SEGMENTAL CONSTRUCTION – PROTECTING INTERNAL POST-TENSIONING TENDONS FOR 100-YEAR SERVICE LIFE

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ABSTRACT

Precast segmental concrete bridges have become the construction method of choice for many of today's major bridge projects that typically require at least 100-year service life. Internal post-tensioning tendons are the principal reinforcement and need to be designed and detailed to protect prestressing steels from corrosion and other deleterious factors. Combination of the post-tensioning tendons' protection level and protection provided by the structure together provides resistance against the aggressivity of the environment and the particular exposure condition of the structural element.

The paper reviews pertinent requirements for post-tensioning tendons contained in fib *Bulletins. Information on evaluating structures per* fib *Bulletins to achieve 100-year service life that affect internal post-tensioning tendons is provided. Recommendations are proposed for protecting internal post-tensioning tendons in concrete segmental bridge construction for at least a 100-year service life.*

The conclusions reached regarding protecting internal post-tensioning tendons in segmental construction include use of corrugated plastic duct, duct couplers at segment joints, and low- or no-bleed, thixotropic grouts regardless of the structure's ability to provide protection.

Keywords: Coupler, Duct, Grout, Post-Tensioning, Segmental, Tendons.

INTRODUCTION

Protecting internal post-tensioning tendons for a 100-year service life is essential in long-term performance of segmental concrete bridges. Post-tensioning companies have a variety of components available to protect tendons to different degrees. Designers have struggled to identify how much protection is needed for their structures.

This paper will review and discuss pertinent requirements for post-tensioning tendons contained in *fib* Bulletins. Information on evaluating structures per *fib* Bulletins to achieve 100-year service life that affect internal post-tensioning tendons will be provided. A simple, straight-forward method of determining post-tensioning tendon protection levels (PLs) is provided allowing the designer to decide what is required for their structure.

If segmental concrete bridge functionality or structural integrity is affected, an avoidance of deterioration approach should be applied.(1) Since post-tensioning tendons are the primary reinforcement in segmental concrete bridges, this paper identifies best practices to avoid deterioration of prestressing steel in post-tensioning tendons. Recommendations are provided for protecting prestressing steel from corrosion by evaluating tendon duct types, segment joints, and materials for filling of tendons.

SERVICE LIFE

Service life of a bridge is the period of time that a bridge is expected to be in operation.(2) Establishing this period of time is a complex issue especially for public bridge projects. There are a host of factors to consider, including public opinion and expectations, similar projects in the vicinity, aesthetics, construction costs, maintenance costs, etc. *fib* Bulletin 34(1) classifies the design service life of bridge structures to be at least 100 years. Bartholomew(2) identifies design service life for Great Belt Bridge, Denmark, as 100 years, Confederation Bridge, Canada, as 100 years, and San Francisco – Oakland Bay Bridge, United States, as 150 years.

Service life for an individual project should be established based upon the owner's desires and expectations. Service life design must address the entire life of the structure taking into account exposure conditions, quality of construction, and expected level of maintenance. Once a time period is ascertained the process of evaluating and choosing quality construction materials and concepts can begin.

SERVICE LIFE DESIGN

Precast segmental concrete bridges' design service life, as noted above, should exceed 100 years. Per *fib* Bulletin 34(1), the basic idea of service life design is to establish a design approach to avoid deterioration caused by environmental action. The design service life is defined by:

- A definition of the relevant limit state (beyond which the structure no longer fulfils the relevant design criteria)
- A number of years
- A level of reliability for not passing the limit state during this period[(1)]

For a quality design process, utilize Six Sigma tools (DMAIC). *Define* the deterioration mechanism using realistic models. *Measure* what is critical and acceptable for appropriate limit states. *Analyze* the probability that the limit states would be exceeded including root causes of defects. *Improve* design based upon the analysis. *Control* construction through an established quality control system.

DESIGNING INTERNAL TENDONS FOR 100-YEAR SERVICE LIFE

Structures must remain durable and fit for use during their design service life. One way to achieve this is using post-tensioning materials that, if well maintained, will not degenerate during this time.[(1)] Protecting post-tensioning tendons from external corrosive sources such as water, oxygen, airborne chlorides, and the infiltration of de-icing chemicals is of prime importance.[(3)] Although the focus in this paper is on internal post-tensioning tendons, external tendons can also be improved by following the recommendations.

The leading cause of deterioration in post-tensioned bridges is chloride attack. Transport mechanisms for chlorides are influenced by combined effects of wind, water, and temperature.[(3)] How does contaminated water reach and attack tendons? Per Matt[(4)] the following are potential "weak points" where water (possibly contaminated with chlorides) can gain access to tendons and cause corrosion:

- Failure of external barriers:
  - Defective wearing course (e.g. cracks)
  - Missing or defective waterproofing membrane, including edge areas
  - Defective drainage intakes and pipes
  - Wrongly placed outlets for drainage of wearing course and waterproofing
  - Leaking expansion joints
  - Cracked and leaking construction or element joints
  - Inserts (e.g. for electricity)
  - Defective concrete cover
- Failure of tendon corrosion protection system:
  - Partly or fully open grouting inlets and outlets (vents)
  - Leaking, damaged metallic ducts mechanically or by corrosion
  - Cracked and porous pocket concrete
  - Grout voids at tendon high and low points

Eliminating avenues for corrosive agents to enter tendons will prevent the attack on the highly stressed steel. This is the focus for protecting internal post-tensioning tendons for a 100-year service life. The primary tendon components protecting prestressing steels are the enclosure (duct) and the grout.

TENDON PROTECTION STRATEGIES

The majority of information presented in this section comes from *fib* Bulletin 33[(3)]. In the past, causes of deterioration in post-tensioned structures have been identified as weak links found either in external protection layers provided by various structural components or in the corrosion protection of the tendons themselves. The objective of the following strategy is to select the protection level (PL) of post-tensioning tendons based on: aggressivity of environment, exposure of structure or element, and protection provided by structure.

Combination of the post-tensioning tendons' PL and the protection provided by the structure together provides the resistance against the aggressivity of the environment and particular exposure conditions of the structural element.

IDENTIFYING AGGRESSIVITY OF THE ENVIRONMENT

In order to provide information on entry points for aggressivity and exposure, *fib* Bulletin 33[(3)] references EN 206-1[(5)]. It defines classifications of principal environments to which concrete structures are exposed and corrosivity of these environments.

For post-tensioned structures, six classes of aggressivity are considered:

1. No risk of corrosion or attack: X0
2. Corrosion induced by carbonation: XC
3. Corrosion induced by chlorides other than from sea water: XD
4. Corrosion induced by chlorides from sea water: XS
5. Freeze/thaw attack with or without de-icing agents: XF
6. Chemical attack: XA

Table 1 – Aggressivity level and exposure examples as entry points.[3]

Aggressivity	Class Designation	Description of Environment	Examples where exposure classes may occur
	1 – No risk of corrosion or attack		
Low	X0	For concrete without reinforcement or embedded metal: all exposures except where there is freeze/thaw, abrasion or chemical attack. For concrete with reinforcement or embedded metal: very dry.	Concrete inside buildings with very low air humidity
	2 – Corrosion induced by carbonation		
Low ↕	XC1	Dry or permanently wet	Concrete inside buildings with very low air humidity Concrete permanently submerged in water
	XC2	Wet, rarely dry	Concrete surfaces subjected to long-term water contact Many foundations
Medium	XC3	Moderate humidity	Concrete inside buildings with moderate or high air humidity External concrete sheltered from rain
	XC4	Cyclic wet and dry	Concrete surfaces subject to water contact, not within exposure class XC2
	3 – Corrosion induced by chlorides other than from sea water		
Medium ↕	XD1	Moderate humidity	Concrete surfaces exposed to airborne chlorides
	XD2	Wet, rarely dry	Swimming pools Concrete exposed to industrial waters containing chlorides
High	XD3	Cyclic wet and dry	Parts of bridges exposed to spray containing chlorides Pavements Parking structure decks
	4 – Corrosion induced by chlorides from sea water		
Medium	XS1	Exposed to airborne salt but not in direct contact with sea water	Structures near to or on the coast
	XS2	Permanently submerged	Parts of marine structures
High	XS3	Tidal, splash and spray zones	Parts of marine structures
	5 – Freeze/thaw attack with or without de-icing agents		
Medium	XF1	Moderate water saturation without de-icing agent	Vertical concrete surfaces exposed to rain and freezing
High	XF2	Moderate water saturation with de-icing agent	Vertical concrete surfaces of road structures exposed to freezing and airborne de-icing agents
Medium	XF3	High water saturation without de-icing agent	Horizontal concrete surfaces exposed to rain and freezing
High	XF4	High water saturation with de-icing agent	Road and bridge decks exposed to de-icing agents Concrete surfaces exposed to direct spray containing de-icing agents and freezing Splash zones of marine structures exposed to freezing
	6 – Chemical attack		
Medium	XA1	Slightly aggressive chemical environment	
Medium-High	XA2	Moderately aggressive chemical environment	
High	XA3	Highly aggressive chemical environment	

Aggressivity of the environment will be used in determining the tendons' PL for segmental concrete bridges. Classification X0 (no risk of corrosion or attack) provides a "low" aggressivity rating and requires a very dry environment. Classification XC (corrosion induced by carbonation) varies from "low" for dry or permanently wet to "medium" for cyclic wet and dry. Classification XD (corrosion induced by chlorides other than from sea water such as airborne chlorides or deicing chemicals) yields a "medium" rating with moderate humidity up to a "high" rating with cyclic wet and dry. Classification XF (freeze/thaw attack with or without deicing agents) is "medium" for freeze/thaw without deicing agents and "high" for freeze/thaw with deicing agents. Classification XA (chemical attack) varies from "medium" for slightly aggressive chemical attack to "high" for highly aggressive chemical attack.

Designers should realize that the only areas with "low" aggressivity are when there is no risk of corrosion in a very dry environment (X0) or when corrosion is induced by carbonation and the environment is dry or permanently wet (XC1). There are many more possibilities for classifying an environment's aggressivity as "medium" or "high". Refer to Table 1 for more detailed information.

IDENTIFYING PROTECTION PROVIDED BY THE STRUCTURE

Designers must identify if the protection provided to the internal post-tensioning tendons by the segmental concrete bridge structure is "high", "medium", or "low". Many factors go into this decision including design concept, detailing, material selection, and construction quality. Designers should always keep in mind that corrosion of post-tensioning tendons is increased by means of ingress of chlorides and other deleterious agents through vulnerable areas of tendons such as anchorages, joints, cracks, porous concrete and inadequate concrete cover.(3)

Protection provided to tendons by individual construction details are an integral part of an overall project's protection scheme. The level of protection provided by construction details can be minimal up to the best possible available protection. The designer should consider the following construction details together when identifying protection provided to the structure.

- Concrete Quality and Cover
- Waterproofing Systems and other Surface Protection Systems
- Drainage System Details
- Expansion Joint Details
- Concrete Cracking
- Construction Joint Details
- Segment Joint Details

Further discussion of the above construction details follows, including the author's recommendations for "low" to "high" ratings. For a structure to qualify for a "high" rating in overall structural protection, all mentioned construction details need to have optimum protection schemes. This total structure rating should be used when determining tendon PLs.

Concrete Quality and Cover

Dense, low-permeability concrete with adequate concrete cover should be specified for segmental concrete bridge structures.(3) Mobility of fluids or gases through concrete allows a vehicle for corrosion. Obviously, more concrete cover provides a greater distance for chlorides or other deleterious materials to travel to tendons. Rostam provides more information on concrete cover requirements in his PCI Article.(6) Providing greater concrete cover than required by code will improve the protection that a structure provides to the post-tensioning tendon's duct. Additionally, by specifying a denser and/or a lower permeability concrete will allow for better structure protection. In order to achieve a "high" rating, concrete covers and permeability of concrete material should be designed so that there is a 90% probability of not having any corrosion initiated before the structure's design life has passed, corresponding with a 10% probability of premature corrosion initiation. A "low" rating is given when no special design analysis is undertaken and typical concrete covers for structural elements and concrete permeability normally achieved with a concrete w/c ratio of 0.4 are used.

Waterproofing Systems and other Surface Protection Systems

Waterproofing systems provide the first line of defense against intrusion of road salts; however, there are currently no systems available that are guaranteed to remain waterproof for the life of the structure.(3) When a surface protection system is installed and life-cycle costs are included for proper maintenance and re-application as necessary, a "high" protection rating is given to this criterion. Conversely, a "low" rating must be recognized with no waterproofing or surface protection system.

Drainage System Details

The drainage system should remove water from the road surface. Drains and slopes should be constructed so that water cannot migrate into tendons. Equipment failure or blockage of drains can allow paths for water to enter tendons.(3) Sloping road surfaces without the possibility of blockages or dams will allow for a "high" protection rating; while no sloping and/or drains that can become blocked would be considered a "low" protection rating.

Expansion Joint Details

Expansion joints usually leak and their effectiveness and life span are dependent on the quality of material, installation and maintenance. Details should be based on the assumption that the expansion joint will leak and will not provide protection against ingress of water and road salts.(3) A "high" protection rating is given when appropriate drainage paths for leakage are provided ensuring that there is no access to tendon anchorages or the structure's bearings. And, obviously a "low" rating is given to structures with expansion joints where no details are provided for drainage paths.

Concrete Cracking

Concrete cracking can occur for a number of reasons; its relevance to durability is largely related to corrosion and depends on the type and magnitude of cracks. Construction detailing is critical in minimizing cracking. Proper layout and sequencing of concrete pours to lessen the risks of cracking are necessary. Proper layout and sequencing of prestressing decreasing risks of cracking particularly in anchorage vicinities should be considered. Proper location and amounts of non-prestressed reinforcement should be checked for adequate distribution to avoid early-age cracking.[(3)] When all of the above considerations are properly addressed and solutions incorporated into the structure to eliminate cracking, a "high" protection rating is realized. With little or no consideration or inclusion of proper details in the structure, a "low" rating should be given.

Construction Joint Details

Protecting well-made construction joints with waterproofing membranes should assist in preventing leakage; however, waterproofing membranes often do not provide a complete seal and do not last indefinitely, and joints leak.[(3)] By keeping construction joints away from anchorages and preventing access for leakage to tendon anchorages will give a "high" structure protection rating. With little or no consideration of construction joint details and/or locations a "low" rating is set for this criterion.

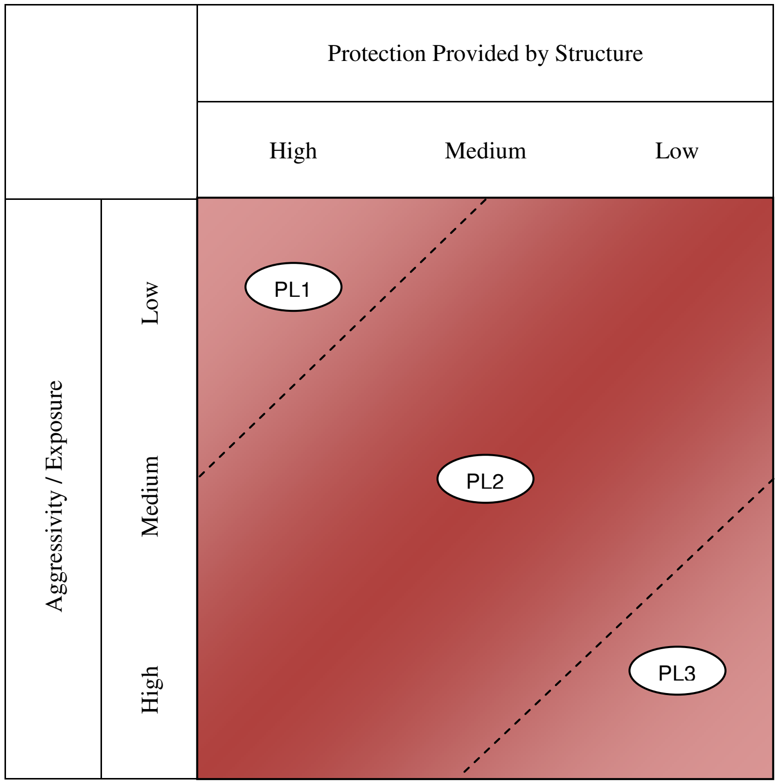
Segment Joint Details

Precast segmental concrete construction typically uses match cast segment joints which if properly sealed with epoxy resin as erected are satisfactory in terms of durability. However particular care is required when considering the continuity of post-tensioning ducts across the joints. Providing a system that seals against ingress of aggressive agents, epoxy glue, or against leakage of cement grout should be considered.[(3)] Using a segmental duct coupler as part of the post-tensioning system will give a "high" protection rating, while erecting segments with just epoxy at the joints necessitates a "low" protection rating (dry joints are not acceptable).

SELECTING TENDON PROTECTION LEVELS

Selecting tendon PLs for a specific project requires that the aggressivity of the environment attacking the prestressing element ("low" – "high") is identified; see Table 1. Then the protection provided by the structure ("low" – "high") is identified. Once these two tasks are completed, the PL for a specific situation can be selected by using Table 2. The combination of the structural protection level and the tendons' PL provide the resistance against the aggressivity of the environment.

Table 2 – Protection levels for post-tensioning tendons based on aggressivity/exposure versus protection provided by structure.(3)



Following are examples for choosing tendon PL using Table 2 for a segmental concrete bridge.

1. Project is located in a very dry environment with no risk of corrosion or attack (X0 = "low") and the protection provided by the structure is "medium – high". This would yield a tendon with a PL1.
2. Project is located in a very dry environment with no risk of corrosion or attack (X0 = "low") and the protection provided by the structure is "low". This would yield a tendon with a PL2.
3. Project is located in a northern climate that has freeze/thaw with moderate saturation with deicing agents (XF2 = "high") and the protection provided by the structure is "high". This would yield a tendon with a PL2.
4. Project is located in a temperate climate six miles (10 km) from the seacoast exposed to airborne salt but not in direct contact with sea water (XS1 = "medium") and the protection provided by the structure is "medium-high". This would yield a tendon with a PL2.
5. Project is located in an area with cyclic wet and dry exposure while being exposed to sprays containing chlorides (XD3 = "high") and the protection provided by the structure is "medium-low". This would yield a tendon with a PL3.

PROTECTION LEVELS (PL)

fib Bulletin 33(3) identifies three PLs providing basic parameters for each. PL1 is defined as a duct with filling material (grout) providing durable corrosion protection. PL2 is PL1 plus a watertight, impermeable envelope providing a leak tight barrier. PL3 is PL2 plus integrity of tendon or encapsulation to be inspectable or monitorable.

Initial costs for post-tensioning systems increase from PL1 to PL3. However, this increase in initial overall structure costs is relatively minimal and consistently beneficial when evaluating the life-cycle costs of the structure.(3)

Protection Level 1 (PL1)

- Duct sufficiently strong and durable for fabrication, transportation, installation, concrete placement and tendon stressing
- Duct sufficiently leak tight for concrete placing and grout injection
- Duct material non-reactive with concrete, prestressing steel, reinforcing steel, and tendon grout materials
- Grout to be chemically stable, non-reactive with prestressing steel and duct
- Grouting procedures to leave no voids in duct
- Example 1: bare strand + corrugated metal duct + cement grout
- Example 2: bare strand + corrugated plastic duct + cement grout or other filling materials (anchorage zone non-encapsulated)

Protection Level 2 (PL2)

- In addition to PL1
- Corrugated plastic duct to be watertight and impermeable to water vapor over entire length including connections (segmental duct couplers required in segmental construction)
- Corrugated plastic duct material to be chemically stable without embrittlement or softening during anticipated exposure temperature range and service life (no free chloride ions extractable from material)
- Anchorage components to have an enclosure that is watertight and impermeable to water vapor (encapsulated)
- Example: bare strand + corrugated plastic duct + cement grout or other filling materials + encapsulation of anchorage zone

Protection Level 3 (PL3)

- In addition to PL2
- Have a demonstrated means to inspect or monitor tendons for integrity and/or corrosion

- Example: bare strand + corrugated plastic duct + cement grout or other filling materials + encapsulation of anchorage zone + inspection or monitoring

PROTECTING INTERNAL POST-TENSIONING TENDONS IN SEGMENTAL CONSTRUCTION

Internal post-tensioning tendons are the principal reinforcement in segmental concrete bridge construction and need to be designed and detailed to protect prestressing steels from corrosion and other deleterious factors. Previously, tendon PLs have been identified based upon the aggressivity of the location where the segmental concrete bridge will be erected and the protection that the structure itself will provide to internal tendons.

In reviewing tendon PLs for use in segmental construction with a 100-year service life, it is clear that several elements are critical in protecting the prestressing steels from deterioration. The tendon enclosure (duct) is critical to keep contaminated water from accessing tendons and causing corrosion. Maintaining duct continuity across joints in segmental construction is essential. As noted in *fib* Bulletin 33(3), preventing water intrusion into the duct enclosure at the joint can only be met if a proper system provides this function. Filling material is the final protection of the prestressing steel. Cementitious grouts are commonly used for this function but when injected must leave no voids in the tendon duct.

DUCT

Per *fib* Bulletin 33(3) ducts serve different objectives in post-tensioning. For internal tendons, they first create the void in a concrete structure, in a defined alignment, that allows installation and free movement of prestressing steel during stressing. Additionally, they form the interface between prestressing steel, grout and structure to transfer bond forces.

PL2 and PL3 require the use of corrugated plastic duct. For PL1 either corrugated metal or plastic duct may be used; however, there are several valid reasons that only corrugated plastic duct should be utilized with precast segmental concrete construction. The first is that even though a waterproofing membrane may be used it often does not provide a complete seal and does not last indefinitely, and joints still leak.(3) Freyermuth in his 2007 introduction at ASBI Grouting Certification Training(7) makes note that for global durability protection robust plastic ducts should be used in segmental construction. The FHWA report on *Performance of Concrete Segmental and Cable-Stayed Bridges in Europe*(8) notes advantages of plastic "robust duct" are enhanced corrosion protection and increased durability, along with reduced friction losses. In Breen's paper on *Improving Corrosion Resistance of Post-Tensioning*(9), he makes the following points regarding duct type in segmental testing:

- Superiority of plastic ducts was evident. Specimens with plastic duct had the best overall performance (quantified in terms of strand, mild steel and duct corrosion).

- All galvanized steel duct specimens showed some degree of duct corrosion: twelve had duct destruction and pitting, two had severe uniform corrosion and one had moderate uniform corrosion.

Breen[9] makes another statement about ducts in his post-tensioned beam corrosion test series: "The galvanized steel ducts performed poorly. Typically they corroded severely with gaping holes. In many cases, the ducts completely corroded away across several inches. Therefore, galvanized steel ducts should not be used in aggressive environments."

Corrugated metal ducts, whether made in black steel or galvanized will quickly corrode once they are exposed to water and de-icing salts. Particularly vulnerable are zones which are not in direct contact with concrete or grout, e.g. zones underneath duct tape. Therefore, these ducts cannot be considered to represent an independent barrier for the corrosion protection of the prestressing steel.[3]

In the research report *Final Evaluation of Corrosion Protection for Bonded Internal Tendons in Precast Segmental Construction*,[10] the authors make the following conclusions regarding duct type based upon their segmental testing:

- Galvanized steel duct was corroded in all specimens.
- Galvanized steel duct showed moderate to severe duct corrosion with epoxy joint specimens.
- Superiority of plastic ducts was evident.
- Plastic ducts performed well in spite of concrete cover lower than allowed by specifications.

Post-tensioning tendons used in segmental concrete bridge construction are the primary reinforcement and should not be subjected to corrosion whether identified as PL1, PL2, or PL3. Due to the susceptibility of corrugated metal duct to corrosion in segmental construction, it is recommended that robust corrugated plastic ducts be used for all tendon PLs. All corrugated plastic duct used for segmental bridge construction should conform to the performance requirements of *fib* Bulletin 7.[11]

SEGMENTAL DUCT COUPLERS

Joints of precast segmental concrete bridges allow entry points for water (possibly contaminated with corrosive agents) to attack prestressing steel. Durable corrosion protection must be provided with any tendon PL. Additionally, it is recommended that the continuity of tendon enclosures be maintained thru all joints.

In segmental construction, precast concrete elements are typically prefabricated using match cast techniques. When erected, the joints between these segments are buttered with epoxy and segments clamped together using temporary post-tensioning tendons. The ability of water borne contaminants to attack permanent post-tensioning tendons through joints causes concern in this type of construction.

In precast segmental construction, dry joints and internal tendons with discontinuous ducts are not acceptable for any tendon PL.(3) For PL2 or PL3 either sealing of the exposed segment joints with a suitable membrane or full encapsulation of the tendon with plastic across the joint is considered necessary in addition to epoxy resin – this can be achieved with special duct couplers across the segment joints.(3) In evaluating the use of membranes or segmental duct couplers, membrane costs including application, maintenance, expected life and re-application which can be significant(3) are evaluated against the one-time initial costs of the segmental duct coupler. When total life-cycle costs are considered, using segmental duct couplers is usually more economical than membranes.

From a corrosion protection standpoint, membranes provide protection usually at the top of segmental bridges but do little or nothing to help with concrete quality and cover, drainage systems, expansion joints, cracking, or construction joints which all can allow access for water into the tendons. Whereas, segmental duct couplers provide protection of the tendon itself; thus, protecting the tendon from water ingress at critical segment joints.

Today, there are several manufacturers producing segmental duct couplers. When evaluating segmental duct couplers, designers should confirm their ability to create an airtight and watertight connection in addition to allowing correct alignment and positioning of ducts. Segmental duct couplers need to be robust and user friendly for ease of installation at jobsites. Segmental duct couplers must include the ability to maintain individual tendon integrity thereby preventing grout crossovers or epoxy leaking into the tendon.(12, 13)

Figures 1 shows one such segmental duct coupler that is currently being used worldwide. It offers the ability to maintain tendon alignment up to 15 degrees and allows field tolerances up to 1/4” (6 mm) in any axis.(12, 13)

Figure 1 – Precast Segmental Duct Coupler.(13)

In 2002, the Florida Department of Transportation (FDOT) recognized the critical nature of segment joints and in *New Directions for Florida Post-Tensioned Bridges*(14) made a determination that segmental duct couplers would be used on all FDOT Segmental Concrete Bridge Projects. Performance testing of segmental duct couplers should include at a minimum: sealing gasket compressive required force test, air pressure test, and assembly toughness test. FDOT Post-Tensioning Specifications(15) include dialogue on this testing. Acceptance criteria include:

- Maximum force required to compress sealing gasket to its final compressed position shall not be greater than 25 psi (170 kPa) of area encircled by the sealing gasket.
- Segmental duct coupler assembly must sustain a 5 psi (35 kPa) internal pressure for a minimum of five minutes with no more than a 0.5 psi (3.5 kPa) reduction in pressure.
- Segmental duct coupler with duct and connectors (assembly) shall be intact and free of epoxy, and remain properly attached without crushing, tearing, or other signs of failure.

Providing durable corrosion protection to post-tensioning tendons is a requirement of *fib* Bulletin 33.(3) Protecting the continuity of the tendon enclosure at segment joints is critical to achieving a 100-year service life for almost all post-tensioning tendons. In limited situations with a "low" environmental aggressivity (see Table 1 for X0, XC1, or XC2) and a structure achieving a "medium" to "high" rating in all protection categories, epoxy at the segment joints may be sufficient – only for tendons with PL1. Post-tensioning tendons for most segmental concrete bridge structures will fall into PL2 or PL3 categories requiring segmental duct couplers to protect segment joints in addition to epoxy.

GROUT

Cementitious grout is the last level of protection of the prestressing steel in post-tensioning tendons used in segmental concrete bridge structures. Its purpose is corrosion protection and bond. Per Schokker(16) the keys to a good grout are completely filling ducts, low permeability, appropriate bleed resistance, and careful use of admixtures.

Internal bonded post-tensioning tendons in segmental bridge construction, when adequately grouted, allow a local stress transfer from the concrete to the tendon and from the tendon to the concrete to occur throughout the section. As a result, structures with bonded tendons typically exhibit a more uniform crack distribution at ultimate load.(3) Thus, making sure grout completely fills the tendon ducts is critical to long-term performance of internal bonded post-tensioning tendons.

Complete filling of post-tensioning ducts is a requirement for all PLs. Grout material is to be chemically stable as well as non-reactive with prestressing steels and tendon ducts. Grout procedures shall leave no voids in tendon ducts. To transfer bond an effective grout must fill ducts and have appropriate strength and shape characteristics (provided by duct profile).(3)

Cementitious grouts used to fill tendons should have low permeability. Water to cementitious material ratio should be no more than 0.45.(17) This ratio will vary based upon mix design and what admixtures are used. Careful use of admixtures is recommended as they may enhance or degrade the quality of grout. The Post-Tensioning Institute (PTI) in their *Specification for Grouting of Post-Tensioned Structure* (17) identifies four classes of grout and appropriate ranges for admixtures. Grout admixtures used for post-tensioning tendons affect the grout's fluidity and bleed resistance.(16)

Bleed is the emergence of water from newly placed grout. Bleed is caused by settlement of solid materials within the mass and filtering action of individual wires of prestressing strands. Bleed water can be trapped within tendon ducts and mix with detrimental materials leading to corrosion of prestressing steel. Additionally, bleed water may allow air voids if it evaporates allowing direct access for corrosive agents to attack prestressing steel. Regardless, areas with bleed water or air voids have no bond with surrounding concrete.

PTI's Specifications[17] identifies two bleed tests with corresponding limits. The first, wick induced bleed test, is only appropriate for non-aggressive indoor or outdoor structures.[17] The second test procedure, Schupack pressure bleed test, was developed from a test originally reported in an article by Schupack[18] and should be used for aggressive environments, prepackaged grouts, or special grouts determined by design engineer.[17] The lower the allowable bleed of post-tensioning grout, the better the bond characteristics of tendons and the longer the service life capabilities of tendons. Limitations on bleed should be identified in project specifications.

Post-tensioning grouts can be specially designed or prepackaged depending on location and competence of workers. Prepackaged post-tensioning grouts remove the uncertainty of correctly mixing ingredients. Most currently specified post-tensioning grouts for segmental concrete bridges are thixotropic in nature; meaning the grout is able to stiffen in a short time while at rest, but to acquire a lower viscosity when mechanically agitated.[17] Thixotropic grouts hold water increasing bleed resistance.[16] High speed mixers are used with thixotropic grouts allowing for proper mixing of ingredients.

Thixotropic grout behavior shows the following benefits for internal post-tensioning tendons for 100-year service life:

- Water retentive while maintaining pumpability
- Does not mix with water in the duct (will push water out)
- Can fill interstices between the wires of prestressing strands
- Most prepackaged post-tensioning grouts have some degree of thixotropy[16]

Written grouting procedures and qualified personnel are critical to successful filling of post-tensioning tendon ducts. PTI Specifications[17] identify requirements for personnel qualifications, grouting procedures, and testing. It is recommended that properly trained and certified grouting technicians are employed to insure that a high-quality grout is achieved. One source for training is ASBI Grouting Certification Training Workshops. These requirements should be modified as necessary for the individual segmental concrete bridge project.

Prior to grouting (and many times prior to inserting the prestressing steel), an air pressure test to locate potential grout leaks and cross-overs can be performed. Leakage will commonly be at segment joints and should be fixed prior to grouting by removing concrete and repairing duct enclosures – this will eliminate a potential source for contaminants to enter tendons and attack prestressing steel. Segmental duct couplers help eliminate this potential problem area. Requirements as to actual pressure to use in this test vary. Pressures in the range of 5-50 psi (35 – 345 kPa) have been used. Actual pressure should only be high enough to find the leaks.[19] There are instances of too high air pressure leaking and causing damage by collapsing adjacent tendon ducts. It should be noted that grouting pressures are usually higher however grout fines will many times fill small spaces that allow air to escape.

All tendon PLs must provide for filling materials and procedures that leave no voids in the duct.(3) Thixotropic grouts combined with high-speed mixing will give the best results. Specifying low- or no-bleed requirements and how to test for bleed (see PTI Specifications(17)) enhance protection provided to prestressing steel.

CONCLUSIONS

Design service life of bridge structures should be at least 100 years. Internal post-tensioning tendons are the primary reinforcement for segmental concrete bridges and thus need to be designed to last at least 100 years. This is done by eliminating the means for corrosive agents to enter tendons thus preventing an attack on the highly stressed steel.

The first step of post-tensioning tendon protection strategies is to select the tendons' protection level (PL) based upon aggressivity of environment, exposure of structure or element, and protection provided by structure. It is the combination of the tendons' PL and protection provided by the structure that determines how durable the post-tensioning system (and the structure) will be.

Three post-tensioning tendon PLs are identified. They are:

1. PL1 is defined as a duct with grout providing durable corrosion protection.
2. PL2 is PL1 plus a watertight, impermeable envelope providing a leak tight barrier.
3. PL3 is PL2 plus integrity of tendon or encapsulation to be inspectable or monitorable.

Corrugated plastic duct is recommended for segmental concrete bridges for any PL. PL1 allows the use of metal duct however research has found that galvanized metal duct performs poorly in segmental concrete construction. PL2 and PL3 require the use of corrugated plastic duct. All corrugated plastic duct shall meet the performance requirements of *fib* Bulletin 7.(11)

Segmental duct couplers are recommended for segmental concrete bridges for any PL. Life-cycle costs should be considered when other options are proposed. Dry segment joints are not acceptable with any PL. Membranes provide little or no assistance in protecting tendons when poor concrete quality and minimum concrete covers are used, or drainage systems are not adequate. Protecting tendons from water infiltration at vulnerable joints is essential.

Low- or no-bleed, low permeable, thixotropic, cementitious grouts are recommended for segmental concrete bridges for any PL. Proper materials and procedures that leave no voids in tendon ducts are essential in providing 100-year service life. Tendons are not bonded at areas with voids and voids allow access for contaminated water to attack the prestressing steel. Properly trained and certified grouting technicians should be employed to insure that a high-quality grout is achieved.

Additionally, requirements for protecting tendon anchorages (encapsulation) and the ability to monitor or inspect the tendons may be required in segmental bridge construction. Requirements of tendon PLs may instruct designers to specify leak-tight protection caps over anchorages or complete electrical isolation of tendons.

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