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IMPROVED PERFORMANCE USING CORRUGATED PLASTIC DUCT IN TIGHT-RADIUS POST-TENSIONING APPLICATIONS

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Abstract

Corrugated plastic duct is used in post-tensioning applications worldwide, corrosion protection being one of its primary functions. This includes protection of tendon enclosures and prevention of concrete spalling and deterioration due to expansion of corroding elements (metal/galvanized duct). Using corrugated plastic duct, also, eliminates the corrosion potential of highly stressed post-tensioning steel in contact with galvanized metal.

Typically, corrugated plastic duct is used along the entire length of the tendon from anchorage to anchorage. However, as design and construction of structures becomes more proficient, there is additional demand for post-tensioning tendon profiles to be more severe. This occurs as tendons exit the structure into anchorage blisters or external tendons are deviated at high and low points.

Specially formulated composite materials allow corrugated plastic duct to be used for tight-radius post-tensioning applications such as anchorage blisters and deviators. Required testing conforming to Fédération International du Béton (fib) Bulletin 7[1] must be achieved.

This paper will examine testing requirements of corrugated plastic duct per fib Bulletin 7[1]; discuss how new material blends allow plastics to meet fib Requirements; provide examples of how corrugated plastic duct may be used in tight-radius applications; and discuss advantages of using corrugated plastic duct in tight-radius applications.

Keywords: Post-tensioning, corrugated plastic duct, anchorage blisters, deviators, tight-radius duct

1 Tight-Radius Post-Tensioning Applications

Post-tensioning is a method of prestressing in which the prestressing steel is tensioned after the concrete has attained a specified strength. Internally bonded post-tensioning tendons are contained in a corrugated duct (plastic or metal) and bonded to the concrete through grouting. Varying the location (profile) of the prestressing steel within the concrete cross section allows the tendons to more effectively resist applied loads. The more severe the tendon profile (curve) – the tighter the radius of curvature of the tendon.

In post-tensioned structures, several applications have tendon profiles that require tighter radii than might normally occur. These include anchorage blisters, deviators for use with external tendons, and radical high-points or horizontal curves.

Corrugated plastic duct is used in post-tensioning applications worldwide. It is used along the entire length of the tendon from anchorage to anchorage. One of its primary functions is corrosion protection of tendon.

What is tight-radius corrugated plastic duct? It is corrugated plastic post-tensioning duct that can be bent to a tight radius while still achieving wear resistance requirements through the use of specially formulated, proprietary composite, high-performance materials.

Why use tight-radius corrugated plastic duct? It is light-weight and made of corrosion resistant materials with superior bonding properties; it prevents concrete spalling and deterioration due to expansion of corroding elements (metal or galvanized metal duct; and it eliminates the stress corrosion potential between highly stressed post-tensioning strand and galvanized metal.

2 Corrugated Plastic Duct

fib Bulletin 7[1] was published in 2000 and contains standards for testing of corrugated plastic duct. Until its publication there were no standard performance requirements and inadequate materials were sometimes used giving plastic duct a flawed performance and quality reputation. Currently, high quality products are being manufactured and used on post-tensioning projects. Designers and owners who are utilizing corrugated plastic duct are encouraged to require all duct be tested and affirmed to meet the requirements of *fib* Bulletin 7[1].

2.1 Minimum Bend Radius of Duct

The minimum bend radius of duct is defined as the minimum allowable curve a tendon can have while the duct wall maintains at least a specified thickness during stressing due to wearing of prestressing steel on the duct. This is important because maintaining continuity of tendon enclosures without gaps or breaches that could possibly allow contaminants to enter the tendon is critical to the overall durability of a structure. Prestressing steel typically wears on the duct at points of tendon curvature, primarily high- and low-points. **Fig. 1** shows the lay of individual strands in tendons at points of curvature.

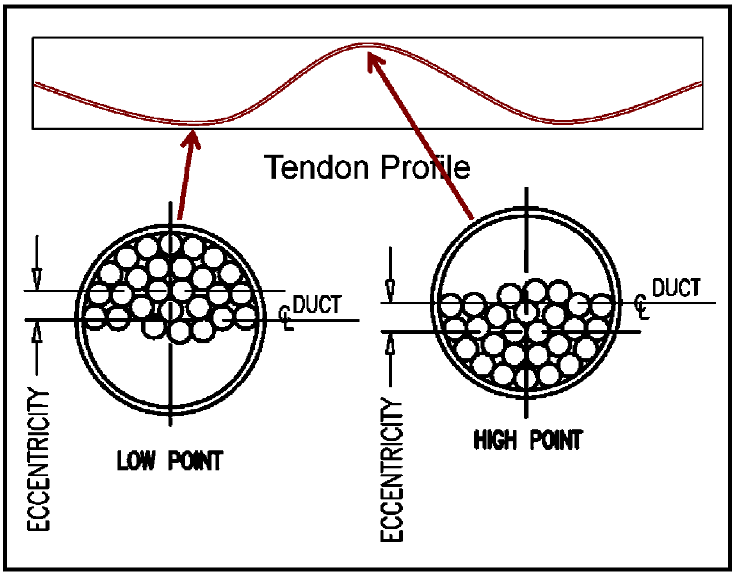

Fig. 1 Tendon Profile[2]

Individual tendons within a structure may have different radii at each point of curvature. The tendon profile creates the curves. The corrugated plastic duct should be manufactured and tested for the most severe curve (tightest radius) that it may be used on.

Each corrugated plastic duct manufacturer typically declares a minimum bend radius for their standard duct. This number varies based upon the specific material formulations that the manufacturer uses and varies with the minimum remaining wall thickness confirmed by testing (see below). **Tab. 1** provides a comparison of published recommended minimum bend radii of two manufacturers for their standard duct.

Tab. 1 Comparison of Recommended Minimum Bend Radii (MBR).

	48 mm	59 mm	76 mm	85 mm	100 mm	115 mm	130 mm	130 mm
Quantity of 15.2 mm Strands	5	7	12	15	19	27	31	37
MBR[1] for VSL PT-Plus Duct (m)	4.8	5.9	7.6	8.5	10.0	11.5	13.0	13.0
MBR[2,3] for GTI Standard Duct (m)	3.3	4.2	4.3	5.2	4.8	5.0	5.5	6.2

Table Notes:

1. Data for VSL PT-Plus Duct was found in *European Technical Approval No. ETA-06/0006, VSL Post-Tensioning System*[3] which states that $R \geq 100\ Øi$, where R is the radius of curvature and $Øi$ = inside diameter of the duct.
2. Data for GTI Standard Duct was found in *GTI TR (Tight-Radius) Corrugated Plastic Duct* Flyer[4].
3. GTI Standard Duct minimum radii based upon 1.5 mm residual wall thickness.

2.2 Performance Testing

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 tests only check duct performance while others also include duct-to-duct connections. The following describes the purpose of each test:[1]

- 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[5] have more stringent acceptance criteria for wear resistance testing on their projects. The author notes that since introduction of *fib* Bulletin 7[1] new material 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.

Tight-radius corrugated plastic duct is typically manufactured using the same profile as standard corrugated plastic duct – the difference being specially formulated composite materials that allow better performance in tight-radius applications. Wear resistance performance testing is critical for tight-radius applications since it confirms that the duct can sufficiently resist wear caused by prestressing steel during stressing when bent to the specified minimum radius. The other performance tests identified above should be performed with the new materials to confirm compliance. With the exception of wear testing, General Technologies, Inc. has found that test results utilizing their specially formulated, proprietary composite, high performance materials do not typically change from standard duct to tight-radius duct.

2.3 Wear Resistance of Duct

Annex 7 of *fib* Bulletin 7[1] describes the process of testing for wear resistance of duct. First, two test specimens are cut from production duct. They are not less than 100 mm in length; are 1/8 of the duct circumference (45 degrees); and shall contain a length of a full rib/corrugation spacing (see **Fig. 2**). The thickness of each specimen is recorded at six locations.

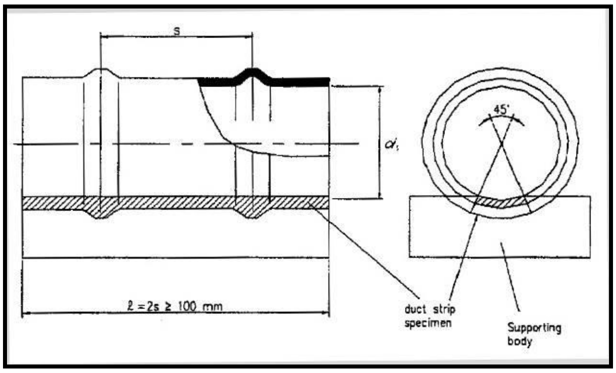

Fig. 2 Test Specimen[1]

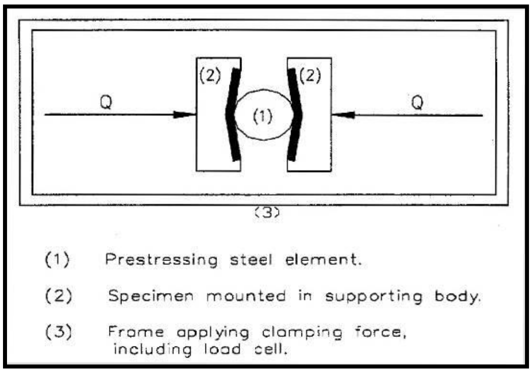

Fig. 3 Test Set-up [1]

Test procedure[1] begins with specimens mounted in a supporting body on opposite sides of a length of stressed prestressing steel, stressed to a force F of 70% of its tensile strength (see **Fig. 3**). The specimens are clamped to the prestressing steel to a force Q. The specimens are then moved along the prestressing steel over a total distance of 750 mm while maintaining the clamping force without allowing the specimens to rotate around the strand. Movement is accomplished in approximately two minutes after application of clamping force Q. After 750 mm of movement the clamping force is held for 3 minutes and then released. The test specimens are removed and the remaining wall thickness is measured at the same six locations initially recorded and at locations deemed to have the minimum remaining wall thickness; these measurements are recorded and compared to the acceptance criteria.

The clamping force Q simulates curvature of duct and identifies the bend radius being tested. It is determined with the following equation: [1] $Q = 0.7 f_{tk} \times A_p \times k \times l / R_{min}$. Where f_{tk} = specified characteristic strength of prestressing steel; A_p = specified cross section of a single tensile element of prestressing steel (strand); k = cable factor to account for effect of actual number n of tensile elements inside one duct (see **Fig. 4**); l = length of specimen; and R_{min} = minimum radius of curvature of tendon specified. The cable factor k quantifies the forces of multiple strands acting on the duct (see **Fig. 5**).

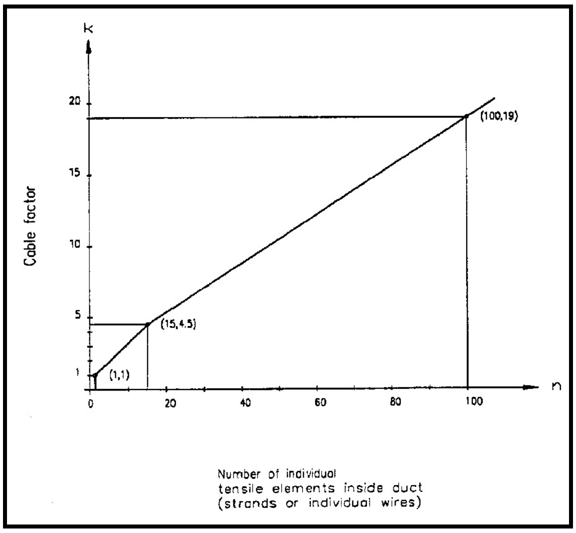

Fig. 4 Cable Factor[1]

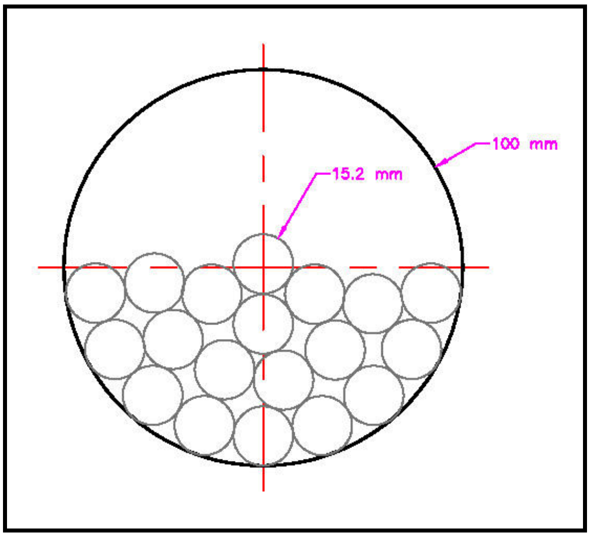

Fig. 5 Multiple Strands Acting on Duct

Acceptance criteria for remaining wall thickness after wear resistance of duct testing per *fib* Bulletin 7[1] is 1 mm for all sizes while FDOT Specifications[5] call out 1.5 mm for duct up to 85 mm and 2.0 mm for duct larger than 85 mm. FDOT Specifications[5] additionally require another wear test. The procedure is similar with the primary difference being the specimens are not moved and the clamping force Q is maintained for a duration of seven days. The residual wall thickness of the duct must pass the same acceptance criteria noted above.

When testing for tight-radius corrugated plastic duct, the clamping force Q is increased to simulate a smaller radius. **Tab. 2** shows the effect to the clamping force Q when the bend radius is modified for a 15.2 Ø x 19-strand tendon in a 100 mm duct.

Tab. 2 Effect of Bend Radius on Clamping Force Q.

Bend Radius	10 m	6 m	5 m	4 m	3 m
Clamping Force Q	**9.5 kN**	**15.7 kN**	**18.9 kN**	**23.6 kN**	**31.5 kN**
Strength of prestressing steel, f_{tk}	1,860 MPa	1,860 MPa	1,860 MPa	1,860 MPa	1,860 MPa
Cross-section of single strand, A_p	140 mm^2	140 mm^2	140 mm^2	140 mm^2	140 mm^2
Cable factor, k	5.182	5.182	5.182	5.182	5.182
Length of specimen, l	100 mm	100 mm	100 mm	100 mm	100 mm

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Tight-radius corrugated plastic duct requires a large clamping force as can be seen in **Tab. 2** above. Modification of testing equipment is sometimes necessary to achieve such high clamping forces. Imagine the force that is applied to the plastic duct specimens and then moved over a strand. The blend of composite materials must be very tough to resist wear-through.

Tab. 3 shows the current published minimum bend radius for General Technologies, Inc. TR Duct.[4] As new material blends and composites are performance tested, the minimum bend radii will improve allowing designers and contractors greater flexibilities in their structures.

Tab. 3 Recommended Minimum Bend Radii (MBR) for Tight-Radius Corrugated Duct.

	48 mm	59 mm	76 mm	85 mm	100 mm	115 mm	130 mm	130 mm
Quantity of 15.2 mm Strands	5	7	12	15	19	27	31	37
MBR for GTI TR Duct (m)	2.4	3.0	3.1	3.7	3.8	4.2	4.3	4.9

Table Notes:

1. Data for GTI TR Duct was found in *GTI TR (Tight-Radius) Corrugated Plastic Duct* Flyer[4].
2. GTI TR Duct minimum radii based upon 1.5 mm residual wall thickness.

3 Anchorage Blisters

Internal post-tensioning tendons are often anchored at intermediate locations within a structure. Anchorage blisters allow access for tendon installation and stressing. In segmental construction, anchorage blisters are used to install and stress longitudinal tendons thus not impeding or delaying erection of the structure. **Fig. 6** shows a sketch of a tendon exiting the structure at an anchorage blister.

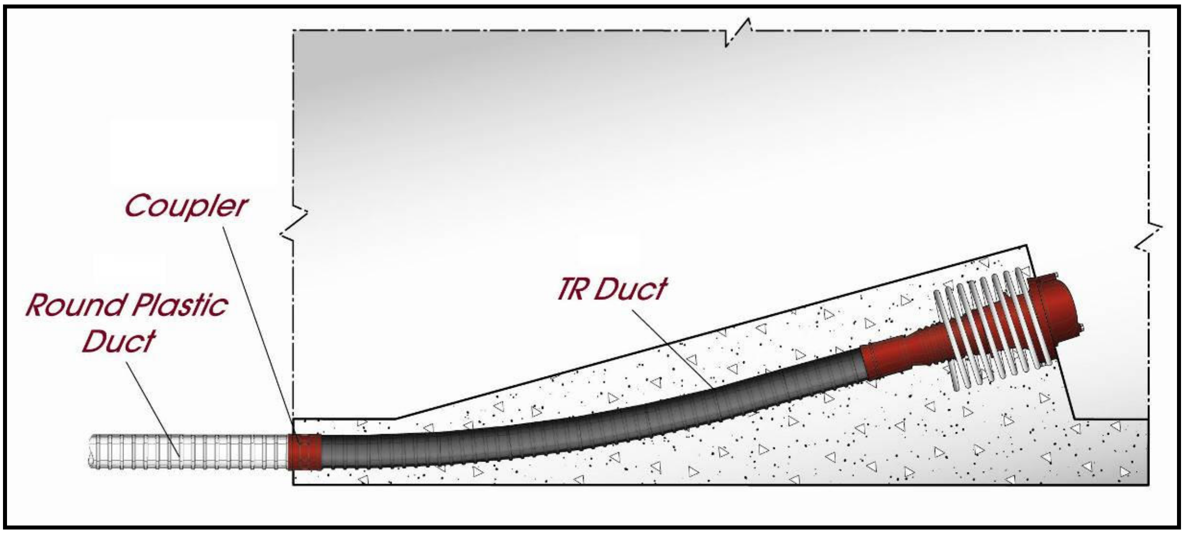

Fig. 6 Anchorage Blister[4]

3.1 Why Require Tight-Radius Corrugated Plastic Duct?

Typically, corrugated plastic duct is used along the entire length of the tendon from anchorage to anchorage. The tendon exiting the structure through an anchorage blister generally must be bent to a tighter radius than anywhere else in the structure. In addition, during stressing, the prestressing steel will elongate the greatest at the anchorage thus wear-through of duct is of prime importance. As design and construction of structures becomes more proficient, there is additional demand for post-tensioning tendon profiles to be more severe at anchorage blisters. Designers must require that the bend radius of corrugated plastic duct at this location be performance tested per *fib* Bulletin 7[1] and FDOT Specifications[5] as appropriate. **Fig. 6** identifies the location in anchorage blisters where tight-radius corrugated plastic duct should be used.

Occasionally, standard corrugated plastic duct, metal flex duct or metal pipe is substituted for tight-radius corrugated plastic duct at anchorage blisters – this is not recommended because of the risk of corrosion and deterioration of the structure. Standard corrugated plastic duct will not meet the required bend radius. Metal flex duct or metal pipe are susceptible to corrosion causing structure deterioration and are not acceptable for tendon protection levels PL2 and PL3. [6] [7] [8] [9] The high tensile stresses in anchorage blisters cause concrete cracks that are not necessarily detrimental to the strength of the structure but may be locally unavoidable;[10] these cracks can allow corrosive agents to attack metal causing the concrete to deteriorate. The owner and designer want a structure that will perform over its lifetime and should not accept an inferior alternative in this critical location.

3.2 Why Use Tight-Radius Corrugated Plastic Duct?

Using tight-radius corrugated plastic duct at anchorage blisters maintains integrity of the tendon enclosure thus ensuring the protection required by owners, designers, and codes. Connections of tight-radius corrugated plastic duct to anchorages and duct-to-duct connections are the same as used with standard corrugated plastic duct so there are no additional connections required. Tight-radius corrugated plastic duct can be used with precast segmental duct couplers in precast segmental construction. **Fig. 7** shows tight-radius corrugated plastic duct in anchorage blisters prior to concrete placement. Tight-radius corrugated plastic duct allows tendons to be bent to a more severe radius giving designers and contractors added flexibility during construction. The need for tight-radius duct at anchorage blisters is evident in **Fig. 8**.

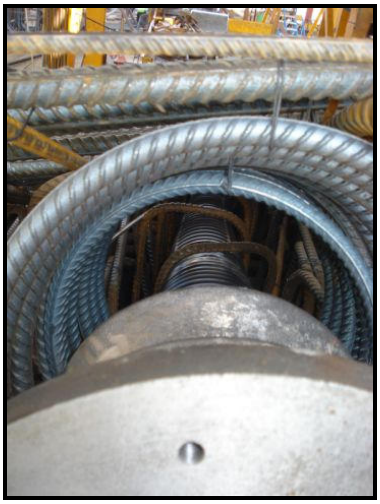

Fig. 7 Tight-Radius Corrugated Plastic Duct in Anchorage Blister prior to Concrete Placement

[photo courtesy of BBR Pretensados y Técnicas Especiales, S.L.]

Fig. 8 Severe Radius of Tendon Exiting at Anchorage Blister

[photo courtesy of BBR Pretensados y Técnicas Especiales, S.L.]

4 External Tendon Deviators

External post-tensioning tendons are popular in bridge structures. In many cases, their use allows the concrete section of bridges to be more slender with less concrete. External tendons in bridge

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structures are typically profiled going from high-points over supports to low-points near mid-span. The tendons pass through concrete diaphragms at each change of direction. **Fig. 9** shows a graphical depiction of a tendon passing through a concrete diaphragm. External tendons generally are straight between these deviation points. The external tendon enclosure is typically HDPE pipe that is attached to the tight-radius corrugated plastic duct as it exits the deviation block.

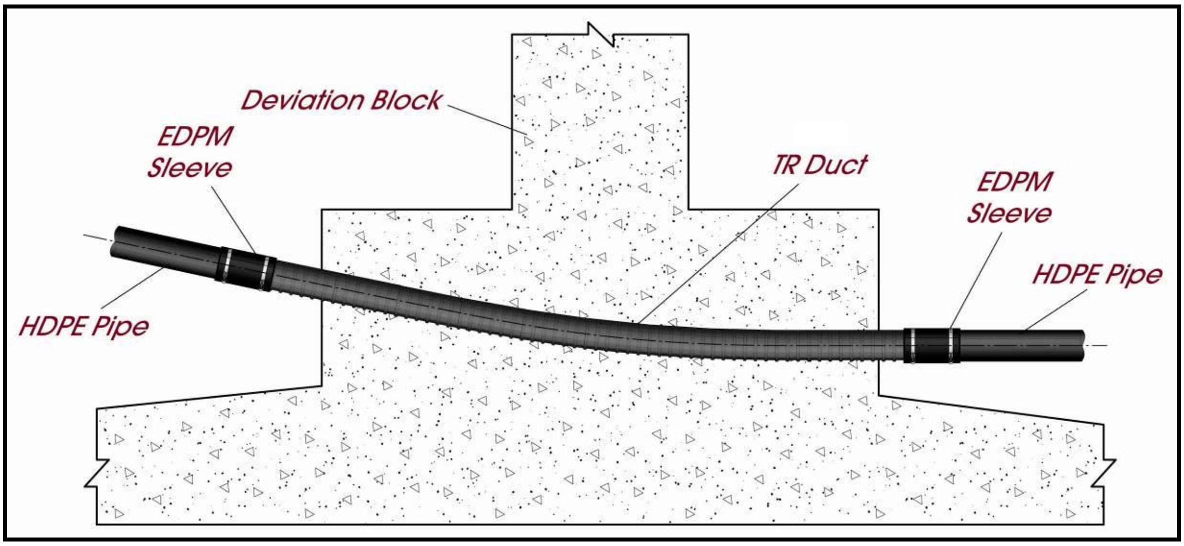

Fig. 9 External Tendon Passing Through Concrete Deviation Block[4]

Galvanized metal pipe and diabolos have been used in the past to deviate external tendons. Following are some of the shortcomings of these two systems. Galvanizing of metal pipe is sometimes suspect; designers should require galvanizing after the pipe is bent to the required radii and any required ribs/lugs are installed. The bent pipes must be correctly orientated and held firmly in place in forms prior to concreting; otherwise, tendon geometry can be affected. If metal pipes are out of alignment coming out of concrete diaphragms, it is very difficult to correct this deficiency. Another shortcoming of galvanized metal pipe is the possibility of hydrogen embrittlement of prestressing strand. In a research report for the Florida Department of Transportation on prestressing steel in galvanized pipe voided pile, Hartt and Suarez[11] conclude "recognizing that alternative materials to galvanized pipe are available and that these have proven satisfactory, it is recommended that galvanized pipe not be used."

Diabolos create a void through the concrete diaphragm at a specified radius allowing the external tendon's HDPE pipe enclosure to pass through the concrete and deviate to the tendon geometry (see **Fig. 10**). One-time use special wood, plastic or metal forms are used to create diabolo voids to specified radii and diameters. The diabolo internal diameter must be designed specifically for the HDPE pipe outside diameter. The HDPE pipe must be robust enough to handle tendon wear-through during stressing and flattening that will occur when the prestressing strands move within the pipe changing its circular shape to an oval as the strands gravitate to get bearing against the concrete surface of the diabolo shape. This adds internal stresses into the HDPE pipe that may initiate cracking allowing unwanted corrosive agents to attack the highly stressed steel.

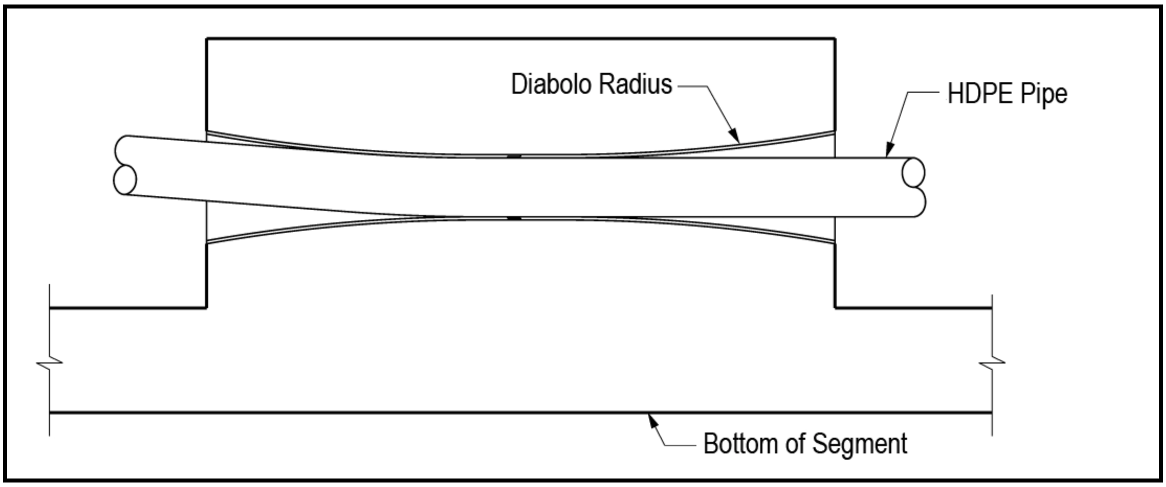

Fig. 10 HDPE Pipe passing through a Diabolo Created Void

4.1 Why Use Tight-Radius Corrugated Plastic Duct?

The use of tight-radius corrugated plastic duct for deviation points on external tendons provides many benefits to contractors, designers, and owners. It allows the use of light-weight, corrosion resistant materials that are easy to transport, handle, and install. It bonds to the concrete diaphragm like an internal post-tensioning tendon – this does not happen with galvanized metal duct or diabolos. It eliminates corrosion potential between highly stressed post-tensioning strand and galvanized metal pipe. Radii are pre-applied to tight-radius corrugated plastic duct prior to shipment and can be applied in multiple directions. It allows an easy orientation fix if incorrectly placed in concrete (procedure is provided by manufacturer). It provides significant cost savings against both galvanized metal pipe and diabolos. [4]

5 Radical High-Points or Horizontal Curves

Tight-radius corrugated plastic duct is an excellent choice when tendons pass through a radical high-point or horizontal curve similar to anchorage blisters. When post-tensioning tendons' profiles have radii beyond the capabilities of standard plastic duct, an alternative enclosure must be substituted. In order to maintain the corrosion protection requirements, tight-radius corrugated plastic duct should be used rather than metal flex duct or metal pipe. Performance testing of the tight-radius corrugated plastic duct should be completed for the minimum bend radii per *fib* Bulletin 7[1] and FDOT Specifications[5].

6 Conclusions

Tight-radius corrugated plastic duct is an exceptional selection for tight-radius post-tensioning applications such as anchorage blisters, external tendon deviation points, and radical high-points or horizontal curves. Tight-radius corrugated plastic duct maintains the corrosion protection of the tendon enclosure and has the same bonding capabilities as standard plastic duct. There is no possibility of concrete spalling and deterioration due to expansion of corroding elements as with metal/galvanized duct or metal pipe. Use of corrugated plastic duct (standard or tight-radius) eliminates any corrosion potential between prestressing steel and galvanized metal.

Wear resistance of tight-radius corrugated plastic duct should be confirmed for the minimum bend radii it will be used in. Performance testing should be per *fib* Bulletin 7[1] and FDOT Specifications[5] as appropriate. Tight-radius corrugated plastic duct is typically manufactured using the same profile as standard corrugated plastic duct thus duct-to-duct and duct-to-anchorage connections are the same.

The benefits of tight-radius corrugated plastic duct are many. Specially formulated, proprietary composite, high performance materials allow light-weight, corrosion resistant post-tensioning duct for tight-radius post-tensioning applications that is easy to transport, handle, and install. Pre-bending with multi-directional bends is achievable so tight-radius corrugated plastic duct is ready to install when it reaches the jobsite. And best-of-all, tight-radius corrugated plastic duct provides significant cost savings when compared to other alternatives.

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