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PLASTIC DUCTS FOR SUSTAINABLE BRIDGE DESIGN: ENGINEERING TO EC2 AND FIB BULLETIN NO. 113

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Abstract

Polymer duct systems for internal bonded post-tensioning are increasingly popular as key components for corrosion-resistant, durable, and sustainable concrete bridges. The new version of Eurocode 2 "Design of Concrete Structures" [1] that has been released end of 2023 considers also the use of plastic ducts and gives some advantages in design that can be used to reduce the overall quantity of prestressing steel or rebars. The first bridge using polymer ducts was built 50 years ago already in Switzerland and in 2002 Florida Department of Transport (FDOT) released the document "New Directions for Florida Post-Tensioned Bridges" [2] and with subsequent specifications allowed only the use of polymer ducts in post-tensioned bridges. Despite this, metal ducts are still used for post-tensioned bridges in many countries, although they are susceptible to corrosion. fib Bulletin No. 113 "Polymer-duct systems for internal bonded post-tensioning" [3] was issued in 2024 as update of the famous fib bulletin no. 75 [4]. It provides information for the structural engineers regarding design and detailing of concrete structures containing tendons with polymer ducts. This article will highlight the requirements for durable post-tensioning structures with reference to fib bulletin no. 113 and EC2 and allow the designer to understand the benefits of plastic ducts according to EC2.

Keywords:

Post-tensioning;
fib bulletin 75/113;
Plastic ducts;
Corrosion protection;
Fatigue resistance.

1 Introduction

Polymer duct systems for internal bonded post-tensioning enjoy growing popularity as one of the key components for corrosion resistant, durable and therefore sustainable concrete bridges. fib Bulletin 75 "Polymer-duct systems for internal bonded post-tensioning" [4] was issued in 2014 and is considered a cornerstone for technical approval process of polymer or plastic ducts. It provides information for the structural engineer regarding design and detailing of concrete structures containing post-tensioning tendons with corrugated plastic ducts.

2 History of Plastic Ducts

The use of plastic ducts for internal bonded post-tensioning began in Switzerland. Between 1968 and 1974, around 300.000 m of corrugated black PE pipes were installed in highway bridges and overpasses [4].

One of the first major bridge projects to utilise plastic post-tensioning duct is the Chillon Viaduct (Fig. 1). This structure is located at the eastern end of Lake Geneva and is part of the Swiss A9 motorway. It was completed in 1969 and consists of 23 spans with a total length of 2.210 metres, with a maximum span of 104 metres. The bridge was originally designed for 10.000 vehicles per day; today it is currently used by 50.000 vehicles per day. During renovation work in 2012, the first signs of alkali-silica reaction (ASR) were discovered, which required bridge deck strengthening in 2014 and 2015 using rebars embedded in a thin layer of ultra-high performance fibre-reinforced cement composite (UHPFRC). No damage to the longitudinal tendons protected with post-tensioning plastic ducts was detected [5].

Fig. 1: Chillon Viaduct (© XBau AG)

Since the early 1990s, the use of plastic ducts has become increasingly important in Europe, the USA and India and, to a lesser extent, in Asia. At the end of the 1990s, fib published bulletin 7 [6], the first technical report with information, tests and performance specifications for corrugated plastic ducts for internal bonded post-tensioning tendons. In 2006, fib bulletin 33 [7] presented the concept of protection levels (PL1-PL3) for tendons, which are included in the Swiss ASTRA 12010 "Measures to ensure the durability of tendons in civil engineering structures" [8] and in PTI/ASBI M50.3-19 "Specification for Multistrand and Grouted Post-Tensioning" [9]. The publication of fib bulletin 75 [4] can be considered a milestone. This comprehensive document provides detailed information for the design and the execution of prestressed post-tensioned concrete structures, a wide range of performance tests to be carried out in the approval phase, as well as periodic factory production control testing, and has system tests assessing the suitability of the anchorage in conjunction with the connection sleeves, which is of particular importance for electrically insulated tendons (EIT). Accordingly, EAD 160004-00-0301 "Post-tensioning kits for prestressing of structures" [10] refers to fib bulletin 75 for the evaluation of systems with plastic ducts and Eurocode 2 [1] refers to it for selection of the protection level.

Finally in 2024, fib bulletin No. 113 " Polymer-duct systems for internal bonded post-tensioning" [3]. Whereas the shift from fib bulletin No. 7 to fib bulletin No. 75 in 2014 marked a substantial evolution — reflected in the notably increased scope — the updates introduced with fib bulletin No. 113 are relatively modest. It is explicitly noted in this new document that fib bulletin No. 75 may continue to be used.

The use of plastic ducts in bridge construction is now standard not only in Switzerland, but also in other European countries such as the UK and Czech Republic and the US states Minnesota, Texas and Florida. But also other European countries such as Italy, France, Slovenia and Norway do have already bridge structures that are built with plastic ducts for internal post-tensioning.

3 Tendon Protection Levels

As per fib Bulletin 33 [7], the selection of the tendon protection level for a specific project requires that the aggressivity of the environment acting on the structure is assessed as low/medium/high. Then the structural protection offered by the structure for the tendons is determined and also rated as low/medium/high. Once these two tasks have been completed, the protection class (PL) for the tendons can be selected, see Fig. 2.

Aggressivity of Environment and Exposure. To obtain information on entry points for aggressivity and exposure, fib Bulletin 33 refers to EN 206-1 [11] and its definition of exposure classes. Six categories are used:

- X0: no risk of corrosion or attack
- XC1-XC4: corrosion induced by carbonation
- XD1-XD3: corrosion induced by chlorides other than from sea water
- XS1-XS3: corrosion induced by chlorides from sea water
- XF1-XF4: freeze/thaw attack with or without de-icing agents
- XA1-XA3: chemical attack

The aggressivity of common bridge structures in Central and Northern Europe should generally be categorised as "medium" or "high". For chloride exposure from de-icing salts (XF4) the classification is always "high" and for chlorides from sea air (XS1) the classification is "medium". In Germany, Railway bridges that are less than 10 m away from areas or roads exposed to de-icing salts (XF2) are also classified as "high" [12].

Protection provided by the structure. The structural protection of the tendon provided by the structure must now be determined or estimated and assessed as low/medium/high [13].

Many factors come into play, such as concept, detailing, material selection, and construction quality. It is important to always keep in mind that the corrosion of prestressing tendons occurs through the penetration of chlorides and other harmful substances at weak points, which can be found at the anchorages, tendon couplers, and sleeve connections of the ducts, as well as in concrete cracks or inadequate concrete cover.

The following factors are included in the assessment according to fib Bulletin 33:

- Concrete quality and cover
- Concrete cracking
- Construction joint details
- Expansion joint details
- Waterproofing Systems and other surface protection systems
- Drainage system details
- Segment joint details

The result is a rating in three levels from "high" for excellent constructive protection to "medium" and "low", although admittedly the categorisation here is not quite as clear as for the exposure classes.

Selecting the Protection Level. After determining the rating for the exposure in accordance with 3.1 and the structural protection in accordance with 3.2, the required protection level of the tendon can be determined using the corresponding fig.1. For example, if the exposure is rated as "medium" and the design protection as "high", this results in protection class PL2. According to fib bulletin 33, this means that the anchorage must be protected with a permanent tight cap and plastic post-tensioning ducts must be used. For PL3 the requirement is that the integrity of the envelope can be permanently tested, which results in the use of Electrically Isolated Tendons.

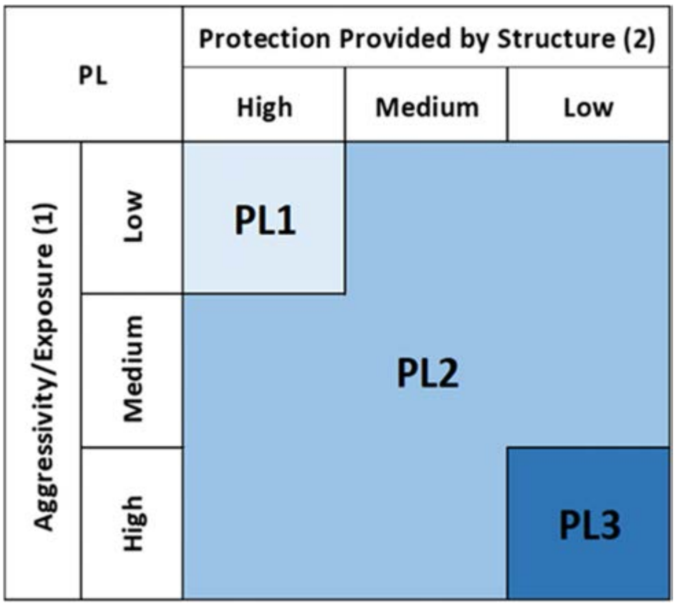

Fig. 2: Selection of Protection Level (PL)

4 Design Considerations

4.1 General Considerations

Once the owner or designer of a structure concludes that corrugated plastic ducts shall be used, it is recommended to clearly specify compliance with fib bulletin 113 [3] to be included as part of the post-tensioning kit. This ensures that a state-of-the-art system will be used. To ensure the highest quality, the bulletin includes comprehensive inspections of the plastic ducts and connections to the entire post-tensioning kit, including anchoring. This involves specific approval tests that are conducted solely to verify that the entire post-tensioning kit will perform as specified, as well as a series of factory production control tests that are continually carried out to confirm that the manufactured components conform to those used in the approval process.

4.2 Radius of curvature

A critical aspect when using corrugated plastic duct is determining the allowable radius of curvature for a specific duct. The plastic duct will need to be sufficiently resistant to wear caused by the prestressing steel during tendon stressing when bent to a specified radius of curvature. Below is information to take in consideration when determining the allowable radius of curvature.

Plastic is softer than metal and thus the prestressing strands will wear into the plastic ducts during stressing of the tendon. This is not a problem as long as there is sufficient residual wall thickness of the plastic duct after stressing. There are two performance tests in fib bulletin 113 [3] to verify this, namely “Wear resistance of duct” (Annex A.8) and “Wear resistance of duct under sustained load” (Annex A.9). Figure 3 shows an apparatus used to clamp the duct during testing.

Test A.8 simulates stressing of a tendon with 125 m length and corresponding elongation of 750 mm while the clamping load Q pressing on the duct wall trough the strand is increasing steadily. Test A.9 considers the creep of plastic under load and accordingly test duration is 14 days to simulate the time between stressing and grouting. The same clamping load Q is used in both A.8 and A.9 testing. The same specimens from test A.8 are used for test A.9. To pass the test a minimum residual wall thickness of 1,5 mm after test A.8 and 1,0 mm after test A.9 is required for Tendon Protection Level 2 and 3.

As the wear of plastic ducts depends also on the temperature, both tests are performed at ambient temperature (23°C) and high temperature (45°C). The clamping load Q may be different based on temperatures being evaluated.

4.3 Minimum radius of tendon curvature

The limitation of the radius of tendon curvature is essential to manage:

a) The lateral pressure on the concrete

b) The potential damage to prestressing steel within the tendon bundle

c) The risk of damage to the duct due to lateral pressure between the prestressing steel and the duct.

Condition a) and b) is independent from the duct material whereas for condition c), wear testing of plastic ducts according to A.8 and A.9, as described above, needs to be performed. Based on the clamping load Q that is applied in the successful tests, the duct manufacturer can declare the minimum radius of tendon curvature Rmin for field installation with equation (1).

$$R_{min} = 0{,}7 * F_{pk} * A_p * k * l/Q \quad (1)$$

where:

F_{pk} is specified strength of prestressing steel,

A_p is cross section of a single strand,

k is cable factor to consider the number of strands in the duct.

It is important to perform the wear resistance test A.8 and A.9 with as high a clamping load Q as possible to achieve a small bending radius Rmin and thus a reasonable tendon geometry. The reachable clamping load Q depends on the characteristics of the material properties and blends which the duct manufacturer is using. For applications that require particularly small bending radii, the manufacturer General Technologies, Inc. (GTI) has developed a proprietary special “Tight Radius” blend. With this blend a R_{min} of 5,0 m for a 100 mm duct filled with 19 strands can be achieved [14].

Fig. 3: Wear testing of duct

4.4 Improved fatigue strength

Prestressing steel installed in plastic ducts has a significantly improved fatigue resistance over prestressing steel installed in metal ducts. According to Table 6.4N in Eurocode 2 [1], $\Delta\sigma_{Rsk}$ can be set at 150 N/mm² when using plastic post-tensioning ducts versus 120 N/mm² with metal ducts (see Fig. 4).

The outstanding properties of plastic post-tensioning ducts in terms of fatigue strength have been proven in several research reports. For example, Hegger and Abbel carried out tests on 14 prestressed concrete beams and found as early as 1999 that metal ducts exhibited the first cracks after 10.000 to 20.000 load cycles at crack amplitudes of 0,1 millimetres, whereas plastic ducts remained crack-free even at crack amplitudes of 0,2 to 0,3 millimetres over 2 million load cycles. The authors concluded: "As plastic ducts thus ensure corrosion protection for tendons even under dynamic stress, restrictive regulations on compliance with decompression can be omitted." [15]. Therefore, under certain conditions, Eurocode 2 [1] also allows a crack width of 0.3 mm for PL2 and PL3 whereas for PL1 the decompression limit is applied, i.e. all parts of the tendon lie at least 25 mm within concrete in compression. This means that the prestressing force can be reduced with PL2/PL3 compared to PL1 and consequently the amount of prestressing steel will be reduced.

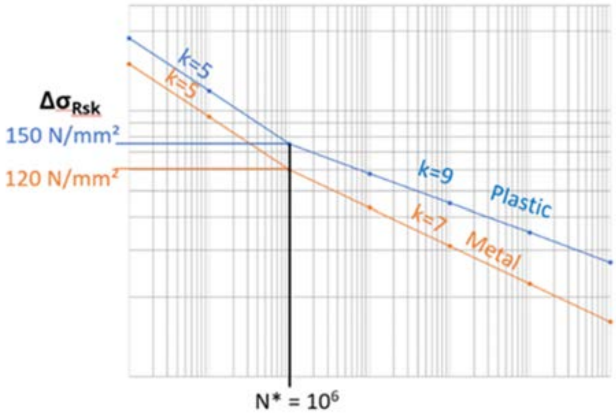

Fig. 4: Fatigue strength acc. to EC2:2023

4.5 Friction losses

The prestressing force in a post-tensioning tendon decreases steadily as a result of friction with the distance from the stressing-end and depends on both the geometry of the tendon (sum of the deflection angles) and the friction in the duct. The coefficient of friction μ depends on the selected duct type and can usually be taken from the approval or a manufacturer's data sheet. For metal ducts, a μ value of 0,19-0,20 is usually used, whereas the friction coefficient μ = 0,12 is used for plastic post-tensioning duct [16], [17].

The positive effects of reduced friction are clearly illustrated by two examples. The friction losses in a 145 m long box girder bridge with a 3-span superstructure (end-spans of 2 x 40 m and centre-span of 65 m) are calculated with μ = 0,20 for metal ducts and alternatively with μ = 0,12 for plastic ducts; this results in 9% lower loses in the centre of the span. Thus, the amount of prestressing steel required can be significantly reduced.

As the possible reduction in friction losses due to reduced friction depends on both the length of the tendons and the sum of the deflection angles, significant reductions are therefore possible for round structures such as tanks and silos. In 2024, eight digester tanks were completed in Singapore for the TUAS Water Reclamation Plant project. The tanks are designed with horizontal tendons comprising 360° and ring anchorages as well as vertical tendons with loops at the bottom, see Figure 5. The tanks have an inner diameter of 25 m with wall thickness of 65 cm and a height of 45 m. The horizontal tendons with 12 nos. Ø 15,7 mm strands are 79,1 m long. The use of plastic ducts allowed the friction loss in the middle of the tendon to be reduced by 28% compared to metal ducts.

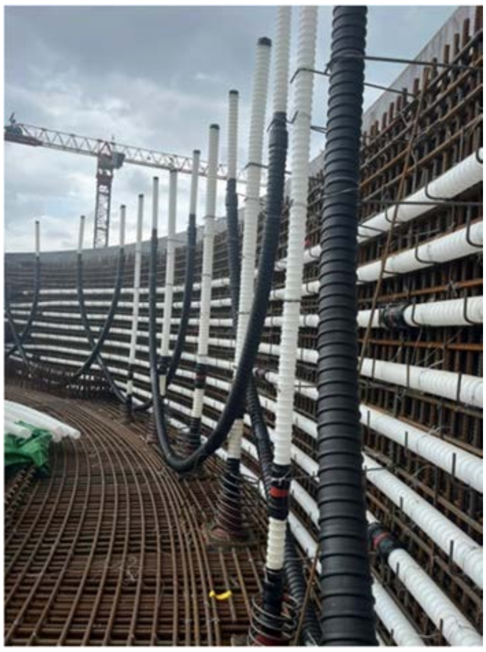

Fig. 5: Tank with GTI® plastic ducts for horizontal and vertical post-tensioning and GTI Tight Radius ducts for the loop tendons

4.6 Shear stress resistance

An important design consideration in the design of box girders is the reduction of the actual web width for the design of the shear load-bearing capacity, particularly where large-diameter ducts affect the web's capacity to resist shear and compressive stresses. According to Eurocode 2 [1], when the cumulative diameter of ducts at a given web cross-section exceeds one-eighth of the actual web width, a reduced nominal web width $b_{w,nom}$ must be applied for structural design verification:

$$b_{w,now} = b_w - k_{duct}\sum Ø_{duct} \tag{2}$$

where :

b_w is minimum width of the cross-section between tension and compression chords and neutral axis,
$b_{w,\, nom}$ is nominal web width due to the disturbance of ducts,
k_{duct} is coefficient for calculating the nominal web with due to the disturbance of ducts,
$Ø_{duct}$ is outer diameter of post-tensioning duct.

Here, $\sum Ø_{duct}$ refers to the total outer diameter of all ducts at the most critical cross-sectional level, and k_{duct} is depending on the duct material. For grouted plastic ducts, EC2 stipulates a reduction factor k_{duct} = 0,8, while for grouted metal ducts, a more favourable k_{duct} = 0,5 shall be considered. The higher coefficient for plastic ducts results in a slightly bigger reduction of the effective web width.

Interestingly, earlier versions of EC2, such as the 2004 edition, prescribed a considerably more conservative value of k_{duct} = 1,2 for plastic ducts. This led to an overestimated loss in web width and unnecessarily penalized design with plastic ducts. Current codes and recommendations reflect updated research and practical performance data. Further insight is provided in fib Bulletin No. 113 [3] chapter 3.2.8, which also includes a comparative table of reduction coefficients used in international standards like AASHTO and fib Model Code 2010.

4.7 Concrete cover

According to Eurocode 2 [1] clause 6.5.2.2 (4), the concrete cover for prestressing tendons should be increased by 10 mm, except when plastic ducts (PL2 or PL3) are used for internal bonded tendons. It should be noted that the required concrete cover can be a governing factor in the design of transverse tendons in bridge decks, which are often placed in the same layer as mild reinforcement to maximize tendon eccentricity. In such cases, the additional 10 mm of cover may lead to increased concrete volume in the structure. This increase can potentially be avoided by using plastic ducts.

4.8 Concrete cover

Structural monitoring, particularly of bridges, has been gaining importance for years, with ongoing development and implementation of new techniques and methodologies. One relatively simple and cost-effective approach to evaluating the corrosion protection of prestressing tendons during inspections—or even on demand—is the use of PL3 systems with electrically isolated tendons (EIT).

This method involves measuring the electrical resistance (impedance) between the internal tendon and the surrounding reinforcement outside the protective duct. To enable this, plastic ducts must be used and the anchorage system must also be designed to fully isolate the prestressing strands and wedges from the external reinforcement. Further information on electrically isolated tendons and extensive references can be found in fib Bulletin No. 113 [3].

5 Conclusion

ASTRA 12 010 [8] gives a good summary of why the use of high quality ducts is so important: “Tendons can be at risk from chloride exposure, fatigue or stray currents. Corrosion damage to tendons has been repeatedly observed. Bridge and building collapses have been reported abroad. The corrosion condition of prestressing steel within metal ducts cannot be assessed using non-destructive methods. For these reasons, plastic ducts have been used in Switzerland since the 1990s in addition to metal ducts, which only offer limited corrosion protection. This not only improves corrosion protection, but also increases the fatigue behaviour of the tendons. Tendons with complete electrical insulation offer additional advantages such as protection against stray currents and the possibility of monitoring corrosion protection over the entire service life by measuring electrical resistance."

Disclosure of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

All data generated or analysed during this study are included in this published article [and its supplementary information files].

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