



## ACHIEVING PROTECTION OF INTERNAL TENDONS THROUGH CONTINUOUS DUCT ENCLOSURES IN SEGMENTAL BRIDGE CONSTRUCTION



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### Abstract

Internal post-tensioning tendons are the primary structural element in segmental bridge construction. It is crucial that the tendon enclosure (duct) provide protection of the highly stressed post-tensioning steel. As construction proceeds there are discontinuities of the duct due to construction sequences. The duct must be adequately connected at the discontinuities to prevent ingress of unwanted corrosive elements.

This paper will examine post-tensioning duct materials and their ability to protect post-tensioning tendons from corrosive agents. It will provide examples of techniques to connect duct at precast segmental joints thus protecting tendons from water infiltration. It will show methods for achieving air and water tightness when connecting post-tensioning duct in cast-in-place segmental construction. Finally, the paper will present recommendations on best practices for achieving protection of internal post-tensioning tendon enclosures in segmental bridge construction.

**Keywords:** Tendons, post-tensioning, segmental duct couplers, tendon enclosures, corrugated plastic duct

### 1 What is an Internal Tendon Enclosure?

An internal tendon is a post-tensioning tendon that is encased in the concrete section of the structure; an internal tendon enclosure can be considered as an envelope (duct) enclosing the tensile

element (prestressing steel) over its length. The duct covers the prestressing steel from anchorage to anchorage and is an essential element of tendon durability. In segmental bridge construction, discontinuities of the duct are created by segment joints. This paper will review requirements for tendon ducts and discontinuities at segment joints providing owners and designers confidence that their structure will achieve their goals for corrosion protection of internal tendons.

Besides providing corrosion protection, internal tendon ducts create a void, in a defined alignment, within the concrete allowing installation and movement of the prestressing steel during stressing. Additionally, their corrugations form an interface between prestressing steel, grout, and structure to transfer bond forces.<sup>[1]</sup> In modern bridge construction, the ducts are primarily made out of two materials – corrugated metal and corrugated plastic.

Tendon enclosure continuity through segment joints was not considered a major issue until the late 1990s when research by Salas et. al.<sup>[2]</sup> showed that precast segment joints leaked even with sound epoxy/gasket at the joints causing deterioration of galvanized metal duct and infiltration of corrosive elements into the tendon. In 2002, Florida Department of Transportation (FDOT) in their *New Directions for Florida Post-Tensioned Bridges*<sup>[3]</sup> made it a requirement to use a segmental duct coupler on all precast segmental bridge projects thus protecting this vulnerable location. *fib Bulletin 33*<sup>[4]</sup> suggests preventing water intrusion into the duct enclosure at the joint can only be met if a proper system provides this function. Similar conditions occur at joints of cast-in-situ segmental bridges, but in this instance, the duct extends through the joint and connecting the duct pieces in the next pour becomes critical.

## 2 Post-Tensioning Tendon Protection Levels

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. Identifying the degree to which a post-tensioning tendon is protected from corrosion and deterioration over time is defined as the tendon protection level (PL). Several documents define and categorize tendon PLs such as *fib Bulletin 33, Durability of post-tensioning tendons*<sup>[1]</sup> and draft of PTI/ASBI, *Guide Specification for Grouted Post-Tensioning*<sup>[4]</sup> along with previous papers by the author *Post-Tensioning Tendon Protection Strategies for Precast Elements*<sup>[5]</sup>, *Segmental Construction- Protecting Internal Post-Tensioning Tendons for 100-Year Service Life*<sup>[6]</sup>, and *Selecting Post-Tensioning Tendon Protection Levels*<sup>[7]</sup>. These documents note the importance of the internal tendon enclosure (duct) along with good quality filling material (grout).

Selecting the required tendon PL for the segmental project is based upon the 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.<sup>[1]</sup> When identifying the aggressivity of the environment, the only areas with "low" aggressivity are when there is no risk of corrosion in a very dry environment or when corrosion is induced by carbonation and the environment is dry or permanently wet; there are many more possibilities for classifying an environment's aggressivity as "medium" or "high".<sup>[6]</sup> The PL for the project should be based upon the worst case condition within the structure; it is not cost-effective or practical to have a variety of tendon PLs on one project.<sup>[7]</sup> Additionally, for the protection provided by the structure, applicable construction details need to have optimum protection schemes for the structure to qualify for a "high" rating.<sup>[6]</sup>

The designer will find that most tendon PLs identified for use in segmental construction fall into category PL2 (occasionally, PL1 or PL3 will be identified). **Tab. 1** shows definitions of tendon protection levels.

**Tab. 1** Protection Level (PL) Definitions.<sup>[1][4]</sup>

<i>fib</i> Bulletin 33 <sup>[1]</sup>	PTI/ASBI Guide Specification <sup>[4]</sup>
Protection Level 1 (PL1)	
PL1 is defined as a duct with filling material (grout) providing durable corrosion protection.	PL1A – defined as a duct with grout providing durable corrosion protection.
	PL1B – defined as PL1A plus engineered grout and permanent grout cap.
Protection Level 2 (PL2)	
PL2 is defined as PL1 plus a watertight, impermeable envelope providing a leak tight barrier.	PL2 is defined as PL-1B plus an envelope, enclosing the tensile element bundle over its full length, and providing a permanent leak tight barrier.
Protection Level 3 (PL3)	
PL3 is defined as PL2 plus integrity of tendon or encapsulation to be inspectable or monitorable.	PL3 – defined as PL-2 plus electrical isolation of tendon or encapsulation to be monitorable or inspectable at any time.

It is clear that several elements are crucial in protecting prestressing steels from deterioration – the tendon enclosure (duct) and a means of maintaining duct continuity across segment joints along with quality grouting. These elements are vital in keeping contaminated water from accessing tendons and causing corrosion of the highly stressed steel

### 3 Post-Tensioning Duct

Corrugated duct is the primary component of the tendon enclosure. As previously stated for post-tensioning applications, the duct is made out of two materials – corrugated metal and corrugated plastic. PL2 and PL3 require the use of corrugated plastic duct. For PL1 either corrugated metal or plastic duct may be used; however, there are valid reasons that only corrugated plastic duct should be utilized with precast segmental concrete construction.

#### 3.1 Recommendation – Corrugated Plastic Duct

Freyermuth in his 2007 introduction at ASBI Grouting Certification Training<sup>[8]</sup> 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*<sup>[9]</sup> 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*<sup>[10]</sup>, 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<sup>[10]</sup> 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 corrosion protection of prestressing steel.<sup>[1]</sup>

The authors of the research report *Final Evaluation of Corrosion Protection for Bonded Internal Tendons in Precast Segmental Construction*<sup>[2]</sup> 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.



**Fig. 1** Corrugated Plastic Duct in Segments prior to Concrete Placement

In current economic times, material costs play a major role in decisions regarding product choice. When comparing the costs of corrugated plastic duct versus thin-wall metal duct, it was noted in *fib* Bulletin 7<sup>[11]</sup> that because of small production quantities plastic ducts may cost twice that of metal duct. Ducts represent roughly 5% of the total installed post-tensioning price and the post-tensioning price represents more or less 10% of the total construction cost of a bridge. Hence, doubling the duct price represents about 1/2 % increase in construction costs while providing a significant improvement in the durability and quality of the main reinforcement of a structure.<sup>[11]</sup> Today, production of corrugated plastic duct has significantly increased since *fib* Bulletin 7<sup>[11]</sup> was written, resulting in considerably less cost disparity between duct types.

Post-tensioning tendons used in segmental concrete bridge construction are the principal 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 and for redundancy of protection, the author recommends 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<sup>[11]</sup>.

### **3.2 Confirming Adequacy of Corrugated Plastic Duct**

Many types of corrugated plastic ducts have been used in post-tensioning applications including drainage pipes. Until *fib* Bulletin 7<sup>[11]</sup> was published in 2000, there were no standards for testing and inadequate materials were sometimes used giving plastic duct a flawed performance and quality reputation. Even today, ten years after publication, inferior materials are sometimes allowed on projects. Designers and owners are encouraged to require that all corrugated plastic duct for internal bonded post-tensioning applications be tested and affirmed to meet the requirements of *fib* Bulletin 7<sup>[11]</sup>.

The primary tests that corrugated plastic duct are subjected to include flexural behavior, flexibility, lateral load resistance, longitudinal load resistance, leak tightness, wear resistance, and bond behavior. All the tests are important for different reasons. Some of the tests only check duct performance while others also include duct-to-duct connections. The following describes the purpose of each test:<sup>[11]</sup>

- Flexural Behavior – confirms that the duct is sufficiently rigid to limit deflections between supports due to temperature variations and during concreting.
- Flexibility – confirms that the duct and duct-to-duct coupler allow easy bending to the specified minimum radius without excessive deformation of the duct cross section.
- Lateral Load Resistance – confirms that the duct is sufficiently strong to sustain concentrated lateral loads introduced at supports and during construction without undue deformation of the duct cross section.
- Longitudinal Load Resistance – confirms that the duct and duct-to-duct coupler are sufficiently strong to resist restraints due to temperature variations after installation.
- Leak Tightness – confirms the ability of the system, including duct-to-duct couplers, to remain sufficiently watertight when bent to specified minimum radius.
- Wear Resistance – confirms that the duct can sufficiently resist wear caused by prestressing steel during stressing when bent to specified minimum radius.
- Bond Behavior – confirms that the duct can sufficiently transfer prestressing forces to the structure through corrugations.

Designers and owners may demand more stringent requirements and acceptance criteria for these tests. Project-specific specifications should always be evaluated. As an example Florida Department of Transportation (FDOT) Standard Specifications<sup>[12]</sup> have more stringent requirements for wear resistance testing on their projects. The author notes that since introduction of *fib* Bulletin 7<sup>[11]</sup> new materials properties and blends have been identified with desirable characteristics for post-tensioning applications. The industry and governmental authorities should not limit innovation as long as the critical performance requirements are met.

### 3.3 Corrugated Plastic Duct Materials

Polypropylene (PP) and High-Density Polyethylene (HDPE) are both used in the manufacture of corrugated plastic post-tensioning duct. They each have desirable properties for different applications. Both PP and HDPE provide excellent chemical resistance and corrosion protection. **Tab. 2** identifies specific attributes and which material provides an advantage to assist the designer when evaluating differing products that meet *fib* Bulletin 7<sup>[11]</sup> Requirements.

**Tab. 2** Specific Attributes – PP versus HDPE.

ATTRIBUTE	ADVANTAGE
Hot Weather and Heat Resistance	PP
Very Cold Weather	HDPE
Linear Thermal Expansion	PP
Flexibility, Cold Temperatures	HDPE
Impact Resistance at High Temperatures	PP
Impact Resistance at Low Temperatures	HDPE
Wear Resistance, Stressing	PP
Shore Hardness	PP
Lateral Load Resistance	PP
Minimum Bend Radius	PP
Weldability, High Temperatures	No Advantage
Weldability, Low Temperatures	HDPE
Ultraviolet (UV)	PP
Environmental Stress Cracking	PP



## 4 Precast Segmental Duct Couplers

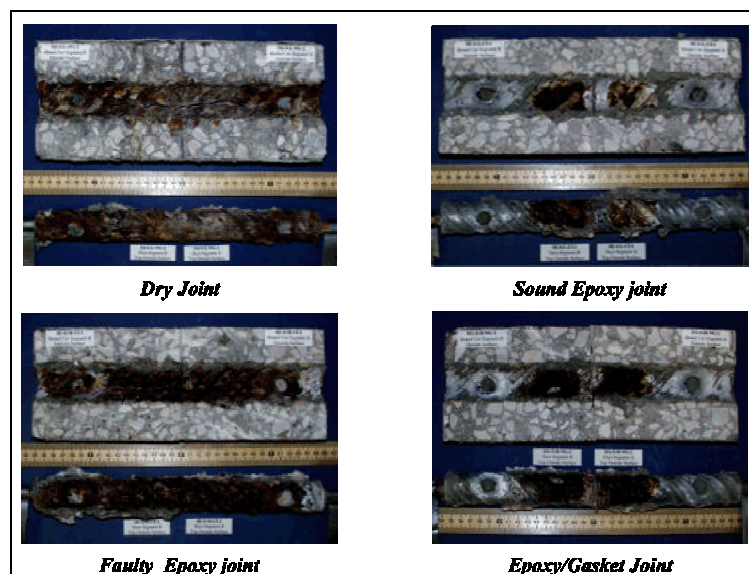
Continuity of tendon enclosures should be maintained thru all joints per *fib* Bulletin 33<sup>[1]</sup>. Joints in precast segmental concrete bridges allow entry points for water (possibly contaminated with corrosive agents) to attack prestressing steel. Durable corrosion protection must be provided with any tendon PL.<sup>[5][6]</sup>

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.<sup>[1]</sup> 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.<sup>[1]</sup> In evaluating the use of membranes or segmental duct couplers, membrane costs (including application, maintenance, expected life and re-application) which can be significant<sup>[1]</sup> are evaluated against the one-time initial costs of the segmental duct coupler representing less than 3% of the total installed post-tensioning price. When total life-cycle costs are considered, using segmental duct couplers is usually more economical than membranes.<sup>[6]</sup>

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. Even when a waterproofing membrane is used, it often does not provide a complete seal and does not last indefinitely, and joints still leak.<sup>[1]</sup> Whereas segmental duct couplers provide protection of the tendon itself, thus protecting the tendon from water ingress at critical segment joints.<sup>[6]</sup>

In the research report *Final Evaluation of Corrosion Protection for Bonded Internal Tendons in Precast Segmental Construction*,<sup>[2]</sup> the authors conclude that segment joints leak regardless of joint type, noting that duct corrosion with dry joints was extremely severe, duct corrosion in sound epoxy joints was moderate to severe, epoxy joints with gaskets performed similar to those without gaskets, and in some cases the gaskets prevented the epoxy from adequately filling the joint area thus allowing moisture and chlorides to penetrate the joint. **Fig. 2** shows examples of joint types and duct corrosion.



**Fig. 2** Effect of Joint Type on Galvanized Steel Duct Corrosion.<sup>[2]</sup>

From the above it is easy to reach the conclusion that precast segmental duct couplers should be used at all joints of precast segmental bridges. An additional benefit of precast segmental duct couplers is the elimination of grout cross-overs. As noted in the FHWA report on *Performance of Concrete Segmental and Cable-Stayed Bridges in Europe*<sup>[9]</sup>, potential cross grouting of ducts through segment joints is a concern especially were the ducts are close to each other.

#### 4.1 Performance Testing of Precast Segmental Duct Couplers

In 2002, the Florida Department of Transportation (FDOT) recognized the critical nature of segment joints and in *New Directions for Florida Post-Tensioned Bridges*<sup>[3]</sup> made a determination that segmental duct couplers would be used on all FDOT Segmental Concrete Bridge Projects. Performance testing of segmental duct couplers is detailed in FDOT Post-Tensioning Specifications<sup>[12]</sup> and include at a minimum: sealing gasket compressive required force test, air pressure test, and assembly toughness test. Acceptance criteria include:

- Maximum force required to compress sealing gasket to its final compressed position shall not be greater than 170 kPa (25 psi) of area encircled by the sealing gasket.
- Segmental duct coupler assembly must sustain 35 kPa (5 psi) internal pressure for a minimum of five minutes with no more than 3.5 kPa (0.5 psi) 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.

#### 4.2 Availability of Precast Segmental Duct Couplers

Today, there are several manufacturers producing segmental duct couplers (see **Fig. 3**). When evaluating segmental duct couplers, designers and contractors should confirm their ability to create an airtight and watertight connection in addition to allowing correct alignment and positioning of ducts (15 degrees or more horizontal or vertical angle at some joints is necessary). From a constructability standpoint, segmental duct couplers need to be robust and user friendly for ease of installation at jobsites allowing field tolerance up to 6 mm in any axis. Segmental duct couplers must include the ability to maintain individual tendon integrity thereby preventing grout crossovers or epoxy leaking into the tendon.<sup>[13][14]</sup>



**Fig. 3** Precast Segmental Duct Couplers

Performance of the precast segmental duct couplers and constructability is of prime importance when choosing a manufacturer. A major performance requirement is not allowing deleterious materials to enter the enclosure; if grout crossovers occur, the coupler does not perform this vital function. In Barry/Bennett's paper<sup>[15]</sup> on successful implementation of duct couplers they note that the presence of grout leaking and crossover leads to the conclusion that the Liaseal System did not

fully meet its intended goals; also, some problems persisted in ensuring that the coupler remained fully engaged during the erection process.

Constructability is a significant consideration for contractors who build segmental bridges; delays or additional steps add time and money. The Freyssinet and VSL couplers require appendages (concrete or mechanical) outside of the segment faces which create forming and erection issues. FDOT's Conditional Approval of the VSL System<sup>[17]</sup> noted six key areas where the coupler system exhibits potential installation difficulties and the impact on construction could range from longer fabrication and erection times to difficulty placing strands to rejection of segments.

The Barry/Bennett paper<sup>[15]</sup> was complimentary of the GTI Precast Segmental Duct Coupler indicating:

- Its flexibility added benefits to construction of segments allowing some room for construction tolerance not available in other systems.
- Connections to the bulkhead had the ability to handle concrete placement forces without the duct becoming dislodged.
- No grout leaks or instances of crossover during grouting and erection operations were detected – there was no need for intrusive repairs.
- Every tendon in the structure was able to meet the field air pressure requirements - the ability to maintain this level of airtight continuity is a major achievement and another indication that the coupler system is providing positive results.
- Finally, concluding that GTI Coupler Technology is not a burden to the project or industry success.

## 5 Cast-in-Situ Segmental Construction

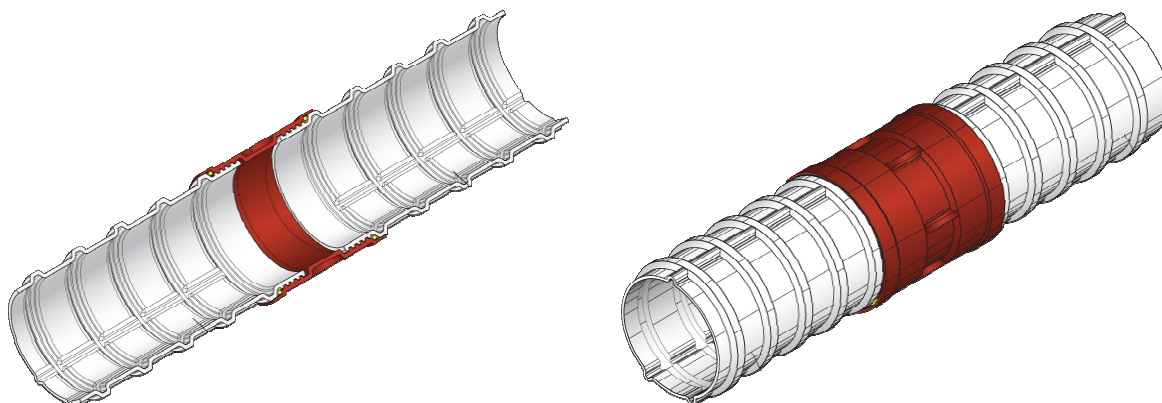
Continuity of tendon enclosures should be maintained thru all joints per *fib* Bulletin 33<sup>[1]</sup>. Joints in cast-in-situ segmental concrete bridges allow entry points for water (possibly contaminated with corrosive agents) to attack prestressing steel. Durable corrosion protection must be provided with any tendon PL.<sup>[5][6]</sup>

In cast-in-situ segmental bridges, post-tensioning duct extends out from the segment just cast into the next segment to be cast. The duct must be fitted with a duct-to-duct coupler. In the past when corrugated metal duct was used in these structures, duct-to-duct couplers were a short piece of the next size larger metal duct that was held in place with duct tape which minimized intrusion of cement paste into the enclosure but did nothing as a barrier for corrosion protection of the prestressing steel. It is imperative to long-term durability of the structure that this connection be watertight because contaminated water can enter the joint and track along the tendon duct to this connection.

Maintaining durable corrosion protection for the tendons requires a watertight duct-to-duct connection for any PL. *fib* Bulletin 7<sup>[11]</sup> establishes testing requirements for the corrugated plastic duct system including duct-to-duct couplers. This report identifies performance requirements for flexibility, lateral load resistance, longitudinal load resistance, and leak tightness of duct system. The essence of the performance testing is that the duct coupler will not allow intrusion of unwanted water into the post-tensioning system thus creating a watertight envelope.

Mechanical connections and shrink sleeves with a slip-on coupler underneath are primarily used for duct-to-duct couplers. Both have shown to perform adequately to the requirements of *fib* Bulletin 7<sup>[11]</sup>. **Fig. 4** shows a mechanical coupler that meets the requirements for watertightness.





**Fig. 4** Mechanical Duct-to-Duct Coupler.<sup>[18]</sup>

It was previously established that corrugated plastic duct should be used with any tendon PL to achieve long-term performance of the tendon enclosure in segmental construction. Note that metal duct and typical metal duct couplers will not meet the leak tightness performance requirements of *fib* Bulletin 7<sup>[11]</sup>. Even though *fib* Bulletin 7<sup>[11]</sup> requirements are for corrugated plastic duct, the leak tightness test is a measure of the ability of any duct coupler to prevent water intrusion.

## 6 Conclusions

Providing durable corrosion protection to post-tensioning tendons is a requirement of *fib* Bulletin 33<sup>[1]</sup>. Protecting the continuity of the tendon enclosure is critical to achieving design service life for post-tensioning tendons in segmental bridge construction.

Corrugated plastic duct is recommended for tendon enclosures in segmental concrete bridges for any PL. PL1 allows the use of metal duct however research has found that galvanized metal duct performs poorly in precast 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<sup>[11]</sup>.

Precast segmental duct couplers are recommended for continuity of tendon enclosures in precast 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. Performance testing of precast segmental duct couplers per FDOT Requirements<sup>[12]</sup> is recommended. Performance and constructability of precast segmental duct couplers should be considered prior to choosing a system.

Mechanical connections or shrink sleeves with a slip-on coupler underneath are recommended for continuity of tendon enclosures at duct-to-duct connections in cast-in-situ segmental concrete bridges for any PL. Even though the duct-to-duct coupler is not physically at the joint, contaminated water can infiltrate the joint and travel along the tendon duct to the connection. It is imperative to the long-term performance of the structure that duct-to-duct connections meets the testing requirements of *fib* Bulletin 7<sup>[11]</sup>.

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