for equipment, inspection, and crew training, experience, and supervision. PTI and ASBI technician and inspector certifications have become standard requirements in most project specifications. There are currently a combined total of 1700 PTI- and ASBI-certified technicians and inspectors (see the Winter 2017 and Summer 2019 issues of *ASPIRE*® for articles on improvements in post-tensioning systems).

The impact of these efforts on the quality of in-place grouted post-tensioning systems has been dramatic. When Structural Technologies/VSL inspected 10,631 post-tensioning tendons, in all types of bridges, that were grouted in the 1980s and 1990s, they discovered voids in approximately 8% of the tendons. By comparison, inspectors discovered voids in less than 0.09% of 5200 tendons inspected that were grouted between 2000 and 2009.

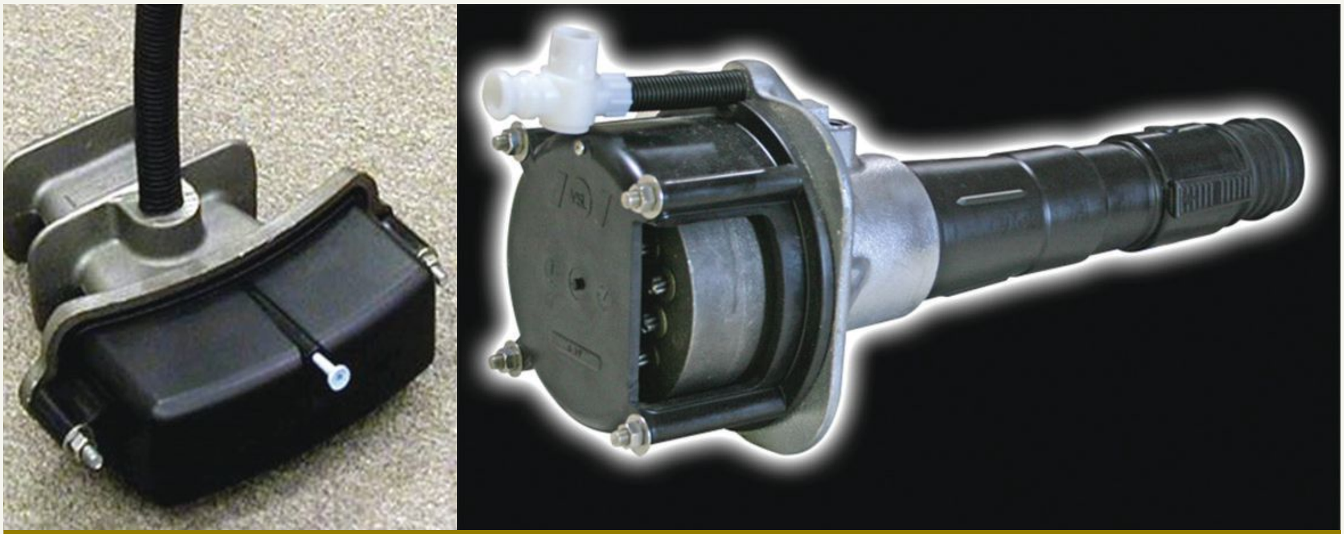
An alternative to using cementitious grouts in post-tensioning ducts is the use of wax or grease, referred to as flexible fillers, an innovation that is relatively new to the U.S. concrete bridge industry. The application of wax involves injecting heated material (approximately 270°F) into the ducts in lieu of cementitious grout. The use of flexible fillers requires special training, equipment, and modifications to standard post-tensioning systems and associated hardware for injecting the material. The unbonded nature of these tendons and the reduction in concrete cross section due to the wax-filled ducts create design implications affecting both flexure and shear.

Inspection and Investigation of Concrete and Post-Tensioning Systems

Inspection of concrete bridges is a multifaceted undertaking, requiring careful planning and execution to ensure that useful results pertinent to the assessment of the structure are obtained. The structure can be inspected through a variety of visual observations, nondestructive testing, and exploratory methods that provide information regarding the bridge system and components.

The inspection of the concrete, mild reinforcement, grout, and post-tensioning systems may entail some or all of the following methodologies.

- **Visual inspection:** Post-tensioned segmental structures, when properly designed and constructed, typically have either no cracks or a few isolated, narrow cracks. Any widespread or severe cracking may indicate a significant problem within the structure. Crack locations and patterns should be documented throughout the structure. Cracking may reduce the durability of the concrete.



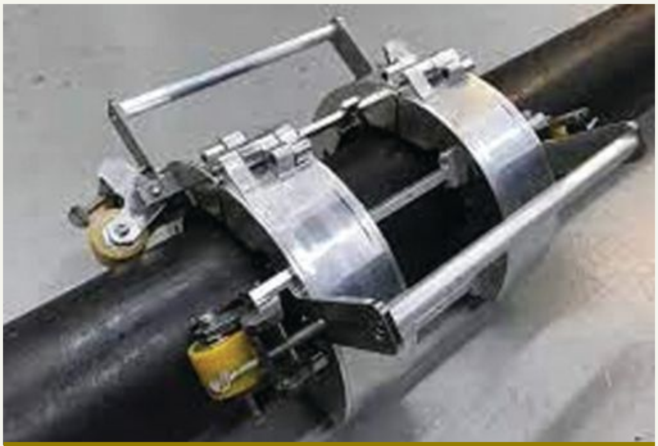
Corrosion-resistant tendon anchorage systems: anchorage for slab tendon (left) and multistrand tendon anchorage with cutaway of grout cap (right). Photos: Structural Technologies.

The presence of spalling and delamination of concrete may indicate active corrosion of the mild reinforcing steel and possible corrosion of the post-tensioning system. Concrete spalling and delamination can provide a pathway for moisture, oxygen, and contaminants from the environment to reach the prestressing steel. The quantity, frequency, and location of spalls and delaminations should be carefully mapped and evaluated.

Special attention should be given to construction and expansion joints as well as closure pours. If the expansion joints are open or the joint seals fail, water can infiltrate the joint and deteriorate the adjacent prestressing steel and anchorages, particularly where the end anchorages are not adequately protected.

- **Acoustic inspection:** Chain-drag and hammer-sounding techniques are economical and relatively accurate methods of determining the general locations and extent of concrete delamination. These methods rely on the differences in sound generated by competent concrete compared with damaged concrete. The process includes striking the concrete with a hammer or dragging a chain across the concrete surface. The change in sound can locate possible concrete voids or delamination.
- **Pacometer testing:** Pacometers can locate—and also determine the concrete cover over—mild and prestressing reinforcement with reasonable accuracy.
- **Impact-echo evaluation:** This nondestructive technique uses stress waves generated by mechanical impact to detect cracks, voids, honeycombing, and debonding in concrete structures, as well as to locate delamination caused by steel corrosion.
- **Compressive strength testing:** Cores taken in the field can be tested in the laboratory to determine the compressive strength of the concrete. Compressive strength testing (ASTM C42[4]) is conducted to assess whether the concrete strength meets the original design requirements and provide information that can be used in a structural analysis.
- **Corrosion testing:** Corrosion potential (ASTM C876[5]) and corrosion-rate testing can be used to identify active areas of possible reinforcement corrosion and the corrosion rate.
- **Chloride testing:** Chloride-ion content evaluation (ASTM C1152M,[6] ASTM C1218,[7] and AASHTO T260[8]) is performed on powder samples of concrete and/or grout from the structure. It is critical to identify the existence of high chloride concentrations because the rate of deterioration of concrete structures is affected by the presence of chloride ions in concentrations above the corrosion threshold level.
- **Carbonation testing:** Carbonation of concrete is caused by the reaction of calcium hydroxide in cement paste with atmospheric carbon dioxide to form calcium carbonate, which reduces the pH of concrete. This condition makes the concrete more conducive to corrosion of the mild steel reinforcement and exposed post-tensioning hardware.
- **Petrographic examination:** Petrographic analysis (ASTM C856[9]) is a microscopic examination of concrete that evaluates the composition of concrete or post-tensioning grout and its strength, condition, and durability. Concrete specimens are prepared for examination by a trained petrographer. The examination assesses the internal structure of the concrete, deleterious compounds that may be formed, the integrity of the cement paste, air content, and the water-cement ratio of the concrete.
- **Electromagnetic investigation:** Magnetic flux leakage (MFL) subjects the steel tendon to a strong magnetic field to determine the extent of corrosion and/or wire breaks in a post-tensioning tendon. At locations where there is section loss or wire breaks, the magnetic field in the tendon is disturbed and is recorded by sensors. This technique can be used on external tendons and stay cables but is generally not applicable for internal tendons.

Inspection of a void in a grouted post-tensioning duct using a borescope. Photo: Structural Technologies.



Magnetic flux leakage technology being used on an external tendon to detect section loss and wire breaks in post-tensioning strands. Photo: Infrastructure Preservation Corporation.

- **Ground-penetrating radar:** Ground-penetrating radar is used to locate tendons and steel reinforcing bars in slabs and web walls. An electromagnetic pulse is reflected by interfacial surfaces (changes in density or layers of different types of materials), and the reflected wave is received and analyzed. This technology can also be used to identify voids in grouted tendons and poorly consolidated regions of the concrete member.
- **Borescope inspection:** A borescope provides a visual image of difficult-to-see areas, which may include post-tensioning anchorage components and inside post-tensioning ducts where voids are discovered or expected.
- **Prestressing steel strength testing:** To assess the strength of post-tensioning strands, tensile testing of removed samples is conducted. Seven-wire strand is tested in accordance with ASTM A370.[10]

Existing Bridge Analysis Methodology

Review Original Design and Specifications

Review of the original design and specifications is guided by the goals of the rehabilitation. The design drawings, specifications, and load rating capacity should be reviewed to determine, for example, what design loads were used, material strengths, creep and shrinkage assumptions, design specifications, and assumed segment ages at erection. Design details that would impact durability such as concrete cover and drainage details should be evaluated for their potential to limit the bridge's durability or capacity relative to the rehabilitation goals. The post-tensioning system should also be reviewed to determine if known issues such as grouting problems are present. The load rating can also provide insight as to whether additional capacity was built into the original design.

Model the Existing Structure

The existing bridge should be modeled with the as-built construction sequence and actual casting and erection schedule. Time-dependent creep and shrinkage parameters should be updated to the more refined model of the *fib Model Code for Concrete Structures 2010*.[11] Use of the actual concrete strengths is an option; however, the actual concrete cylinder breaks should be evaluated, and actual 28-day concrete strength should be back-calculated statistically for use in the analysis. Inspection reports should be thoroughly reviewed to determine the level of cracking and whether linear-elastic behavior is a valid assumption for all locations within the structure, or whether section loss or nonlinear behavior should be considered. Any distress such as cracking should be reviewed to determine whether cracks are systemic or random. If cracking is systemic, the behavior that correlates to the distress observed in the bridge should be confirmed through the elastic model and the model should be updated accordingly. This procedure allows the current state of stress in the structure to be determined and leads to a better evaluation of the proper repair technique to achieve the rehabilitation goals of the project.

Repair Design Considerations

Repair strategies are developed based on rehabilitation objectives, which can involve considerations such as restoring strength and durability, cost, and aesthetics. There are many types of repair methods available, such as epoxy injection, retrofit post-tensioning, and external carbon-fiber fabric wrapping. Epoxy injection can restore structural sections; however, it should be noted that the elastic modulus of epoxies is approximately 15% that of concrete, as this fact may need to be considered for large cracks and repair areas. Retrofit post-tensioning can consist of external tendons that can be straight or deviated to add both moment and shear capacities while also adding beneficial precompression. The tendon layouts should also take into account that local anchorage and deviator stresses can be induced into the existing structure. Surface-mounted post-tensioning can also be used to address local stress concentration issues. Application of external carbon-fiber fabric wrap can add significant capacity to a structure. These are just a few of the repair options that can be used to develop a complete repair and rehabilitation strategy.

Conclusion

There is a wealth of valuable experience and advanced technologies to leverage for repairing and extending the service lives of segmental concrete bridges. A forthcoming article will describe common defects found in segmental construction and present case studies that demonstrate in greater detail repair solutions for strengthening and protecting these important structures.

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