Polymer-duct systems for internal bonded post-tensioning
Polymer-duct systems for internal bonded post-tensioning

Recommendation prepared by
Task Group 9.16

December 2014
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<th>Minimum Approval Procedure Required Prior to Publication</th>
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<tr>
<td>Technical report</td>
<td>approved by a task group and the chairpersons of the commission</td>
</tr>
<tr>
<td>State-of-the-art report</td>
<td>approved by a commission</td>
</tr>
<tr>
<td>Manual, Guide (to good practice)</td>
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<tr>
<td>Model code</td>
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Any publication not having met the above requirements will be clearly identified as preliminary draft.

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This report was drafted by Task Group 9.16: Plastic ducts, within fib Commission 9: Reinforcing and prestressing materials and systems:

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Cover image: Round Corrugated Plastic Duct used for internal bonded post-tensioning (Photo courtesy of General Technologies, Inc.)

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Foreword

Thick-walled plastic ducts have been used since early 1990 for internal bonded prestressing applications. Based on the first ten years of experience, *fib* Bulletin 7 *Corrugated plastic ducts for internal bonded post-tensioning* was published in 2000. Since then polymer ducts have found their way into many national standards and are to be found on the market in various products (ducts and accessories) that differ in material and geometry details.

*fib* Commission 9 felt the time had come for a new report that updates information and provides valuable guidance to agencies, owners and engineers for the approval of corrugated plastic ducts. Indeed this report, proposed by Task Group 9.16, has the merit of presenting extensive information about material components, fabrication processes, on-site installation, and testing and approval processes for the ducts, their associated accessories and PT systems. In particular, annexes A and B provide testing details that could be considered a basis for the future standardization of corrugated polymer ducts, associated accessories and PT systems. This new report should, therefore, replace *fib* Bulletin 7 and be used whenever *fib* Bulletin 7 is referenced.

We hope that this document will help those interested in the durability of post-tensioned concrete structures to benefit from the additional corrosion protection offered by corrugated plastic ducts.

I would like to acknowledge the contribution of all the members of Task Group 9.16. In particular, this document would not have been possible without the leadership of Dr Hans-Rudolf Ganz and the dedicated work of Mr Larry Krauser. In addition, the final editing of the technical report by Marianne Fourie of the *fib* secretariat is greatly appreciated.

Josée Bastien

Chair of *fib* Commission 9 *Reinforcing and Prestressing Materials and Systems*
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1 Introduction, scope of report

1.1 General

Polymer ducts have been used since the 1960s in prestressing technology for such applications as greased and sheathed monostrands, ground anchors and external tendons, as well as for stay cables that are mostly in the form of smooth pipes, namely, that do not allow the transfer of bond stresses from the tendon to the structure. An early example is the Schillersteg in Stuttgart, completed in 1961. The stay cables are protected inside black polyethylene pipes. Material samples of the stay pipes were taken after 13 years of exposure to the environment and compared with virgin material. No particular changes in the properties of the polyethylene have been observed over this period [Saul (1990)]. While there were a few isolated issues, the experience from use over more than half a century has confirmed the satisfactory performance and durability of the polymer ducts for these applications.

Corrugated polymer ducts have been used for ground anchors in bond length.

Ducts for internal bonded post-tensioning tendons have traditionally been made from steel strips with a special corrugation. There has been much experience with these ducts for many different applications. Their standardized use has allowed the creation of national and international standards [EN 523 (2003)].

However, between 1968 and 1974 about 300 kilometres of corrugated black polyethylene ducts were installed in highway overpasses, the Chillon viaduct and other bridges in Switzerland for bonded post-tensioning. After up to 30 years of use, no deterioration of these polyethylene ducts has been observed in bridges that were eventually dismantled or rehabilitated [Vogel (2006)]. If the ducts remained intact during installation, the good protection of the prestressing tendons was also maintained. However, perforations in some ducts were found, caused by the prestressing steel cutting through thin duct walls.

Around the beginning of the 1990s thick-walled corrugated polymer ducts were introduced for use with internal profiled tendons. They were mainly introduced for their positive characteristics, such as the improved corrosion protection of the tendons, the reduced friction losses during stressing of the tendon, the increased fretting fatigue resistance of the tendon as well as their feasibility for the electrical monitoring of the tendon [Ganz (1997)]. Substantial efforts have been made to document the knowledge and investigate the performance of thick-walled corrugated polymer ducts for post-tensioning [Matt (1990); Kollegger (1994); Cordes (1996)]. The use of polymer ducts has expanded since the early 1990s in Europe, the USA, and India and, to a lesser degree, elsewhere in Asia. At the end of the 1990s, the fib published a first technical report with information about, testing of and performance specifications for plastic ducts for internal bonded tendons [fib 7 (2000)].

Today a range of polymer duct systems and accessories are available on the market. The typical cross sections of ducts are round but flat; oval ducts are also available, mainly for smaller-size tendons in building floors and bridge decks. The typical corrugations of polymer ducts are either circular (toroidal) or intermittent, or spirally (helically) or continuously wound around the ducts. The authors of this report estimate that since the mid 1990s a total length in the lower tens of thousands of kilometres of this new generation of polymer ducts has been installed in structures all around the globe.

Polymer ducts have found their way into national specifications: TR 47 (1996), which was up-dated into TR 72 (2010); ASTRA (2001), which was up-dated into ASTRA (2007); JPCEA (2007); AASHTO LRFD (2010) and FDOT (2013). The Florida Department of Transportation (FDOT) released in 2002 their ten-volume document entitled New Directions
for Florida Post-Tensioned Bridges [FDOT (2002)] and subsequent specifications that allowed only polymer ducts and required precast segmental duct couplers. TR 47 and TR 72 specifications also call for the sole use of polymer ducts. ASTRA specifications require tendons with metal and with polymer ducts. However, highway bridges are all specified with polymer ducts. ASTRA specifications have also been adopted by the SBB (Swiss Rail) for all their bridges.

The fib published Recommendations for the durability of post-tensioning tendons [fib 33 (2006)]. The Post-Tensioning Institute (PTI) and the American Segmental Bridge Institute (ASBI) jointly published Guide Specification for Grouted Post-Tensioning: M50.3-12, a detailed post-tensioning specification that includes material and performance requirements [PTI / ASBI (2012)].

After almost 20 years of experience with this new generation of polymer ducts, the generally perceived advantages are:

- improved corrosion protection of tendons
- better leak-tight connection details than for metal ducts
- full encapsulation of tendons with proper sealing of duct connections
- possibility for monitoring tendon protection
- increased fatigue resistance
- reduced friction losses.

There are a number of aspects of polymer ducts that require special attention, either during design and detailing or during installation and use on site. These aspects include:

- flexibility of polymer ducts
- performance of polymer ducts being temperature and time dependent
- wear resistance during stressing limiting the radius of curvature of polymer ducts
- susceptibility to damage.

The question is often asked whether post-tensioning systems with polymer ducts cost more than systems with steel-strip ducts. There is no simple answer to this question. Firstly, initial costs for post-tensioning systems vary between countries and regions, and relative cost between metal and polymer may fluctuate significantly. Secondly, the costs of systems with steel strip ducts strongly depend on the actual thickness of the steel strip used, which may vary from 0.25 millimetres to more than 0.6 millimetres. A further question is whether the steel-strip duct is galvanized or not. Thirdly, that tendons with polymer ducts have lower friction coefficients than steel-strip ducts has to be taken into consideration. Hence, depending on actual tendon curvature and friction losses, potential savings in prestressing steel quantity may, in fact, reduce the overall cost of the post-tensioning system. Anyway, even if the initial cost should be higher when using polymer ducts, this increase typically is minimal for the overall structure and may be shown to pay off easily when the life-cycle costs of the structures are considered.
While the new generation of corrugated polymer ducts for bonded post-tensioning have now been used for about 20 years, products still differ in material properties, geometrical details, installation procedures and on-site use. For these reasons, they have not been standardized yet, as was done for corrugated steel ducts or smooth PE pipes. It is the opinion of the task group and commission that these plastic ducts should, therefore, still be subjected to a ‘system approval’ process. This report aims to update information and experience from the past 20 years and provide specifications that will, hopefully, soon lead to the standardization of polymer-duct systems.

In order to benefit from the advantages offered by polymer ducts for corrosion protection and the monitoring of tendons, it is essential to consider the overall polymer-duct system, with all the connections between duct segments and to anchorages, and the entire process from fabrication to assembly and on-site installation. Only when all the aspects are adequately addressed will the polymer-duct system provide the desired results. Hence, it is essential that any assessment of polymer ducts consider the entire system, with all its parts and connections, and not be limited to individual isolated components, such as the duct alone.

1.2 Lessons learned

The following is a brief summary of main points that have been learned over the last 20 years of the use of the new generation of polymer-duct systems. This summary is provided in bullet-point form. It should be noted that these points apply to the typical materials used in the past and, therefore, may or may not fully apply to recent materials. Most, if not all, of these points will be discussed in more detail in the chapters following this one.

- Polypropylene (PP) versus Polyethylene (PE):
  1. PP can handle temperatures that are 10 to 20 °C higher than those that PE can before it softens. PP maintains shape and rigidity well in hot weather conditions.
  2. PE has better cold weather performance and deformation capacity without cracking, especially below -20 °C.
  3. PE has slightly better impact resistance than PP.
  4. PP has better wear resistance under transverse loading than PE in particular at elevated temperatures. This is important during stressing when the prestressing steel tries to wear through the duct thickness.
  5. PP has better lateral load resistance than PE, meaning that duct made with PP may not deform or deform less than PE duct, where the duct is resting on support bars.
  6. PE has better weldability properties in low temperatures than PP and can be welded at temperatures below 0 °C.

- Transportation and storage of polymer ducts: Small round and flat polymer ducts are suitable for transportation and storage on coils. However, larger sizes of round polymer ducts should be transported and stored in straight length. Nevertheless, for some applications, prefabricated tendons (ducts with prestressing steel installed) that are transported and stored on coils may be preferred. This may, however, lead to the damage of the ducts if not properly done. The coiling of tendons with PP ducts in the workshop at ambient temperature and subsequent transport and storage outside at low temperature may result in damage (cracks) of the PP ducts when uncoiling the
tendon on site at low temperatures near or below freezing. Hence, under such conditions, the PP ducts have to be uncoiled at temperatures comparable to those at which they were placed on the coils. Such damage has not been observed with polymer ducts made of PE.

- Virgin versus regrind material: With regrind or recycled material, the mechanical properties vary with the type and origin of recycled material, making them inconsistent. Hence, the polymer ducts will not produce the specified performance consistently. Likewise, the durability of polymer ducts made of recycled material will be significantly reduced.

- Natural versus black versus coloured material: The white colour of natural material keeps the duct surface 10 to 20º C cooler than black material when exposed directly to the sun. Black polymer material has demonstrated good ultraviolet (UV) stability. UV stabilizers may be added to naturally coloured material or other coloured material to provide UV protection comparable to that of black material.

- Drainage-pipe-type polymer ducts are not suitable: Drainage-pipe-type polymer ducts have a typically insufficient wall thickness for post-tensioning applications. Drainage pipes with continuous corrugations have poor wear resistance. Accessories (connections and couplers) for drainage-pipe-type polymer ducts do not exist. Hence, leak tight connections to anchorages and for grouting cannot be consistently provided as required for tendon protection levels PL2 and PL3 tendons (see Section 3.1).

- Electrically Isolated Tendons (EIT) allow the monitoring of tendons with polymer ducts: Experience has shown that the specified EIT acceptance criteria are tough to meet. Compliance/conformity with specifications requires well detailed systems with suitable connections and accessories, well designed/detailed cross sections and reinforcement details of concrete members to avoid damage to the duct system, and finally high quality workmanship on site of all parties involved in the installation of the system and placing of concrete. However, if successfully applied, these tendons provide reliable assurance to the owners of the structures that the tendons are properly installed and, in fact, provide specified full encapsulation and long-term protection. In addition, EIT tendons provide an early warning system for the ingress into the duct of water that is possibly contaminated with chlorides.

- Experience with electrically isolated tendons has demonstrated the significant benefits of using half-shell duct supports for the protection and stiffening of polymer ducts at duct supports, in particular, at tight tendon curvature. On-site damage to the ducts and defects in encapsulation are significantly reduced if such half shells are used at tight tendon curvature even though the polymer-duct system complies with the requirements of these recommendations without such half shells.

### 1.3 Scope of report

This report aims to provide guidance to the various parties, such as owners, designers, producers, post-tensioning (PT) specialist companies and contractors, involved in the fabrication and planning, design, construction and maintenance of post-tensioned structures that use internal bonded tendons with polymer-duct systems:

- Chapter 2 provides definitions and terms appropriate to polymer-duct systems for internal bonded post-tensioning.
• Chapter 3 covers general and design/detailing considerations and provides guidance that is mostly relevant for designers of structures with polymer-duct systems.

• Chapter 4 addresses both designers and construction companies and provides guidance for the installation of polymer duct systems and their on-site use.

• Chapter 5 provides requirements for materials as far as is relevant for the performance of the polymer-duct system and as far as they are not covered by system or components assessment.

• Chapter 6 gives requirements for the individual components of the system as far as they are not already covered as part of the system assessment.

• Chapter 7 provides the requirements for polymer-duct-system assessment and approval.

• Chapter 8 proposes procedures for polymer-duct-system approval.

• Chapter 9 gives requirements for the evaluation of the conformity of polymer duct systems.

• Chapter 10 provides a list of the references and standards used in the report as well as other literature of general interest in this report.

• Annexes A and B give specific procedures for the testing of, respectively, polymer-duct components and systems. These annexes are written to serve as a basis for future testing standards.

• Annex C provides a recommended specification for polymer-duct systems that may be used in project specifications

This report strictly applies to polymer duct systems made of poly-olefins. It is primarily based on experience with polymer duct systems made of PP and PE and for duct diameters up to approximately 160 millimetres. Other types of polymers may possibly be used for ducts and particularly for duct-system components, in particular, for connectors and other auxiliary components. Although such other materials are not covered, this report may provide some guidance on how polymer ducts and components made of other materials may be assessed, if need be.

This report replaces fib Bulletin 7 Corrugated plastic ducts for bonded internal post-tensioning [fib 7 (2000)]. Hence, this report should be applied in substitution whenever reference is made to fib Bulletin 7.
## 2 Terms, definitions and abbreviations

This chapter provides selected definitions for the specific terms used in the report. Symbols used in this report are explained directly when and where they are used in the text.

<table>
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<tr>
<th>Term</th>
<th>Definition</th>
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<tr>
<td><strong>Additives</strong></td>
<td>Materials to modify various properties of the base resin, namely its colour, UV resistance, anti-oxidants and extrusion aids.</td>
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<tr>
<td><strong>Approval body</strong></td>
<td>A body authorized by a country, state or client to issue technical approvals in a specific construction product area or areas.</td>
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<td><strong>Approval testing</strong></td>
<td>Assessment testing to verify conformance with requirements for obtaining technical approval. Testing is overseen and certified by a qualified independent body.</td>
</tr>
<tr>
<td><strong>Attestation of conformity</strong></td>
<td>Provisions and procedures aiming to ensure that, with acceptable probability, the specified performance of the product is achieved throughout production.</td>
</tr>
<tr>
<td><strong>Audit testing</strong></td>
<td>Planned, independent and documented assessment testing to determine whether stated conditions and performance requirements are being met.</td>
</tr>
<tr>
<td><strong>Batch</strong></td>
<td>Part of an entire production run made of prime resin (granulate) or compound produced from the same prime resin and additives.</td>
</tr>
<tr>
<td><strong>Batch number</strong></td>
<td>A specific identifier for a material batch of prime resin (granulate) or compound.</td>
</tr>
<tr>
<td><strong>Blend</strong></td>
<td>See compound.</td>
</tr>
<tr>
<td><strong>Calliper</strong></td>
<td>A device used to measure the distance between the opposing sides of an object. Vernier and digital callipers give a direct reading of the distance measured with high accuracy and precision. They are functionally identical, with different ways of reading the result. These callipers comprise a calibrated scale with a fixed jaw and a second jaw, with a pointer, that slides along the scale. The distance between the jaws is then read in different ways for each type.</td>
</tr>
<tr>
<td><strong>Certification body</strong></td>
<td>See independent body.</td>
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<tr>
<td><strong>Clamping force</strong></td>
<td>The compressive force that is exerted on a duct specimen to simulate the force applied by a specific number of strands, stressed to a specific force, inside a particular size of duct at a specific radius of curvature.</td>
</tr>
<tr>
<td><strong>Colour batch</strong></td>
<td>A package of pigments and additives to be mixed with a prime resin or a compound or blend.</td>
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<tr>
<td>Term</td>
<td>Definition</td>
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<tr>
<td>Compacted strand</td>
<td>A seven-wire strand that is drawn through a dye after stranding to obtain an almost round outer surface shape.</td>
</tr>
<tr>
<td>Compound</td>
<td>An international term for a mixture of prime resin and additives, such as a UV package and stabilizers.</td>
</tr>
<tr>
<td>Data Sheet</td>
<td>A document from raw material manufacturers describing the typical values of a resin brand and type.</td>
</tr>
<tr>
<td>Dial gauge</td>
<td>An indicator used to accurately measure small distances and to display them in a circular array around a dial, with a needle pointing to graduations.</td>
</tr>
<tr>
<td>Drainage pipe</td>
<td>A polymer pipe with tightly spaced, helically wound corrugation and thin wall thickness that is typically used for drainage or service-pipe applications and not designed for post-tensioning applications.</td>
</tr>
<tr>
<td>Duct</td>
<td>An enclosure forming a conduit in which several tensile elements are placed and which temporarily or permanently allows relative movement between the tensile elements and the surrounding concrete. The remaining void within the duct can subsequently be injected with a filling material such as grout.</td>
</tr>
<tr>
<td>Duct coupler/connector</td>
<td>A device that connects individual lengths of ducts and forms a continuous enclosure around the prestressing steel.</td>
</tr>
<tr>
<td>Note: Mirror welding is not considered a duct coupler or connector in the context of this report</td>
<td></td>
</tr>
<tr>
<td>Duct system</td>
<td>The duct and duct coupler/connector and the other accessories provided by a single manufacturer that connect individual duct pieces between themselves and the duct to anchorage trumpets, and provide access for the filling and venting of ducts.</td>
</tr>
<tr>
<td>Electrically isolated tendon</td>
<td>A prestressing tendon in which the prestressing steel is electrically isolated from the surrounding concrete or structure over the entire tendon length, including the anchorages</td>
</tr>
<tr>
<td>Encapsulation</td>
<td>A watertight envelope made of a non-corrodible, durable material extending over the entire tendon length, including the anchorages.</td>
</tr>
<tr>
<td>Extensometer</td>
<td>A device that is used to measure changes in the length of an object.</td>
</tr>
<tr>
<td>Factory production control</td>
<td>The permanent internal control of production exercised by the manufacturer. All the elements, requirements and provisions adopted by the manufacturer are documented in a systematic manner, in the form of written policies and procedures</td>
</tr>
<tr>
<td>Granulate</td>
<td>The form in which prime resin material, compounds/blends and, partly also, additives are sold.</td>
</tr>
<tr>
<td>Term</td>
<td>Definition</td>
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<td>-------------------------------------------</td>
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<tr>
<td>Independent body</td>
<td>A body nominated by a country, state or client to perform specific tasks, such as certification, inspection or testing, that will lead to the authentication of the conformity of specific construction products. It may also be called a certification body or third-party inspection agency.</td>
</tr>
<tr>
<td>Load cell</td>
<td>A transducer that is used to convert a force into an electrical signal. The output (electrical signal) from the transducer is scaled to measure the force applied to the transducer.</td>
</tr>
<tr>
<td>Lot number</td>
<td>A specific identifier for a material batch/charge of prime resin (granulate) or compound. Another term for a charge/batch number.</td>
</tr>
<tr>
<td>Master batch</td>
<td>See colour batch.</td>
</tr>
<tr>
<td>Measuring and testing equipment</td>
<td>Equipment that is used during assessment testing to accurately measure and perform the test. Its attributes and parameters are periodically calibrated to determine if they are in conformance with the specified tolerance limits.</td>
</tr>
<tr>
<td>Monitoring</td>
<td>The gathering of information with a range of possible techniques and procedures. It is often taken to involve the automatic recording of performance data for the structure.</td>
</tr>
<tr>
<td>Negative pressure</td>
<td>The pressure applied on a duct from the outside (or the inside, via a vacuum) that causes compressive stress in the duct wall.</td>
</tr>
<tr>
<td>Positive pressure</td>
<td>The pressure applied from inside on the duct that causes tensile stress in the duct wall.</td>
</tr>
<tr>
<td>Polymer</td>
<td>A natural or synthetic substance that consists of high-molecular-weight molecules formed from monomers by polymerization.</td>
</tr>
<tr>
<td>Poly-Olefin</td>
<td>A polymer produced from a simple olefin (also called an alkene, with the general formula C_nH_{2n}) as a monomer. For example, polyethylene is the polyolefin produced by polymerizing the olefin ethylene. Polypropylene is another common polyolefin which is made from the olefin propylene.</td>
</tr>
<tr>
<td>Post-tensioning</td>
<td>A method of prestressing in which prestressing steel is tensioned after the concrete has reached a specified strength.</td>
</tr>
<tr>
<td>Precast segmental duct coupler</td>
<td>A device that maintains the integrity of the post-tensioning tendon duct across segment joints in precast segmental construction by creating a leak-tight connection.</td>
</tr>
<tr>
<td>Prime Resin</td>
<td>A pure, non-stabilized, virgin raw material.</td>
</tr>
<tr>
<td>Qualified third party inspection agency</td>
<td>See independent body.</td>
</tr>
<tr>
<td>Quality assurance</td>
<td>All the planned and systematic activities implemented to ensure</td>
</tr>
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</table>
that a product or service fulfils the requirements for quality.

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
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<tbody>
<tr>
<td>Quality control</td>
<td>The operational techniques and activities used to verify the requirements for quality.</td>
</tr>
<tr>
<td>Sheathing</td>
<td>An enclosure encapsulating a single tensile element that is usually extruded onto and separated with a layer of grease or wax from the tensile element.</td>
</tr>
<tr>
<td>Tendon protection level</td>
<td>The designation of a level of protection to be provided to prestressing tendons. Each level has the specific minimum required parameters necessary to protect the prestressing tendons from the aggressivity of the environment.</td>
</tr>
<tr>
<td>Tensile element</td>
<td>A single element of prestressing steel in a tendon, such as a strand, wire or bar.</td>
</tr>
<tr>
<td>Tensile strength</td>
<td>The maximum stress that a material can withstand without breaking while being stretched.</td>
</tr>
<tr>
<td>Test apparatus</td>
<td>A tool or piece of equipment used for specific testing activities.</td>
</tr>
<tr>
<td>Test specimen</td>
<td>A representative sample, regarded as typical of its class or group, used to test the performance of a product.</td>
</tr>
<tr>
<td>Trumpet</td>
<td>A transition piece between the bearing plate and the duct that collects the tensile elements into a tight bundle and that fits inside the duct.</td>
</tr>
<tr>
<td>Ultimate tensile strength</td>
<td>See tensile strength.</td>
</tr>
</tbody>
</table>

The following abbreviations are used in the report.

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>EIT</td>
<td>Electrically isolated tendon</td>
</tr>
<tr>
<td>ESCR</td>
<td>Environmental stress crack resistance</td>
</tr>
<tr>
<td>FPC</td>
<td>Factory production control</td>
</tr>
<tr>
<td>HDB</td>
<td>Hydrostatic design basis</td>
</tr>
<tr>
<td>MFR</td>
<td>Melt mass-flow rate</td>
</tr>
<tr>
<td>MVR</td>
<td>Melt volume-flow rate</td>
</tr>
<tr>
<td>MTE</td>
<td>Measuring and testing equipment</td>
</tr>
<tr>
<td>OIT</td>
<td>Oxidation induction time</td>
</tr>
<tr>
<td>Term</td>
<td>Definition</td>
</tr>
<tr>
<td>------</td>
<td>------------</td>
</tr>
</tbody>
</table>
| PE   | Polyethylene  
*Note: For this report, the term is meant to cover all grades of PE, from high density (HDPE or PE-HD) to low (LDPE or PE-LD).* |
| PL   | Protection level provided to tendons |
| PP   | Polypropylene, either as a homopolymer or copolymer.  
*Note: In this report only the abbreviation PP will be used to cover all types of PP* |
| PT   | Post-tensioning |
| PVC  | Polyvinyl chloride |
| QA   | Quality assurance |
| QC   | Quality control |
| UTS  | Ultimate tensile strength |
3 General and design/detailing considerations

3.1 General considerations

3.1.1 Design strategy for durable tendons

Designers are aware that structures must remain durable and fit for use during their design service life. One way to achieve this with post-tensioned structures is by using post-tensioning materials that, if well maintained, will not deteriorate during service life [fib 34 (2006)]. 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 [fib 33 (2006)].

Weak links in either the external protection layers provided by various structural components or in the corrosion protection of individual tendons can lead to the deterioration of post-tensioned structures. The leading cause of deterioration in post-tensioned structures is chloride attack. Transport mechanisms for chlorides are influenced by the combined effects of wind, water and temperature [fib 33 (2006)]. Eliminating avenues for corrosive agents to enter tendons will prevent attack on prestressing steel. How does contaminated water reach and attack tendons? According to Matt (2000), 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 (mechanically or by corrosion) metallic ducts
  - Cracked and honeycombed concrete
  - Grout voids at tendon high and low points that leave the prestressing steel exposed

One objective of the design process of a prestressed structure is to select the ‘protection level’ (PL) of post-tensioning tendons based on the aggressivity of the environment, the exposure of the structure or element, and the protection provided by the structure. Combining the post-tensioning tendons’ PL and the protection provided by the structure together provides
resistance against environmental hostility and the particular exposure conditions of the structural element [fib 33 (2006)].

### 3.1.2 Identifying aggressivity of the environment

In order to provide information on the entry points for aggressivity and exposure, fib Bulletin 33 references EN 206-1 (2000). It gives classifications of the principal environments to which concrete structures are exposed and the corrosivity of these environments. EN 206-1 was updated in 2013; however, without changing the classification of the 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.

The aggressivity of the environment is used in determining the tendons’ PL. Classification X0 provides a ‘low’ aggressivity rating and requires a very dry environment. Classification XC varies from ‘low’ for dry or permanently wet to ‘medium’ for cyclic wet and dry. Classification XD yields a ‘medium’ rating with moderate humidity up to a ‘high’ rating with cyclic wet and dry. Classification XS designates ‘medium’ when exposed to airborne salt, gradually increasing to ‘high’ in splash and spray zones. Classification XF is ‘medium’ for freeze/thaw without de-icing agents and ‘high’ for freeze/thaw with de-icing agents. Classification XA 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’. The reader is asked to refer to Table 3.1 for more detailed information.

**Table 3.1: Aggressivity level and exposure examples as entry points**

<table>
<thead>
<tr>
<th>Aggressivity</th>
<th>Class designation</th>
<th>Description of environment</th>
<th>Examples where exposure classes may occur</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>X0</td>
<td>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.</td>
<td>Concrete inside buildings with very low air humidity</td>
</tr>
<tr>
<td>Aggressivity</td>
<td>Class designation</td>
<td>Description of environment</td>
<td>Examples where exposure classes may occur</td>
</tr>
<tr>
<td>--------------</td>
<td>-------------------</td>
<td>-----------------------------</td>
<td>------------------------------------------</td>
</tr>
<tr>
<td>Low</td>
<td>2 – Corrosion induced by carbonation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low</td>
<td>XC1</td>
<td>Dry or permanently wet</td>
<td>Concrete inside buildings with very low air humidity, Concrete permanently submerged in water</td>
</tr>
<tr>
<td>Low</td>
<td>XC2</td>
<td>Wet, rarely dry</td>
<td>Concrete surfaces subjected to long-term water contact, Many foundations</td>
</tr>
<tr>
<td>Low</td>
<td>XC3</td>
<td>Moderate humidity</td>
<td>Concrete inside buildings with moderate air humidity, External concrete sheltered from rain</td>
</tr>
<tr>
<td>Low</td>
<td>XC4</td>
<td>Cyclic wet and dry</td>
<td>Concrete surfaces subjected to water contact, not within exposure class XC2</td>
</tr>
<tr>
<td>Medium</td>
<td>3 – Corrosion induced by chlorides other than from sea water</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Medium</td>
<td>XD1</td>
<td>Moderate humidity</td>
<td>Concrete surfaces exposed to airborne chlorides</td>
</tr>
<tr>
<td>Medium</td>
<td>XD2</td>
<td>Wet, rarely dry</td>
<td>Swimming pools, Concrete exposed to industrial waters containing chlorides</td>
</tr>
<tr>
<td>Medium</td>
<td>XD3</td>
<td>Cyclic wet and dry</td>
<td>Parts of bridges exposed to spray containing chlorides, Pavements, Parking structure decks</td>
</tr>
<tr>
<td>High</td>
<td>4 – Corrosion induced by chlorides from sea water</td>
<td></td>
<td></td>
</tr>
<tr>
<td>High</td>
<td>XS1</td>
<td>Exposed to airborne salt but not in direct contact with sea water</td>
<td>Structures near to or on the coast</td>
</tr>
<tr>
<td>High</td>
<td>XS2</td>
<td>Permanently submerged</td>
<td>Parts of marine structures</td>
</tr>
<tr>
<td>High</td>
<td>XS3</td>
<td>Tidal, splash and spray zones</td>
<td>Parts of marine structures</td>
</tr>
<tr>
<td>Medium</td>
<td>5 – Freeze/thaw attack with or without de-icing agents</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Medium</td>
<td>XF1</td>
<td>Moderate water saturation without de-icing agent</td>
<td>Vertical concrete surfaces exposed to rain and freezing</td>
</tr>
<tr>
<td>High</td>
<td>XF2</td>
<td>Moderate water saturation with de-icing agent</td>
<td>Vertical concrete surfaces of road structures exposed to freezing and airborne de-icing agents</td>
</tr>
<tr>
<td>Medium</td>
<td>XF3</td>
<td>High water saturation without de-icing agent</td>
<td>Horizontal concrete surfaces exposed to rain and freezing</td>
</tr>
</tbody>
</table>
### Table 3.1.7: Aggressivity Classes

<table>
<thead>
<tr>
<th>Aggressivity</th>
<th>Class designation</th>
<th>Description of environment</th>
<th>Examples where exposure classes may occur</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>XF4</td>
<td>High water saturation with de-icing agent</td>
<td>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</td>
</tr>
<tr>
<td>Medium</td>
<td>XA1</td>
<td>Slightly aggressive chemical environment</td>
<td></td>
</tr>
<tr>
<td>Medium-High</td>
<td>XA2</td>
<td>Moderately aggressive chemical environment</td>
<td></td>
</tr>
<tr>
<td>High</td>
<td>XA3</td>
<td>Highly aggressive chemical environment</td>
<td></td>
</tr>
</tbody>
</table>

### 3.1.3 Identifying exposure of structure or element

The exposure of a structure or element is critical in determining the correct PL to use for the structure’s tendons. Table 3.1 identifies examples of where exposure classes may occur. In a specific structure there may be multiple exposure classes.

To simplify detailing and construction, the designer may opt to determine the tendon PL based on the most severe exposure class of the structure. Based on the authors’ experience, post-tensioning material costs vary slightly from PL1 to PL3 in increments of 5 to 15% per PL. Labour costs are marginally higher per PL. However, mixing PLs on a structure can cause confusion and add to costs because several systems are used and labour learning curves are not as efficient. Quality control and inspection costs increase for the same reasons. Using the same PL for the entire structure will simplify the detailing, installation and inspection of the post-tensioning system. The designer can feel confident that the design life of the structure will not be compromised because of an incorrect PL used for the most critical exposure class. However, if well organized, tendons of different PL may be used for different members of a structure with different exposure classes.

Table 3.1 is clear when identifying exposure classes for civil structures both for corrosion induced by carbonation and by chlorides. For buildings, the situation is complex because of the many different types of uses and, hence, different environmental conditions apply. Open buildings, such as many parking structures, or members of buildings that are directly subjected to the environment, such as balconies, may be subjected to similar conditions as civil structures since they are exposed, at least partly, to the environment and, potentially, to chlorides from de-icing salts. However, residential or office buildings and other similar types of concrete structures can be considered as representing low aggressivity when tendons are well protected inside the closed envelope/façade, temperature varies relatively little and humidity is fairly stable and low, in the order of 30 to 50 % relative humidity. Rooms with high but fairly stable humidity also represent low aggressivity in terms of carbonation. Hence, the only type of exposure considered as moderate aggressivity is for cyclically wet and dry concrete members, which in the opinion of the authors is fairly rare in buildings with closed envelopes.
3.1.4 Identifying protection provided by the structure

Designers must identify the protection provided by the structure to the internal post-tensioning tendons as ‘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 the corrosion of post-tensioning tendons is increased by the ingress of chlorides and other deleterious agents through the vulnerable areas of tendons, such as anchorages, joints, cracks, porous concrete and inadequate concrete cover.

The level of protection provided by construction details can vary from minimal up to the best possible available protection. The designer should consider the following construction details together when identifying protection provided to the structure, as noted in 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

Further discussion of the above construction details follows, including the authors’ recommendations for covering the range from ‘low’ to ‘high’ ratings. For an entire structure to qualify for a ‘high’ rating in overall structural protection, all construction details necessary for the project need to have optimum protection schemes. This total structure rating should be used when determining tendon PLs.

3.1.4.1 Concrete quality and cover

Concrete quality involves using adequate mix designs and materials that do not add to structure deterioration. In some areas of the world, such as the Arabian Gulf, it is sometimes difficult to find aggregates, sands and mix water that are not contaminated with salts. Low-permeability concrete mixtures of quality materials with adequate concrete cover should be specified for the structure, thus providing optimal protection of reinforcing steel and tendons. The mobility of fluids or gases through concrete offers a vehicle for corrosion. Obviously, less permeable concrete provides greater resistance to this mobility and more concrete cover provides a greater distance for chlorides or other deleterious agents to travel to tendons. The interested reader is referred to Rostam (2008) for more information on concrete cover requirements. Providing greater concrete cover than required by a design code may improve the protection that a structure provides to the post-tensioning tendon’s duct but may not be acceptable for other reasons. Primarily, specifying a dense and low permeability concrete will allow for better structure protection. In order to achieve a ‘high’ rating, concrete cover and the 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 to an acceptance of a 10% probability of premature corrosion initiation. This can be assumed if the concrete properties, concrete cover and curing specified in recent standards such as the fib
General and design/detailing considerations

Model Code for Concrete Structures 2010 [fib MC (2010)] are met. Many structures have been or still are built with lower quality concrete, lower cover and inadequate curing. These structures need to be rated ‘medium’ or ‘low’, depending on the actual details.

3.1.4.2 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, orientation and magnitude of cracks. Construction detailing and, in particular, concrete curing are critical in minimizing cracking. Proper layout and the sequencing of concrete pours to lessen the risks of cracking are necessary. Decreasing the risks of cracking by properly laying out and sequencing prestressing, particularly in anchorage vicinities, should be considered. Early stressing of tendons may prevent or reduce early cracking. The location and amounts of non-prestressed reinforcement should be checked for adequate stress distribution to avoid early-age cracking. When all of the above considerations are properly addressed and solutions incorporated into the structure to eliminate or properly control cracking, a ‘high’ protection rating is achieved. With little or no consideration or inclusion of proper details in the structure, a ‘low’ rating should be given.

3.1.4.3 Construction joint details

Construction joint details are critical when protecting post-tensioning tendons. The proper preparation of the surfaces as per recent standards is essential. 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.

3.1.4.4 Expansion joint details

Exposed expansion joints often leak and their effectiveness and life span are dependent on the quality of the material, installation and maintenance. Details should be based on the assumption that the expansion joint will leak and will not provide protection against the ingress of water and corrosive agents. Post-tensioning anchorages should be kept away from expansion joint faces. A ‘high’ protection rating is given when appropriate drainage paths for leakage are provided, ensuring that there is no access to tendon anchorages. A ‘low’ rating is given to structures with expansion joints where no details are provided for drainage paths.

3.1.4.5 Waterproofing systems and other surface protection systems

Waterproofing systems provide the first line of defence against the intrusion of road salts; however, there are currently no systems available that are guaranteed to remain waterproof for the life of the structure. 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.

3.1.4.6 Drainage system details

The drainage system should remove water from the structure’s surface as quickly as possible. Drains and slopes should be designed and constructed so that water cannot migrate...
into tendons. Equipment failure or the blockage of drains can allow paths for water to enter tendons. Sloping surfaces without the possibility of blockages or dams will allow for a ‘high’ protection rating; no sloping and/or drains that can become blocked would be considered a ‘low’ protection rating.

3.1.4.7 Segment joint details

Precast segmental concrete bridge construction typically uses match-cast segment joints, which, if properly sealed with epoxy resin, are satisfactory in terms of durability, certainly in environments with low aggressivity. However, particular care is required when considering the continuity of post-tensioning tendons across the joints in more aggressive environments. Providing a system that seals the tendons against the ingress of aggressive agents and epoxy glue or against the leakage of cement grout should be considered. Using a segmental duct coupler as part of the post-tensioning system will give a ‘high’ protection rating whereas erecting segments with just epoxy at the joints necessitates a ‘low’ protection rating [Salas (2002)]. Alternatively, waterproofing systems protecting the joints may be considered to provide protection to tendons across the segment joints. Dry joints are not acceptable with internal bonded tendons.

3.1.5 Selecting the post-tensioning tendon Protection Level

Selecting the tendon’s PL for a specific project requires the identification of the aggressivity of the environment that will attack the prestressed element (‘low’ to ‘high’) (see Table 3.1). This is followed by the identification of the protection provided by the structure for the prestressed element with the greatest exposure (‘low’ to ‘high’). For the element to qualify for a ‘high’ rating in overall structural protection, all the construction details necessary for the element need to have optimum protection schemes. Once these two tasks have been completed, the PL for a specific project can be selected by using Figure 3.1. The combination of the protection offered by the structure and the tendon’s PL provide the resistance against the aggressivity of the environment.

Below is a method for choosing tendon PL using Figure 3.1 for a bridge structure [Krauser (2011)]:

1. The 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 ‘high’. This would yield a tendon with a PL1.
2. The 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. The project is located in a Northern climate that has freeze/thaw with moderate saturation with de-icing agents (XF2 = ‘high’) and the protection provided by the structure is ‘medium-high’. This would yield a tendon with a PL2.
4. The project is located in a temperate climate 10 kilometres from the seacoast and exposed to airborne salt but not in direct contact with seawater (XS1 = ‘medium’), and the protection provided by the structure is ‘low’ or ‘medium’ or ‘high’. This would yield a tendon with a PL2.
5. The 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 ‘low’. This would yield a tendon with a PL3.

![Figure 3.1: Protection Levels for post-tensioning tendons based on aggressivity/exposure versus protection provided by structure or member [fib 33 (2006)]](image)

### 3.1.6 Defining post-tensioning protection levels (PLs)

*fib* Bulletin 33 and PTI/ASBI Guide Specification (2012) identify three PLs and provide basic parameters for each. PTI/ASBI Guide Specification further splits PL1 into an ‘A’ and ‘B’ section. There are subtle differences in definitions and performance requirements between *fib* Bulletin 33 and PTI/ASBI. Table 3.2 differentiates between the definitions and Table 3.3 differentiates between the performance requirements.

<table>
<thead>
<tr>
<th>Table: 3.2: Protection Level (PL) definitions</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>fib Bulletin 33</strong></td>
</tr>
<tr>
<td>Protection Level 1 (PL1)</td>
</tr>
<tr>
<td>PL1 is defined as a duct with filling material (grout) providing durable corrosion protection</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Protection Level 2 (PL2)</td>
</tr>
<tr>
<td>PL2 is defined as PL1 plus a watertight, impermeable envelope providing a leak tight barrier</td>
</tr>
<tr>
<td>Protection Level 3 (PL3)</td>
</tr>
<tr>
<td>PL3 is defined as PL2 plus inspectable or monitorable integrity of the tendon or encapsulation</td>
</tr>
</tbody>
</table>
**Table 3.3: Generic performance requirements for each Protection Level (PL) [Krauser (2011)]**

<table>
<thead>
<tr>
<th>Protection Level 1 (PL1)</th>
<th>Requirements</th>
</tr>
</thead>
</table>
| **fib 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 |
| **PTI/ASBI PL1A**        | • Bare strand or bar  
• Galvanized or polymer duct  
• Basic grout or engineered grout  
• Grouting that leaves no voids in duct |
| **PTI/ASBI PL1B**        | PL1A plus  
• Only engineered grout  
• Permanent grout cap |

<table>
<thead>
<tr>
<th>Protection Level 2 (PL2)</th>
<th>Requirements</th>
</tr>
</thead>
</table>
| **fib PL2**              | In addition to PL1:  
• Corrugated polymer duct to be watertight and impermeable to water vapour over entire length, including connections (segmental duct couplers required in segmental construction)  
• Corrugated polymer 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 vapour (encapsulated) |
| **PTI/ASBI PL2**         | PL1B plus:  
• System pressure tests  
• Embedded anchorage components: epoxy-coated or galvanized  
• Thixotropic engineered grout  
• Only polymer duct  
• Segmental couplers |

<table>
<thead>
<tr>
<th>Protection Level 3 (PL3)</th>
<th>Requirements</th>
</tr>
</thead>
</table>
| **fib PL3**              | In addition to PL2:  
• Have a demonstrated means to inspect or monitor tendons for integrity and/or corrosion. |
| **PTI/ASBI PL3**         | PL2 plus:  
• Electrical isolation of tensile element  
• Ability to be monitorable or inspectable at any time |

Examples of materials used for tendons in each PL are identified below:

- **PL1** = bare strand + corrugated metal duct + cement grout
- **PL1** = bare strand + corrugated polymer duct + cement grout or other filling materials (anchorage zone non-encapsulated)
• PL2 = bare strand + corrugated polymer duct + cement grout or other filling materials + encapsulation of anchorage zone
• PL3 = bare strand + corrugated polymer duct + cement grout or other filling materials + encapsulation of anchorage zone + inspection or monitoring (e.g. by EIT)

While the obvious concern in selecting the appropriate protection level is durability (corrosion protection level), the designer should also consider such aspects as the feasibility of monitoring of tendons and the presence of fatigue actions or of electrical stray currents.

While the above and fib Bulletin 33 address mainly internal bonded post-tensioning tendons, the strategy and concepts apply equally to structures with internal unbonded tendons, external tendons and pretensioning tendons.

Since the publication of TR 47 (1996) and fib Bulletin 33 (2006), a number of owners have implemented the above or similar strategies for tendon protection and have amended their specifications for prestressed structures [ASTRA (2007)] [PTI/ASBI (2012)].

3.1.7 Polymer duct system assessment

Polymer ducts can be used for all protection levels (PLs) but are specifically required for PL2 and PL3. However, in order to achieve the desired tendon protection level full encapsulation of the tendon over its entire length is required. Auxiliary components such as caps for anchorages, connectors of duct segments, grout connections and vents, and so forth, are, therefore, required and form an integral part of the polymer duct system. Any assessment of polymer duct systems for PL2 and PL3 must, therefore, be performed on the partly or fully assembled system. Specific component or material testing may be needed to complement the system assessment.

Polymer duct systems for PL1, however, may be assessed mainly based on component and material testing.

Polymer duct systems still differ in material properties, geometrical details, installation procedures and use on site. Therefore, they have not been standardized yet as was done for corrugated steel ducts or smooth PE pipes. It is the opinion of the task group and the commission that these polymer duct systems should, therefore, still be subjected to a ‘system approval’ process, as outlined in Chapter 8. Because of the very particular technological aspects involved, such system approval is believed to be best performed by specialist approval bodies rather than by project specific approval by the designer.

3.2 Design considerations

The focus of this section is on the design of prestressed members or structures using tendons with polymer duct systems. However, some information is also provided on the behaviour of polymer ducts that is considered of interest to designers.

3.2.1 Choice of polymer for ducts

The choice of polymer type is made by the duct-system supplier based on system and component performance tests, with particular attention paid to the expected exposure conditions, such as temperature exposure. The actual performance of polymer ducts is the result of the choice of polymer, the design of the duct (shape and dimensions) and the quality
of fabrication. The choice of polymer material alone means little. Hence, the designer should not specify the type of polymer in general but restrict the project specification to the required duct-system performance.

The colour of ducts may vary based on materials and performance requirements. Natural, black and coloured ducts are used. Light colours or white (natural) ducts are recommended for areas where the ducts will be exposed to hot sunlight. However, as just mentioned above, the designer should not specify a specific colour in general but restrict the project specification to the required performance criteria.

3.2.2 Corrosion protection of tendons

For durability (corrosion protection) aspects the designer should refer to Section 3.1 and Figure 3.1 for his choice of tendon protection level (PL). The selected PL should be specified in the project specifications.

3.2.3 Monitoring of tendons

If the designer or owner wishes or requires monitoring of all or a part of the tendons, PL3 should be specified. When PL3 is specified, the designer should place tendon anchorages and connections so as to provide easy and convenient access for measurements, for monitoring and for maintenance of the monitoring equipment. Electrical cables for monitoring are preferably collected in a few well placed cabinets to allow convenient access for measurement or direct on-line monitoring. Connections and cabinets need to be located to remain dry and locked.

It is recommended to provide electrical connections at both tendon ends for improved measurement options that will allow, for example, the use of methods that locate any damage in the tendon encapsulation, namely by determining at what tendon location the encapsulation is compromised [Elsener & Büchler (2011)].

Also refer to Section 3.3.8 for additional details on the monitoring of EIT tendons.

3.2.4 Protection of tendons against stray currents

Stray currents as a consequence of direct current sources are considered a potential risk to the durability of post-tensioning tendons. PL3 may be used to encapsulate and protect tendons from stray currents both at the entry into (causing hydrogen embrittlement) and at the exit point from (causing intensified metal dissolution) the prestressing steel. This protection may be verified by monitoring the encapsulation through measuring the electrical isolation of the tendon from the structure. The acceptance criteria for protection against stray currents are more stringent than for monitoring. Such acceptance criteria can be found in ASTRA (2007).

If tendon isolation is not desired or not successful because the encapsulation is compromised, tendons may be electrically connected to the earth at both tendon ends to prevent the electrical current entering and exiting the tendon into surrounding grout or concrete, which may cause hydrogen embrittlement and intensified local dissolution of the prestressing steel.

3.2.5 Fatigue

The designer should choose PL2 if he requires improved fatigue resistance for tendons. However, PL3 with EIT should be specified if the owner wishes to verify that no contact of
the prestressing steel to steel parts outside the duct exists, which could cause fretting fatigue and rapid damage to the tendon. The EIT measurement, in fact, permits the detection of any metallic contact between the prestressing steel inside the polymer duct and the metal components outside the duct.

The fatigue resistance of grouted tendons in steel strip ducts and polymer ducts has been investigated under several research projects in particular in Switzerland, USA, Germany and Japan [Wollmann (1988); Müller (1994); Eskola (1996); Abel (1996); Arai (1999)]. This research has recognized that fretting fatigue is most severe between the prestressing steel and the steel-strip duct surface. The elimination of fretting at this interface with the use of polymer ducts significantly improves the fatigue life of the tendons. Fretting fatigue inside the prestressing steel bundle between individual tensile elements (strands) may still occur. However, the conditions inside the bundle are less severe and hence the fatigue life time, that is, the number of cycles to failure, is significantly improved through the use of polymer ducts. Figure 3.2 shows the fatigue life / number of cycles to failure observed in fatigue tests on full-scale beams with curved tendons of 19 strands (with a tendon radius of curvature of 6.7 metres) subject to a stress range of 200 N/mm², either installed in steel strip duct or polymer duct [Eskola (1996)]. The fatigue life of tendons with polymer ducts was roughly doubled in these tests compared to tendons with steel strip ducts.

![Graph showing fatigue life of curved tendons](image)

**Fig. 3.2: Fatigue life of curved tendons subject to 200 N/mm² stress range, placed either in steel strip duct (S) or in polymer duct (P)**

Note: \( w_m \): Mid span deflection of beam; \( N \): Number of load cycles

The improved fatigue resistance is mainly caused by the reduction of the maximum transverse pressure between steel elements in a cracked section where the fatigue of prestressing steel may occur. When using polymer ducts the maximum steel-on-steel pressure occurs between individual tensile elements inside the duct and not between tensile elements and steel duct. The procedure by Weiher (2008) allows the quantification of this reduction of pressure. For the tendon size of 19 strands with a strand type of 15.3 millimetres (or 0.6 inches) tested by Eskola with a ratio of strand/duct diameter of 15.3/100 = 0.15, the maximum steel-on-steel contact stress is reduced to about 72% when compared to the maximum pressure at the duct. In general, higher filling degrees of ducts and a higher number of tensile elements give smaller reductions and, hence, are less advantageous for fretting fatigue.
The improvement of the fatigue resistance of tendons installed in polymer ducts has been recognized in several standards, of which SIA 262 (2003) and EN 1992-1-1 (2004). Figure 3.3 provides the fatigue strength of pretensioning and post-tensioning tendons in steel strip and polymer (plastic) ducts according to EN 1992-1-1 (2004).

<table>
<thead>
<tr>
<th>S-N curve of prestressing steel used for</th>
<th>Stress exponent</th>
<th>( \Delta \sigma_{Rsk} ) (N/mm²) at ( N^* ) cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pretensioning</td>
<td>( 10^6 )</td>
<td>5 9 185</td>
</tr>
<tr>
<td>Post-tensioning</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Single strands in polymer ducts</td>
<td>( 10^6 )</td>
<td>5 9 185</td>
</tr>
<tr>
<td>Straight tendons or curved tendons in polymer ducts</td>
<td>( 10^6 )</td>
<td>5 10 150</td>
</tr>
<tr>
<td>Curved tendons in steel ducts</td>
<td>( 10^6 )</td>
<td>5 7 120</td>
</tr>
<tr>
<td>Couplers (splicing devices)</td>
<td>( 10^6 )</td>
<td>5 5 80</td>
</tr>
</tbody>
</table>

(Note: \( \Delta \sigma_{Rsk} \) is the fatigue stress range (fatigue strength) which for design must be reduced with a material factor of \( \gamma_s = 1.15 \)

**Fig. 3.3: Parameters for S-N curves of prestressing tendons [EN 1992-1-1 (2004)]**

Note: \( \Delta \sigma_{Rsk} \): Fatigue stress range (resistance); \( N \): Number of load cycles; \( k_1, k_2 \): Slope of S-N curves

The fatigue behaviour of tendons with polymer ducts is, however, further improved by a reduced fatigue action. Tendons with metal and polymer ducts have, in general, longer bond lengths than ribbed reinforcing steel. Therefore, the stress increase in a cracked section will, in general, not be exactly identical to the typically calculated values in cracked sections assuming rigid bond. In fact, due to the shorter bond length, the stress increase in ribbed reinforcing steel will be somewhat higher and the stress increase in tendons will be lower than calculated. This applies in particular for individual, isolated cracks but less in fully developed crack patterns. This is recognized and considered in some standards by a coefficient in the calculation of the applied fatigue stress range [EN 1992-1-1 (2004)], which gives these coefficients for tendons in metal duct. This coefficient may be estimated based on the comparison of bond lengths for tendons in polymer ducts in comparison with the bond length of ribbed reinforcing steel.
3.2.6 Friction losses of tendons and tendon elongation

Friction losses reduce the tendon force along the tendon length from the jacking force $P_j$ at the anchorage to the actual force $P(x)$ at a distance $x$ from the anchorage in accordance with the well-known equation:

$$P(x) = P_j e^{-(\mu \alpha + kx)}$$

Where $\mu$ and $k$ are the friction coefficient and wobble coefficient, respectively, and $\alpha$ is the total angular deviation (in space) of the tendon from the anchorage to the location $x$.

The friction and wobble coefficient of a particular type of duct should be given in the post-tensioning-system documentation. However, for the PP and PE materials considered in this report, the friction coefficient between polymer duct and prestressing steel is sufficiently well known. The typical range of the friction coefficient is as follows:

- for 7-wire strands: $\mu = 0.10 – 0.14$
- for wire and compacted strands: $\mu = 0.08 – 0.12$

Note: In Europe a slightly different equation is used in some countries to calculate the tendon force: $P(x) = P_j e^{-\mu(\alpha+kx)}$. While the friction coefficient is identical to the above, the wobble coefficient is different by a factor equal to the friction coefficient.

The friction parameters for a proprietary duct system should be specified in the system documentation. Since these values have some scatter between projects, they should preferably be given with a 'range' and a 'recommended design value' for both the friction and wobble coefficient. With the given range the designer has a means to check the sensitivity of the post-tensioned structure or member for variations of the actual friction parameters on site. If the sensitivity analysis shows that the effect of a slight variation of the tendon force is significant for the performance of the member or structure, precautions may be taken, such as providing one or several supplementary empty ducts into the structure to add prestressing tendon force if friction losses measured on site exceed the expected values used in design. In such structures, which are considered sensitive, it is recommended to perform friction tests at the start of the project to confirm the actual friction losses and either overstress the tendons or add tendons as and when required.

There is significant experience with friction coefficients for polymer ducts and, therefore, the above-mentioned values may be assumed for design. In any case, the actual friction losses of all tendons are indirectly controlled by the tendon elongation measurements performed on site during stressing. For special structures or unusual tendon profiles specific friction-loss measurements may be performed on some selected tendons at the start of a project to confirm the design assumptions.

It has been noted that there is some creep in the tendon movement inside polymer ducts immediately after tendon jacking or when maintaining the jacking force for a short period of time. This leads to a small additional tendon elongation in the first few minutes after stressing.
and a corresponding reduction of the effective friction coefficient (1 to 2 points in reduction, namely, a friction coefficient of 0.12 instead of 0.14). The upper range of values given above does not consider this effect.

Based on the tendon force diagram $P(x)$ the designer and/or specialist contractor can calculate the tendon elongation as a function of the jacking force and actual tendon profile.

### 3.2.7 Wear of polymer ducts

#### 3.2.7.1 Effect of transverse load (clamping force) and tendon elongation

During stressing the tendon will be pressed against the polymer duct on the inside of any tendon curvature. The transverse pressure increases proportionally to the jacking force. At the same time the tendon will be sliding relative to the duct surface by an amount corresponding to the elongation of the tendon between the fixed end and the particular tendon location. The combined actions of transverse pressure (clamping force) and relative sliding movement cause the wear/indentation of the tendon into the polymer duct, namely, the wall thickness of the duct is reduced on the inside of the tendon curvature.

The performance of polymer ducts for wear is verified in a particular duct component test (see Section 6.8 and Annex A.8). The test is performed with a relative sliding movement of the tendon to the duct of 750 millimetres while the tendon force is held constant at 70% UTS. Assuming that the maximum tendon force of 70% UTS and the tightest tendon curvature (with the highest transverse pressure) happen both close to the jacking end of the tendon one can easily calculate that these test parameters cover maximum tendon lengths on site of about 125 metres. However, the test parameters cover even longer tendons if the critical tendon location is further away from the jacking end or if the simultaneous two-end jacking of tendons is applied. In any case, if critical, the designer may easily verify whether the test parameters specified in Section 6.8 and Annex A.8 cover the particular parameters of his project. If this is not the case, the designer may specify the actual parameters applicable for the project in the project specification, and the duct system supplier will have to verify his/her polymer duct performance for these project specific requirements.

As mentioned above, wear is a function of the transverse load (clamping force) and the actual applied relative movement between the tendon and the polymer duct. Several researchers have investigated the effects of transverse pressure and relative sliding movement. Figure 3.4 illustrates the effects of transverse tendon pressure and relative movement based on tests performed at ETH Zurich [Oertle (1988)].
3.4a: Wear of polymer duct (PE) as effect of transverse load ($Q=6$ kN) on duct specimen of 40 mm length and relative movement of strand according to Oertle (1988)

Note: Total test duration was about 4.5 minutes

<table>
<thead>
<tr>
<th>Test</th>
<th>Lateral pressure $Q$ (kN)</th>
<th>Tendon movement $\Delta l$ (mm)</th>
<th>Residual wall thickness (mm)</th>
<th>Residual wall thickness (mm)</th>
<th>Duration of test (minutes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>9.0</td>
<td>50</td>
<td>3.9</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>9.0</td>
<td>750</td>
<td>1.75</td>
<td></td>
<td>4</td>
</tr>
<tr>
<td>3</td>
<td>0.5</td>
<td>1500</td>
<td>2.0</td>
<td></td>
<td>210</td>
</tr>
<tr>
<td></td>
<td>1.0</td>
<td>1500</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2.0</td>
<td>1500</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3.0</td>
<td>1500</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>6.0</td>
<td>1500</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>9.0</td>
<td>750</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 3.4b: Effect of different loading histories on residual wall thickness in terms of applied relative strand movement ($\Delta l$); however, identical maximum transverse load ($Q$) on wear of polymer ducts (PE) according to Oertle (1988)

Note: Wear may be calculated as initial thickness of polymer samples (4.0 mm) minus residual wall thickness. The length of the test specimens was 40 mm.

Based on Figure 3.4a one can see that the application of the particular transverse load ($Q = 6$ kN) on the specimen without relative sliding caused a duct wear of 0.9 millimetres. Maintaining the same transverse load and subjecting the sample in addition to a 750-
millimetre relative sliding movement increased the duct wear from 0.9 millimetres to 1.1 millimetres. Applying further relative sliding movements of 750 millimetres increased the duct wear by 0.15 millimetres in each cycle. Hence, based on these results it seems that the main cause of wear is the maximum transverse pressure. The relative sliding movement contributes to the wear, but to a significantly lesser degree.

Comparing the results of tests number 2 and number 3 in Figure 3.4b, one can conclude that applying the maximum load right from the start of a test and keeping it constant during the relative movement is significantly more severe than gradually increasing the lateral load while applying the relative sliding movement. In fact, test number 2 with a maximum load of \(Q = 9\) kN constant during the sliding movement of 750 millimetres resulted in a residual wall thickness of 1.75 millimetres. However, gradually increasing the lateral load from 0.5 kN for the first cycle of a 750-millimetre relative sliding movement to 9 kN for the last cycle of the relative sliding movement resulted in a residual wall thickness of 2.0 millimetres, namely, 0.25 millimetres less in wear even though the relative movement was six times larger. *fib* Bulletin 7 specified the full transverse load to be applied right from the start of the test over the entire range of applied tendon elongation of 750 millimetres to compensate for other effects which were not or not adequately considered, such as the effect of the sustained load and the temperature. Since these recommendations now specify testing that takes into consideration both the elevated temperature and the effect of the sustained load (see Section 6.9 and Annex A.9), the clamping force is now increased proportionally to the applied tendon movement.

3.2.7.2 Effect of time

Polymer materials creep under sustained load. Therefore, the actual wear of polymer ducts will increase from the immediate initial value at the time of stressing by some amount if the transverse pressure (clamping force) due to the tendon force is sustained. The increase of wear may be expected to stop once the tendon is injected with grout and it has sufficiently hardened. Several researchers have investigated the effect of time on the wear of polymer ducts [Foure (1993); Hegger (2001)]. While both of these tests show an effect of time on the wear, the increase of wear seems to happen mainly within the first few days, say up to one week, and then approach asymptotically an end value (Fig. 3.5). The increase measured for PE materials in these test series is in the order of 0.1 to 0.2 mm and hence, fairly modest. According to Hegger 95% of the wear measured after 3 weeks happen within the first hour of testing.
Fig. 3.5a: Wear of smooth PE pipes measured on external tendons with 19 strands and radius of curvature of 3m, according to Foure (1993)

Fig. 3.5b: Percentage increase of wear of smooth PE sheathing as a function of time under sustained load measured by Hegger (2001)

Note: The graph shows the additional deformation over time (in hours) beyond the initial deformation immediately at the time of load application
The effect of time is not reproduced in the polymer-duct test specification of Section 6.8 and Annex A.8. However, an additional wear resistance under sustained load test has now been specified that verifies the effect of time over a period of 14 days (see Section 6.9) and Annex A.9. According to Figure 3.5b this test duration ensures that the actual wear in real structures will rarely, if ever, exceed the tested value even if grouting is delayed.

3.2.7.3 Effect of temperature

The wear of polymer ducts depends also on the temperature of the duct. An increase in temperature while maintaining all other test parameters identical will cause an increase in duct wear. Therefore, wear testing of polymer ducts in accordance with Section 6.8 and Annex A.8 and for wear resistance under sustained load, in Section 6.9 and Annex A.9, are specified at ambient temperature (23 °C) and at high temperature (45 °C). Relevant for the duct temperature and, hence, the actual wear on site is the temperature of the concrete surrounding the duct at the time of stressing. If early stressing is applied within a few days after the placing of the concrete, the temperature of the concrete and the duct will be affected by the heat of the hydration of the concrete, which depends on the type of cement used and the thickness of the concrete section. If later stressing is applied, the temperature of concrete mainly depends on the ambient temperature. The designer and specialist contractor will have to consider, for the particular project, whether the test parameters in accordance with Sections 6.8 and 6.9 and Annexes A.8 and A.9 cover, in fact, the actual parameters expected on site for the intended stressing programme of the tendons. If this is not the case, the designer may either adapt the stressing programme (the time of stressing or the maximum jacking force) or the tendon curvature or specify the actual parameters and, in particular, the expected concrete temperature at the time of tendon stressing, in the project specification.

Figure 3.6 illustrates the development of the heat of the hydration of two typical concrete mixes, one for building and the other for bridge construction, over time for different types of cement and thicknesses of concrete members. As can be seen from these graphs, the heat of hydration must typically be considered if tendon stressing is performed within the first few (perhaps one to three) days from concrete placement. For later stressing a lower temperature or a typically ambient temperature will govern unless concretes with very slow strength development are used or tendons are placed in very thick members. It should be noted that the temperatures after peak hydration for the curves in Figures 3.6a and b are based on a constant ambient temperature of 20 °C, hence not undergoing cooling during the night and experiencing no effect from the wind or rain that would accelerate the cooling of the concrete. If cooling during the night and exposure to the wind or rain apply, the reduction of temperature is probably more like that shown in Figure 3.6c. As can be seen from these graphs, the peak temperatures of the heat of hydration of about 45 to 50 °C and 50 to 55 °C must be assumed for typical building and bridge construction concrete mixes respectively, where the lower value applies for relatively thin members of 0.25 metres and the upper value applies for relatively thick members of 2.0 metres. Also shown in these graphs is the development of the mean concrete strength over time.
3 General and design/detailing considerations

a  Typical concrete for buildings [courtesy of Holcim (Switzerland)]

b  Typical concrete for bridges [courtesy of Holcim (Switzerland)]
3.2.7.4 Effect of type of tensile element

The testing for actual wear resistance under sustained load is performed with a 7-wire prestressing strand. Performing these tests with strand is also considered to cover the possible use of wire as the tensile element. Hence, a test performed in accordance with Sections 6.8 and 6.9 and Annexes A.8 and A.9 with strand is also considered valid and representative for the use of tendons with wire. A test performed with strand and a specific clamping force represents a strand tendon at a given radius of curvature (see Section 6.8). The same radius of curvature applies for a wire tendon with the same tendon ultimate capacity.

However, the case of curved tendons with bars is not covered by this report. In fact, ribbed bars are considered to be more aggressive in terms of wear than wire and strand. In addition, the clamping force may also be affected by bar stiffness. Hence, use of bars in polymer ducts is not covered by this report although straight bar tendons inside polymer ducts have been successfully used in some countries.

3.2.8 Effects of ducts on the compressive strength of concrete panels

The flow of compressive stresses in uniaxially loaded concrete panels is transversely deviated at the location of tendon ducts, as schematically illustrated in Figure 3.7a. It has been documented that empty ducts, namely, ungrouted, as well as grouted ducts in such uniaxially loaded panels, may have an effect on the maximum compressive strength of the panels if the ducts occupy a significant part of the panel thickness.

Instead of reducing the compressive strength of concrete, several standards require a reduced effective thickness of members with tendon ducts to be considered when checking for compressive loads. This requirement applies, for example, when checking the maximum shear resistance of webs governed by concrete crushing. In accordance with these standards the ratio of the maximum shear strength of webs with ducts or webs without ducts is:

$$\eta_D = 1 - k \delta$$
with $\delta = \Sigma \varnothing / b_w$ being the ratio of duct diameter $\varnothing$ over web width $b_w$ (Note: the sum of duct diameters is to be considered if several ducts are placed within the width of the web), and $k$ is a proportionality factor depending on the type of duct. Table 3.4 summarises different code provisions for the proportionality factor $k$.

Table 3.4: Code provisions for the effect of ducts on the maximum shear strength of webs

<table>
<thead>
<tr>
<th>Code</th>
<th>Year</th>
<th>$k$ Empty duct</th>
<th>Grouted steel duct</th>
<th>Grouted polymer duct</th>
</tr>
</thead>
<tbody>
<tr>
<td>AASHTO</td>
<td>2004</td>
<td>0.5</td>
<td>0.25</td>
<td></td>
</tr>
<tr>
<td>BS 5400-4</td>
<td>1990</td>
<td>1.0</td>
<td>0.67</td>
<td></td>
</tr>
<tr>
<td>CEB MC90</td>
<td>1993</td>
<td>1.2</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>CEB MC78</td>
<td>1978</td>
<td>0.5</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>EC2</td>
<td>2004</td>
<td>1.2</td>
<td>0.5</td>
<td>1.2</td>
</tr>
<tr>
<td>EC2</td>
<td>1992</td>
<td>-</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>fib MC 2010</td>
<td>2010</td>
<td>1.2</td>
<td>0.5</td>
<td>0.8</td>
</tr>
</tbody>
</table>

Muttoni (2006) has carried out testing with panels and both steel and polymer ducts that occupy half of the panel thickness ($\delta = 0.5$). He confirmed the reduction effect of ducts on the compressive strength of the panels if the ducts represent more than 20% of the panel thickness. He found that the ratio $\eta_D$, namely, the compressive strength of panels with ducts or the compressive strength of panels without ducts, for normal weight concrete is:

$$\eta_D = 1 - k \delta$$

where

- $k = 0.4$ for grouted steel ducts
- $k = 0.8$ for grouted polymer ducts
- $k = 1.2$ for ungrouted ducts (steel and polymer)

The compressive strength of the panels is illustrated in Figure 3.7b.
a Flow of stresses around ducts in concrete panels

As mentioned above this reduction factor $\eta_D$ applies strictly only to the compressive strength of uniaxially loaded panels with ducts. However, it has been adopted in several codes for calculating the maximum shear capacity of webs of beams governed by the crushing of concrete. While it is true that web crushing failure in beams will occur at the location of the tendon ducts, in general, it is still a matter of debate whether the ducts in fact reduce the effective compressive strength of concrete beyond the value adopted in design for elements with inclined shear cracks (which is already reduced to about 60% of the compressive cylinder strength of the concrete). In fact, using elastic-plastic stress fields, Rupf (2014) found slightly better agreement of the mean value of the ratio of actual ultimate loads in 15 tests

Fig. 3.7: Effect of ducts in concrete panels according to [Muttoni (2006)]
(F_{test, ave}) divided by the calculated ultimate load (F_{calc,ave}) when neglecting the reduction factor \( \eta_D \) (mean value \( F_{test, ave} / F_{calc,ave} = 1.03 \)) than when considering the reduction factor \( \eta_D \) (mean value 1.05). The corresponding variation coefficients were 8.4% and 8.0% respectively. No effect of ducts applies in any case for lower values of shear forces where the yielding of the shear reinforcement is governing.

It should be noted that the above tests performed by Muttoni were carried out with polymer ducts with an internal diameter 59 millimetres and a wall thickness of about 2.0 to 2.5 millimetres. The above equation for the strength reduction should be applied with caution if polymer ducts with a significantly larger ratio of wall thickness to duct diameter are used.

### 3.2.9 Bond

The bond strength of tendons may be governed by either (i) the strength in the interface of the prestressing steel with the grout or (ii) the interface between the duct and the grout or (iii) the interface between the duct and the surrounding concrete. There is no difference in bond strength between steel and polymer ducts in cases where the interface between the prestressing steel and the grout is critical. A similar bond strength between metal and polymer ducts may apply for highly corrugated polymer ducts (similar to corrugated steel ducts) with relatively weak bond on the prestressing steel surface. However, for polymer ducts with relatively few corrugations the bond strength at the interface of a duct with grout or surrounding concrete may be critical. In this case, there will likely be a difference in strength between steel and polymer ducts.

Testing by Ullner (2007) on a proprietary polymer duct system has shown that the bond of tendons inside these polymer ducts is softer and less strong than the bond of tendons inside steel ducts. Figure 3.8 illustrates the bond strength of tendons as a function of the applied stress increase in the tendons for steel and polymer ducts respectively.

![Fig. 3.8: Bond strength of tendons according to Ullner (2007)](image_url)
Ullner proposed the following bond-strength equations for the particular type of polymer duct and for metal ducts to EN 523 (2003) as a function of the applied tendon force increase $\Delta P$:

**Bond strength of polymer ducts:**

$$\tau_{bp,K} = 0.75 + 7.5 * \frac{\Delta P}{A_p * f_{pk}} \ [N/mm^2]$$

**Bond strength of metal ducts:**

$$\tau_{bp,S} = 1.25 + 11.0 * \frac{\Delta P}{A_p * f_{pk}} \ [N/mm^2]$$

*Note: Index ‘K’: Polymer; Index “S”: Steel; $\Delta P$: Tendon force increase; $A_p$: Cross sectional area of prestressing steel in tendon; $f_{pk}$: UTS of prestressing steel; $\tau_{bp,m}$: $\Delta P/(p_{bp} l_{ep})$ average bond stress over activated bond length $l_{ep}$, calculated with relevant tendon circumference $p_{bp}$.*

It should be noted that the tests performed by Ullner (2007) were performed with proprietary polymer ducts with an internal diameter of 59 to 130 millimetres and wall thicknesses of 2.0 to 3.5 millimetres. The above equation for the bond strength of polymer ducts should be applied with caution if ducts other than the specific proprietary polymer ducts or ducts with significantly different rib spacing and a larger ratio of wall thickness to duct diameter are used.

The bond of the prestressing steel to the surrounding concrete is necessary to generate a stress increase in the prestressing steel at cracked sections. Sufficient bond strength ensures that the stress in the prestressing steel may increase from effective stress at service conditions to the yield or tensile strength at ultimate conditions. Hence, sufficient bond is essential for the application of the well known principle of plane sections remaining plane after cracking, which is used for the flexural design of concrete members. As demonstrated by Marti (2008) the bond demand in most typical structures with critical sections at mid span or over supports of continuous beams is relatively modest and the actual bond length in the structure is therefore sufficient for the typical assumption of fully bonded tendons to apply; this is also the case for polymer ducts with behaviour as per Figure 3.8. However, careful checking is advised for cases in which tendons need to be cut near critical sections in existing structures during repair.

Crack initiation does not depend on the bond of the tendon but is only dependent on the tensile strength of the concrete and the applied actions and effective prestressing force in the section. However, for the fatigue verification of cracked sections, the stress increase in the prestressing steel and reinforcing steel needs to be calculated. This requires consideration of the bond properties and in particular of the relative bond strength of reinforcing and prestressing steel. If both types of steels have identical bond strength and are located at the same distance from the neutral axis, the stress increase in both steels will be identical. Since prestressing steel has lower bond strength than reinforcing steel in general, the stress increase in prestressing steel is lower than in the reinforcing steel. This fact is considered in some design standards with a ratio $\xi$. EN 1992-1-1 (2004) gives this coefficient for steel ducts and post-tensioning strand as $\xi=0.5$ (see Table 3.5). No information is provided in EN 1992-1-1 (2004) for polymer ducts.
### Table 3.5: Ratio $\xi$ of bond strength between tendons in corrugated metal duct and reinforcing steel in concrete according to [EN 1992-1-1 (2004)]

<table>
<thead>
<tr>
<th>Prestressing steel</th>
<th>Ratio $\xi$</th>
<th>bonded, post-tensioned</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>pretensioned</td>
<td>$\leq$ C50/60</td>
</tr>
<tr>
<td>smooth bars and wires</td>
<td>not applicable</td>
<td>0.3</td>
</tr>
<tr>
<td>strands</td>
<td>0.6</td>
<td>0.5</td>
</tr>
<tr>
<td>indented wires</td>
<td>0.7</td>
<td>0.6</td>
</tr>
<tr>
<td>ribbed bars</td>
<td>0.8</td>
<td>0.7</td>
</tr>
</tbody>
</table>

**Note:** For intermediate values between C50/60 and C70/85 interpolation may be used.

**Note in EN 1992-1-1:** $\xi$ is the ratio of bond strength between bonded tendons and ribbed reinforcing steel in concrete. The value is subject to relevant European Technical Approval. In the absence of this the values given in Table 3.5 may be used.

According to the results of Ullner (2007) for the particular proprietary polymer duct (Fig. 3.8) there is an approximate 50% increase in bond length when comparing that particular polymer duct with a corresponding corrugated metal duct. Hence, a ratio of $\xi = 0.35$ would apply.

For the general application of internal bonded tendons, the bond strength is needed for a stress increase in the tendon from an effective stress after all losses up to a maximum of the tensile strength of the tendon. Typically, this corresponds to a force increase of about 40% of the tendon tensile strength. However, if during the repair of a structure a tendon needs to be cut, a significantly higher force equal to the effective tendon force needs to be transferred at service conditions and at an ultimate force equal to the full tensile strength of the tendon.

Therefore, the bond behaviour of the tendon inside grouted polymer ducts must be investigated and declared in the duct-system documentation so as to allow a structural engineer to assess the eventual implications for the design of the structure under service and ultimate conditions for particular applications. The effect of the tendon size seems to be small according to the results of Ullner (2007), in Figure 3.8, if the polymer duct sizes have a geometrically similar design. Therefore, this report now specifies bond testing for three polymer duct sizes, namely, a small, a medium and the largest size, in accordance with Section 6.10 and Annex A.10. This report specifies bond testing to determine the actual bond length able to transfer 40% of tendon tensile strength in not more than 16 duct diameters, namely, through extrapolation 100% of the tendon tensile strength will be transferred in not more than 40 duct diameters.

### 3.2.10 Acceptable crack widths

Crack widths in concrete structures are limited for several reasons, including aesthetics and the durability of the member. Most standards have specified different acceptable crack widths for reinforced and for prestressed members. This was done because the highly stressed prestressing steel is considered to be more susceptible to corrosion than the non-stressed reinforcing steel. While acceptable crack widths for reinforced concrete are typically in the range of 0.2 to 0.4 millimetres, the corresponding values for prestressed concrete are in the range of 0.1 to 0.2 millimetres, or for severe exposure, the cross sections of prestressed
members are required to remain pre-compressed at the tendon location or within about 100 millimetres from the tendon.

Cracks and joints in concrete allow a path for possibly contaminated water to reach internal ducts. These cracks can occur either longitudinally or transversely to the tendons and may simply be the result of the design within permissible code limits, depending on the type of design (partial prestressing concept). For example (i) longitudinal cracks along longitudinal tendons in a transversely reinforced concrete deck slab, and (ii) transverse cracks along transverse tendons in the deck slab of steel composite bridges above supports of continuous decks. In both cases the cracks could run along the line of the ducts, which is considered particularly unfavourable for the durability of non-encapsulated tendons.

Cracks normal to tendons are less likely, unless there has been an unexpected or excessive loss of precompression due to the restrained shortening of the prestressed concrete or if low partial prestressing is used, but could also provide a passage for water to the tendons.

In all the above-mentioned cases polymer duct systems with PL2 or PL3 should be considered for both longitudinal and transverse tendons to provide full encapsulation to tendons and, hence, avert the ingress of possibly contaminated water into the tendon ducts. Where structural elements are prestressed in both directions and designed to be crack-free, there is less risk that metal ducting would be susceptible to corrosion and the penetration of contaminated water. However, the protection then purely depends on the concrete cover. Since the extra cost of polymer ducting is small compared to the added benefits, or may even be compensated for by a reduced need for prestressing steel, polymer ducts should be the preferred choice for all the above-mentioned applications.

To provide full encapsulation during the design service life of the structure, the polymer ducts should not crack when the above-mentioned cracks occur along or across the tendon path even if there is cyclic crack opening at low temperatures. In Abel (1996) the results are presented of testing on concrete specimens with metal ducts and polymer ducts in which a maximum crack opening of 0.5 millimetres was applied across the ducts. A cyclic crack opening of up to 0.3 millimetres was applied and the duct specimens were monitored for cracking. Figure 3.9 illustrates the test results for corrugated metal duct, polymer duct with helical/continuous corrugation (Type A in Figure 3.9), and a proprietary polymer duct with circular (toroidal)/intermittent corrugation (Type B in Figure 3.9). As can be seen, corrugated metal duct starts to crack at a cyclic crack opening of 0.1 millimetres or less and with only a small number of cycles. Polymer ducts of Type A cracked at a cyclic crack opening of up to 0.3 millimetres within a few hundred thousand cycles. However, the polymer duct Type B did not crack in any of the tests with a 0.3-millimetre cyclic crack opening and two million or more load cycles, even at temperatures as low as -20 °C.

**Fig. 3.9: Number of cycles until duct cracking for cyclic crack opening Δw across tendon ducts and maximum crack opening of 0.5 mm according to [Abel (1996)]**
This performance criterion of the permanent full encapsulation of polymer ducts for PL2 and PL3 across active cracks is verified with the fracture-resistance test specified in this report (Section 6.12 and Annex A.12). Polymer ducts that comply with these requirements may be considered to provide full encapsulation during the design life of the structure corresponding to 2 million load cycles and a cyclic crack width variation of 0.3 millimetres at a maximum crack opening of 0.5 millimetres, which was verified in the specified test.

With the introduction and verification of the permanent full encapsulation of the tendons, the risk of tendon corrosion due to member cracking is controlled. Hence, in recent design recommendations prestressed members with tendons PL2 or PL3 fully encapsulated in polymer duct systems have acceptable crack widths that are identical to those for reinforced concrete [fib MC (2010)].

3.2.11 Fire

The behaviour of concrete under high temperatures and fire exposure is covered in the most recent standards [fib MC (2010)]. The behaviour of prestressing steels at high temperatures has also been documented by several researchers [Galvez (2011)] and these results have also been included in recent standards [fib MC (2010)]. Prestressing steel loses strength once the steel temperature exceeds approximately 150 to 200 °C. However, polymer ducts made of PE or PP forming the interface between prestressing steel and concrete are elements that are not covered in standards and that are known to melt at temperatures of 120 to 130 °C and 160 to 170 °C respectively. Hence, there are questions of what consequences such melting may have on the behaviour in fire of prestressed members with polymer ducts.

To the knowledge of the authors of this report there has been little research done on the performance of prestressed members or structures exposed to fire with tendons inside polymer ducts. However, research performed in the UK [Ellobody (2008), Bailey (2009)], provides some valuable information. One-way-spanning prestressed concrete slabs were tested and analysed under fire conditions both for longitudinally free and for restrained-end supports. Unbonded tendons (individually greased and PE sheathed) and bonded tendons with both corrugated-metal duct and polymer duct were investigated. A total of 16 slabs were tested, 4 at ambient temperature as reference and to document the actual ultimate load, and 12 under fire conditions, of which 8 slabs had bonded tendons. All the slabs were 4.3 metres long with a clear span of 4.0 metres, 1.6 metres wide and 160 millimetres thick. Each slab had 3 tendons, each made of a single strand of 15.7 millimetres and 1860 N/mm² strength, placed in a parabolic profile from mid-depth at the ends to a low point at midspan. The centre of all the ducts had a distance of 42 millimetres from the concrete surface at midspan. The tendons were stressed to a jacking force of 70% UTS. The slabs had target concrete cube strengths of 40 N/mm² (Note: Test specimen TB2 only reached 30 N/mm² strength at the time of testing). Two different types of aggregates were tested.

Figure 3.10a illustrates the slab behaviour at ambient temperature as tested and by analysis. Both slabs with metal and polymer duct showed ductile behaviour with deflections at ultimate load in excess of span/40. The observed lower load capacity of the slab TB2 with metal duct is a consequence of the larger duct diameter, which reduced the tendon eccentricity, and of the lower concrete strength. Otherwise, the two specimens with metal and polymer duct performed similarly.

For the fire tests, all slabs were subjected to a load corresponding to 60% of the nominal design capacity, held constant during the entire test period. The central 3.2 metres of the slabs were exposed to fire in accordance with the standard ISO fire/temperature curve. Figure 3.10b shows the measured and calculated temperatures of specimen TB3 with polymer ducts over...
the test period. As can be noted, the temperature at tendon level (graph marked ‘T’) went well beyond the above-mentioned melting points of the polymers. Figure 3.10c illustrates the deflection of the slabs at midspan over the test period. As can be seen from these graphs the behaviour of the slabs with metal and polymer ducts is similar. Again, the slight difference between slabs with metal duct and polymer duct is mainly caused by the different eccentricity of the tendons.

a  Behaviour of slabs in polymer duct (TB1) and metal duct (TB2) at ambient temperature

b  Temperature in specimen TB3

Note: HS= hot surface, T= tendon, MS= mid surface, CS= cold surface
c Deflection at mid span for slabs with polymer duct (TB3 – TB6) and metal duct (TB 7 – TB10) [courtesy of Professor Collin Bailey]

Fig. 3.10: Fire testing of prestressed slabs with metal and polymer ducts according to Elllobody (2008) and Bailey (2009)

Note: Equivalent test specimens with polymer and metal ducts are: TB1 & TB2; TB3 & TB7; TB4 & TB8; TB5 & TB9; TB6 & TB10.

In these test results no significant difference was noted between specimens with metal duct and polymer duct. In fact, the main difference in behaviour was caused by the different type of aggregate used. Based on the test results and numerical modelling performed, the authors concluded: “Using different aggregates influenced the deflection-time response but did not significantly affect the failure fire resistance time. The numerical results were compared with values calculated using current design codes. The comparison has shown that the bonded post-tensioned concrete slabs investigated in this study are capable of achieving the designed 90 minutes fire resistance. It is also shown that the fire resistance given by BS 8110 (1985) and BS EN 1992-1-2 (1992) are conservative for bonded post-tensioned one-way-spanning concrete slabs under fire conditions. It was shown that BS 8110 (1985) predictions were more aligned with the finite element analysis predictions.”

Unfortunately, there was no information on the conditions of the ducts and the remaining load capacity of the specimens after fire testing. However, it is important to note that there was no or only very limited and local spalling of the concrete cover. Hence, the above results
may not apply once spalling of the concrete cover occurs early in the test and over extended areas of the specimens.

3.2.12 Cryogenic conditions

Hoop and vertical bonded tendons are typically used in the concrete external containment walls of liquid natural gas (LNG) tanks and other types of reservoirs. During normal operation the concrete wall and the prestressing tendons inside are exposed to approximately ambient temperature. However, in the accidental case of the leakage of the inner containment the external concrete containment wall may be exposed locally or over an extended area to cryogenic temperature on the inside face while the outside face is still at ambient temperature. Hence, a high temperature gradient across the concrete containment wall will apply and some of the tendons may be exposed to significantly lower temperatures (Fig. 3.11).

Tendon components located at the outside face of the concrete containment will remain at approximately ambient temperature. The hoop tendons are usually placed just next to the reinforcement along the outside face of the wall, at approximately 100 to 120 millimetres from the outside wall face. Depending on actual wall thickness and tendon location, the hoop tendons may be expected to be exposed to temperatures in the range of -20 °C (Fig. 3.11), hence, to still normal design conditions for prestressing steel and other components. The vertical tendons in these containment walls are installed usually concentrically in the middle of the wall. Hence, assuming approximately -165 °C on the inside face and +20 °C on the outside face, these vertical tendons may be exposed to temperatures in the range of about -70 to -80 °C (Fig. 3.11). Typically, the vertical tendons are installed inside rigid steel pipe for construction reasons. Only tendon components near or at the inside concrete wall face will be exposed to cryogenic conditions, namely -165 °C. However, in today’s typical containment designs there are, in general, no tendons near the inside wall face. For typical applications it may, therefore, be concluded that:

- Polymer ducts are perfectly suitable for tendons at the outside face of the wall and in particular for the hoop tendons under the above mentioned temperature distribution across the concrete containment wall since the estimated temperature range is within normal operating conditions. The use of polymer ducts is particularly interesting for hoop tendons since the reduced friction losses will provide a more effective prestress for a given number of tensile elements.

- Special considerations and particular tests may be required for tendons with polymer ducts near or at the inside face of the concrete containment since polymers become brittle at such very low temperatures as may occur during an accidental spill of LNG. However, such particular tests are not within the scope of this report.
3.3 Detailing considerations

3.3.1 Size of polymer ducts

Polymer ducts for internal bonded tendons are available up to approximately 160 millimetres in diameter. Typically, polymer duct diameters are slightly larger than steel ducts for the same tendon size due to greater duct wall thickness and in many cases larger duct corrugations. This must be taken into consideration for the minimum spacing of ducts and for minimum member thickness. Sufficient tolerance must be allowed in detailing to avoid the reinforcement squeezing the polymer ducts when the formwork is closed. While this applies to all applications of polymer ducts, it is particularly important for PL3 tendons with EIT. Deformed polymer ducts will likely not achieve the specified electrical resistance.

Depending on the actual design, duct couplers may require more space than polymer ducts. This should also be considered in detailing and for the minimum dimensions of members and cross sections.

3.3.2 Shape of polymer ducts

Round polymer ducts are typically used for multistrand tendons in bridge or civil engineering structures. They are available in sizes ranging from 1 strand to 55 strands, namely, with internal diameters in the range of 22 millimetres to approximately 160 millimetres.

Flat or oval ducts are typically used for the small tendons of up to 4 to 5 strands commonly used in building floors or for transverse tendons in bridge decks. These ducts have inside dimensions of about 22 millimetres in height by 75 to 90 millimetres in width.

More recently oval ducts have been produced for tendons of up to 22 strands.

Round ducts must be designed to be sufficiently robust to withstand typical loading during construction and concreting. With such robust ducts, the prestressing steel can either be installed before or after the casting of the concrete. In bridge construction, the installation of
the prestressing steel is done preferably after the casting of the concrete and just prior to stressing to avoid any problems with the temporary corrosion protection of tendons before grouting. If the permissible time between the placement of tendons and the grouting is exceeded, additional temporary protective anti-corrosion measures need to be taken, for example, the application of water-soluble oils on the prestressing steel before installation.

Flat ducts provide a relatively low resistance to loads / pressure acting perpendicularly to the flat surface. There is a risk that the ducts are squeezed across the small dimension during installation and concreting and that it may not be possible to install the prestressing steel after casting the concrete. Therefore, the prestressing steel often is installed in flat ducts prior to casting the concrete even though flat ducts are tested to the same concrete pressure test as round ducts (Section 6.7 and Annex A.7).

Oval polymer ducts have a better resistance to transverse loads than flat ducts but not as high a resistance as round ducts. Hence, caution should be applied and the supplier’s recommendations for tendon installation should be strictly followed.

Three types of corrugation have been used for polymer ducts: (i) continuous circular (toroidal), (ii) intermittent circular (toroidal), and (iii) continuous helical (spiral).

Typical polymer duct shapes and corrugations are illustrated in Figure 3.12.

![Fig. 3.12: Typical polymer duct corrugations and shapes](image)

### 3.3.3 Cover to ducts, spacing of ducts

#### 3.3.3.1 Cover to ducts

The concrete cover to any duct, irrespective of whether it is of metal or polymer, must be adapted to the requirements for the:

- corrosion protection of tendons
- fire protection of tendons
- bond transfer of tendons.
In addition, the cover also needs to allow for the risk of cracking and spalling of the cover due to grouting pressure. While this is usually not an issue for round ducts, it must be considered when flat ducts are used with a small concrete cover and little ordinary reinforcement between the duct and the concrete surface. This may particularly be the case in building floors near tendon low points. There have been reports of concrete spalling during the grouting of flat ducts in building floors with grouting pressures of several bars. Hence, grouting pressure needs to be controlled, in particular with flat ducts with little concrete cover and little or no surface reinforcement.

The minimum cover to tendons for round ducts is specified in most of today’s standards for durability/corrosion protection, fire protection and bond requirements as a multiple of the duct diameter. The minimum nominal cover (before allowance for installation tolerance) for corrosion protection is in the range of 30 millimetres to 65 millimetres for Exposure Classes XC1 and XD3 respectively (Table 3.1), for 50 years of service life. The minimum cover for bond is in the order of a half to one duct diameter. For flat ducts, the same minimum covers apply for durability and fire. However, there is little guidance given for the minimum cover of flat ducts for bond. It is the opinion of the authors of this report that the multiple of duct diameter given for round ducts should be applied to the small dimension of the flat duct, meaning that a flat duct with a single layer of strands inside should have the same cover for bond as a single strand tendon in a round duct.

3.3.3.2 Spacing of ducts

Relatively little is said in today’s standards about the minimum spacing of tendon ducts in either polymer or metal. FIP (1999) permits the bundling of up to two tendon ducts transversely to the tendon curvature or for straight tendons, which means that these two ducts are permitted to come into contact with each other. Tendon ducts may also touch locally if they cross approximately perpendicularly, or if they touch only over a small length longitudinally.

Transversely to the plane of tendon curvature, ducts or duct bundles should be spaced so as to facilitate the placing and compacting of the concrete with sufficient space for the maximum aggregate size. A typical minimum spacing of a 0.7 and 1.0 duct diameter should be allowed for between individual ducts and duct bundles respectively.

Special attention has to be paid to the spacing between ducts in the plane of curvature of the tendons, in particular if the tendons on the outside of the curvature shall be stressed before the tendons on the inside of the curve are grouted. The minimum spacing required can be estimated based on strut-and-tie models designed to deviate the transverse forces due to tendon curvature around the next empty, ungrouted duct. If transverse reinforcement is provided, relatively small duct spacing may be used. However, if no transverse reinforcement is provided, larger spacing between ducts is required and a very conservative assumption for the design tensile strength of concrete to take the deviation forces should be applied. For a 35 N/mm² concrete grade (cylinder strength) a design tensile strength in the order 0.5 N/mm² (material factor already considered) may apply. Minimum spacing in the plane of tendon curvature should typically be at least 0.7 but, preferably, 1.0 in duct diameter.

Figure 3.13 illustrates minimum concrete cover and the minimum spacing of ducts transversely to the plane of tendon curvature ($b_1$ and $b_2$) and in the plane of tendon curvature ($c_1$ and $c_2$).
Cross sections of members should be detailed to provide sufficient tolerance for duct installation inside the concrete members. Providing insufficient tolerance may cause polymer ducts to be crushed or squeezed between reinforcement layers and/or other ducts or inserts. Placement tolerances should be considered. If polymer ducts are pre-deformed before or during placement, their resistance to transverse loads or pressure such as that which is applied during concrete placing may reduce and local duct collapse could result, which in turn will cause problems for strand installation.

3.3.4 **Minimum radius of tendon curvature**

The radius of tendon curvature must be controlled for several reasons:

1. the lateral pressure of the tendon duct on the concrete on the inside of the tendon curvature
2. the transverse pressure inside the tendon bundle between tensile elements, which could cause potential damage to the prestressing steel
3. the lateral pressure between the prestressing steel and the duct, which could damage the duct

There is also an effect of tendon curvature on the friction loss; however, this effect is relatively small and, for the typical values of radii given below, is within the tolerance/scatter of the friction coefficient.

Condition (1) above is the basis for the definition of a normal minimum radius of tendon curvature for the general case. FIP (1999) has proposed a minimum radius of tendon curvature for this case of $R \, (m) = 3.0 \sqrt{UTS} \, (MN)$. With this limitation, the concrete stresses on the inside of the tendon curvature are limited to the order of 10 N/mm$^2$ or less at tendon UTS. Under such low stresses no confinement reinforcement is normally required around the duct at these tendon curvatures, both for service and ultimate-limit-state conditions, even if the early age stressing of the tendons is applied.
The limits for condition (2) are not that well established. However, Kollegger (2012) performed testing with a wide range of tendon sizes providing maximum transverse contact pressures between the strand bundle and the duct calculated according to Weiher (2007) of up to 3550 kN/m. These tests demonstrated that transverse loads between the strands inside the tendon bundles can reach several hundred kN/m (in excess of 500 kN/m) before the transverse pressure affects the tensile strength of the tendon, even when combined with relative movement between individual strands. These recent results confirm the results of older tests performed by the nuclear industry in the 1960s. For the minimum radii of curvature typically specified for internal tendons, \( R (m) = 3.0 \sqrt{UTS} (MN) \), and external tendons, \( R (m) = 1.5 \sqrt{UTS} (MN) \) [FIP (1999)], the transverse pressure between strands inside the tendon bundles remain below the above limits. Figure 3.14a illustrates all tests performed while 3.14b is an extract of the tests with maximum pressures of up to 800 kN/m performed by Kollegger.

There are also specific cases such as looped tendons (namely, with the tendon path in the form of a U and the tendon stressed simultaneously from both ends) that permit the application of even smaller tendon radii than given above for condition (2) because there is no relative movement between tendon and duct at the critical location of tendon curvature. Even for tendons with minimum radii of curvature in the order of \( R (m) = 0.6 \sqrt{UTS} (MN) \) and maximum lateral contact pressure of 800 kN/m, little reduction of tensile strength is observed when comparing with the corresponding size of a straight tendon. However, such small radii of tendon curvature are only permitted for quasi-static load conditions, that is, tendons subjected to fatigue loading may not be curved to such low radii.

\[ \text{Fig. 3.14: Tensile strength of tendons as a function of maximum lateral pressure due to tendon curvature, according to Kollegger (2012)} \]

\[ \text{Note: Legend in b. indicates size of tendon: ‘1x0.5’ = 1 strand of 12.9 mm (0.5 inches) in nominal diameter, ‘12x0.6’ = 12 strands of 15.7 mm (0.6 inches) in nominal diameter, and so forth} \]

The limits for condition (3) for polymer ducts are verified through the component testing specified in this report in Sections 6.8 and 6.9 and Annexes A.8 and A.9, as part of the polymer duct system approval. In particular, the wear of the duct under the transverse pressure is verified. This wear however, is not only a function of the tendon size and the radius of the curvature but also of the duct material, the design of the duct wall and duct corrugations, the relative movement of the tendon on the duct wall due to tendon elongation, the duration of the transverse loading and, in particular, of the temperature to which the duct
is exposed. The effects of these parameters have already been discussed in Section 3.2.7 above. As mentioned in Section 3.2.7, the test parameters specified for the performance testing in accordance with this report cover the applications of tendons of up to about 125 metres long. The effect of time is covered by the specified test procedure for the wear resistance under sustained load (Section 6.9 and Annex A.9), where the full transverse load is held over a period of 14 days. The effect of the temperature and the magnitude of the transverse loads are the test parameters from which the polymer duct system supplier can back-calculate the recommended minimum radii of curvature for polymer ducts as a function of tendon size and temperature of duct in order to comply with the specified acceptance criteria.

It should be noted that the test procedures specified in this report (Sections 6.8 and 6.9; Annexes A.8 and A.9) do not strictly apply to looped tendons. However, these test procedures may be modified to check the specific applications of looped tendons with reduced or zero tendon elongation if they are stressed simultaneously from both ends and the clamping force is applicable to the actual radius of curvature.

### 3.3.5 Duct and rebar conflicts

Particular care must be taken during detailing to look at all the potential conflicts of reinforcement with polymer ducts. Such conflicts may occur at the tendon anchorages because of dense local zone reinforcement or may happen when tendons need to cross a plane of reinforcing steel, for example, when they need to cross the plane of stirrups to enter or exit the webs of girders for anchorage in a blister. All these zones need very careful detailing to avoid sharp curvatures in the duct that could cause excessive friction losses, damage or wear to the duct, or local deformations of the duct that could lead to problems when installing the prestressing steel or even to the collapse of the duct during concreting because of the applied concrete pressure.

### 3.3.6 Permanent anchorage caps

Permanent anchorage caps provide an additional level of protection at the anchorage by sealing the anchor head. While the use of temporary grout caps is recommended for all tendons, duct systems and Protection Levels during grouting, permanent anchorage caps are required for PL2 and PL3.

Permanent anchorage caps can be made from different materials. Some specifications require caps made of a fibre-reinforced plastic. Other specifications permit the use of either caps made of polymer material or caps made of metal with a suitable corrosion protection coating. In the opinion of the authors of this report, all these options are suitable and fit for the purpose.

Permanent anchorage caps should ensure a watertight connection with the anchorage for the encapsulation of tendons PL2 and PL3 during the design service life of the structure. The fixation of the cap to the anchorage should be provided with durable means having at least the same design life as the cap itself (e.g. suitable stainless steel bolts).

If used during grouting, permanent anchorage caps should be pressure-rated to remain leak tight during the maximum grouting pressure (service condition) and to provide an adequate safety margin against collapse if the maximum permissible grouting pressure is accidentally exceeded. Suggested pressure ratings for the two above conditions are in the range of 10 bars and 15 to 20 bars respectively.
The designer should specify the use of permanent anchorage caps in the project specifications and whether the permanent anchorage caps shall be cast in or left exposed for PL2 and PL3 tendons. Proper allowance for space and the cover of the permanent anchorage caps should be made in the detailing.

### 3.3.7 Duct joints between precast segments

For PL1, ducts are typically stopped short of the segment faces. There is no continuity of the duct across the joint. The sealing of the joint during concreting is done with special hoses (mandrels) placed inside the ducts and inflated during the casting of the concrete to avoid any ingress of concrete into the ducts. At the time of the erection of the precast segments, the segment joints are sealed with epoxy resin for all applications with internal tendons. Dry joints are not permitted with internal tendons. However, they are permitted in some countries when only external tendons are used.

For all PL2 and PL3 applications, the continuity of the tendon encapsulation needs to extend across segment joints. Such continuity may be provided with special proprietary segmental coupling devices tightly fixed to the polymer duct ends and crossing the segment joint. These coupling devices are subjected to performance testing in accordance with Sections 6.11 and Annex A.11. For PL2 and PL3 applications, the designer must specify the use of segmental coupling devices in the project specifications; segmental coupling devices may also be used for PL1 applications, where specified by the designer. Proper allowance for space and the cover of the segmental coupling devices should be made in the detailing.

### 3.3.8 Electrically Isolated Tendons (EIT)

EIT provides a fairly simple method for the monitoring of tendon encapsulation. The method relies on the measurement of the electrical resistance between the steel tendon inside the encapsulation and the reinforcement or structure outside the encapsulation. This electrical resistance is made up of the resistance provided by the duct and the resistance provided by the grout and surrounding concrete. If the electrical resistance is high, this means an intact encapsulation. If the electrical resistance is low, this means that the encapsulation is compromised to some degree. If the electrical resistance is zero, it means that the prestressing steel is in direct contact with an electrical conductor in the structure, which in most cases will be the reinforcing steel of the structure (potential risk of fretting fatigue). The actually measured value of the electrical resistance normalized to the tendon length allows judgment on the conditions and integrity of the encapsulation. Elsener & Büchler (2011) present the results of the tests on the effect of holes of different size in ducts and of the type of duct connectors/connections.

In general, the electrical resistance of a tendon inside the structure increases over time since the concrete is drying (note that this may not be true in structures immersed in water or for structures in a damp environment). If there is ever a significant drop in the electrical resistance during the design life of the structure, this clearly indicates without any doubt that the encapsulation has been compromised and that humidity or water, possibly contaminated with chlorides, has entered the tendon encapsulation. Hence, the EIT method allows the simple but efficient monitoring of the quality of tendon encapsulation and, hence, tendon protection. It is also an early warning system as the ingress of water is detected long before the corrosion of the prestressing steel is initiated. Figure 3.15 illustrates the steady increase of measured electrical resistance over time due to concrete and grout hydration and drying out (approximately linear increase in double logarithmic scale). As mentioned above, a sudden
significant drop of the measured electrical resistance of a particular tendon is a clear sign of a breach of the encapsulation (see red arrow indicated in Fig. 3.15).

The interested reader is referred to further publications on EIT method and applications such as Elsener (2005), Della Vedova (2006) and Elsener & Büchler (2011).

![Fig 3.15: Typical evolution of electrical resistance of tendon measured on a bridge in Switzerland [Elsener (2005)]](image)

Note: The red arrow in the figure marks a sudden drop of measured electrical resistance, which indicates the entry of water into the encapsulation

EIT tendons and their electrical connections for measuring require special details. The interested reader is referred to ASTRA (2007). EIT monitoring requires at least one electrical connection at one tendon end for measurement. However, if there is a risk of stray electrical currents, it is recommended to equip both tendon ends with electrical connections. With this solution the tendon can be connected to the earth at both tendon ends, if for some reason the electrical resistance of the tendon is compromised. The connection of the earth to both tendon ends eliminates the risk of electrical current entry into and exit from the tendon into the grout or concrete along the tendon length, which could cause hydrogen embrittlement and intensified metal dissolution respectively. These same connections can eventually be used to perform other types of monitoring of the tendons.

Electrical connections at both tendon ends also permit the use of a particular method to locate any defect in the tendon encapsulation in cases where the specified electrical resistance is not satisfied [Elsener & Büchler (2011)]. Hence, connecting both tendons ends is recommended for all applications.

The Swiss guideline ASTRA (2007) specifies three different minimum electrical resistance values for tendons to be considered as EIT with respect to the specified requirements:

1. excluding the metallic contact of prestressing steel to structure (i.e. no fretting fatigue risk)
2. being monitorable (i.e. having a sufficiently high electrical resistance for monitoring of full encapsulation)
3. providing protection against stray currents (i.e. providing sufficiently high isolation to preclude the access of stray currents to the tendons)

The required electrical resistance increases from (1) to (3). However, tendons that do not meet condition (2) or (3) may still be monitored for the effect of the ingress of humidity into the tendon as indicated in Figure 3.15 above. It should be noted that the acceptance values specified in ASTRA (2007) are valid for typical conditions in Switzerland. The same tendon
in a location that has an ambient temperature of about 10 °C higher than Switzerland may provide electrical resistance values of half or less than those measured in Switzerland. A very damp environment may prevent the drying out of concrete; hence, whether the ingress of humidity into the tendon possibly contaminated with chlorides will actually cause a sufficiently significant drop of electrical resistance in such a damp environment still needs to be confirmed by actual applications. Thus, it is important to first collect experience at the intended place of use before setting acceptance criteria for electrically isolated tendons.

EIT testing requires an electrolyte between the tendon encapsulation and the structure. With internal grouted tendons the grout inside and the concrete around the polymer duct perform this role. For external tendons there is no such electrolyte on the outside of the tendon over the majority of the tendon length. Hence, for external tendons the EIT method permits the verification of the encapsulation only in areas where the tendon is in direct contact with the concrete, such as at tendon anchorages and tendon deviators. For the free tendon length, the EIT method will not provide any useful information on tendon encapsulation.
4 Considerations for installation and use on site

4.1 Prior to installation

4.1.1 Project specifications

With reference to this report, project specifications should:

- specify polymer duct systems to comply with this recommendation
- specify the tendon protection level (PL) required for the project
- only specify the use of approved PT systems, components and materials that comply with ETAG 013 (2002) or equivalent specifications
- only specify PT works to be carried out by PT specialist companies that comply with CWA 14646 (2003) or equivalent specifications
- only specify the inspection of PT works by suitably trained and experienced inspectors.

Although not limited to using polymer ducts, the designer should consider the effect of the delayed grouting of tendons while preparing the project specifications. If, for example, the project is located in an area where the temperature may get close to or below freezing, the owner/designer should anticipate the potential need of temporary corrosion protection for the prestressing steel with either water soluble oils or the circulation of dry air in case the grouting must be delayed because of low temperatures beyond the maximum permissible periods specified in standards. Other reasons for delay may apply. These measures should be included in the project specifications for prestressing systems and materials prior to tender, and implemented when required.

4.1.2 Review of project specifications for polymer duct systems

The PT specialist company should review the project specifications and particular requirements for the post-tensioning and polymer-duct systems to confirm whether his/her polymer duct system is suitable and fit for the specific project as initially approved. With relevance to this report, this review should include the expected effects of:

1. hot temperature/sun or cold temperature as applicable for the project
2. concrete pressure during concrete placing as applicable for the project
3. heat of hydration on the polymer duct system at the specified time of stressing.

Selected considerations for these three aspects are provided below.
4.1.2.1 Effects of exposure of ducts to sunlight

Polymer ducts exposed to sunlight may reach temperatures in the duct walls significantly above ambient. Measurements performed by polymer duct suppliers indicate that at approximately 30 °C in ambient temperature, white polymer ducts experience temperatures ranging from ambient to 10 °C higher and black polymer ducts exhibit temperatures ranging from 10 °C to 20 °C higher than ambient (Fig. 4.1). The temperature difference between ambient and duct wall increases with higher ambient temperatures as documented by these measurements. It also seems from these measurements that UV radiation has an effect and that higher UV radiation increases the temperature difference, hence contributing to the scatter of results shown in Figure 4.1. Other duct colours are expected to be within the range of values for black and white ducts.

![Temperature of duct versus air](image)

*Fig. 4.1: Temperature in polymer-duct wall versus ambient temperature*

Temperature variations cause deformations in the ducts. Longitudinal duct deformations, however, are restrained once the polymer ducts are fixed inside the rebar cage of the structure. Since the coefficient of the linear expansion of polymer ducts is 10 to 20 times higher than for reinforcing steel, these restraints can be fairly significant at high temperature variations. Attachments of the polymer ducts to the duct supports, connections/couplers between duct segments and from duct to anchorage or anchorage trumpet need to be strong enough to perform without failure due to restraints/expansion. Any failure, if left undetected, would form a breach in the encapsulation of the tendon.

Polymer duct and connections are tested, in accordance with this report, for such actions due to restraints, using the longitudinal load resistance test (Section 6.4 and Annex A.4). In this performance test, a daily temperature variation of 40 °C in the duct wall was assumed.

The PT specialist should check that the expected conditions for the particular project will be within the range of the polymer duct approval testing and this report, or otherwise take appropriate action for the specific project.
4.1.2.2 Effects of concrete placing

Ducts are subject to outside pressure when fresh concrete is placed. Immediately when the fresh concrete is placed, this pressure is approximately equal to the hydrostatic pressure of a liquid of 24 kN/m³ in density. For conventional concrete, the pressure reduces fairly quickly over the first few hours. However, the pressure can come back locally to a near hydrostatic level in the proximity of a poker/vibrator. For self-compacting concrete, near hydrostatic pressure is reached if the concrete is filled into the forms from the top, and about 10% above hydrostatic is reached close to the valve if the concrete is pumped into the bottom of a vertical formwork. With time, the reduction of the pressure of the self-compacting concrete is delayed when compared with conventional concrete, due to the retarders typically used in self-compacting concrete. Figures 4.2a and 4.2b illustrate the effect of fresh concrete and concrete vibration for conventional and self-compacting concrete.

![Fig. 4.2: Pressure inside fresh concrete according to [Leemann (2003)] and [Leemann (2006)]](image)

Polymer ducts are tested in accordance with this report for concrete pressure when bent to the minimum radius of curvature for field installation (Section 6.7 and Annex A.7). In this performance test, the polymer ducts are subjected to a uniform outside (negative) pressure of 0.75 bars (corresponding to about 3 metres of hydrostatic pressure of normal-weight concrete).

The PT specialist should check that the expected conditions for the particular project (such as the type of concrete and the maximum depth of polymer ducts inside fresh concrete) will be within the range of the polymer-duct approval testing and this report or otherwise take appropriate actions for the specific project. It should also be noted that the reduction of concrete pressure over time depends on the concrete setting and the hydration process, both of which are influenced by the ambient temperature.

As described under Clause 4.1.2.1 above, the polymer ducts may have a temperature significantly higher than ambient when exposed to the sun. Once the formwork is closed for the placing of the concrete, direct exposure to sunlight is, typically, reduced or avoided. As soon as the fresh concrete is placed around the polymer ducts, the duct is expected to adjust quickly to the temperature of the fresh concrete, which is often in the order of 15 to 20 °C. The heat of the hydration of the concrete only develops as the concrete sets and, hence, the concrete pressure will be largely gone (Fig. 4.3). While the behaviour shown in Figure 4.3 was observed for self-compacting concrete, the same also applies for conventional concrete.
Hence, the concrete pressure test specified in this report (Section 6.7 and Annex A.7) is performed at ambient temperature only.

![Graph showing the reduction of pressure and increase of temperature in concrete according to Leemann-2 (2006)](image)

**Fig. 4.3: Reduction of pressure and increase of temperature in concrete according to Leemann-2 (2006)**

4.1.2.3 Effects of heat of hydration of concrete

As explained in Section 3.2.7.3, the temperatures inside concrete may reach peaks of 45 to 55 °C due to the heat of hydration. For very thick members even higher temperatures of up to 70 °C have been observed. Typically, this peak temperature is reached depending on the ambient temperature and the type of concrete mix and cement used, 1 to 3 days after the concrete has been placed. These high temperatures may be critical for the wear resistance of the polymer ducts if early stressing of the tendons is specified such that the timing coincides with the peak of hydration. This may be the case for balanced cantilever bridge construction, where the segments are often cast at the end of the week and the tendons are stressed early on Monday morning.

Polymer ducts are tested in accordance with this report for wear resistance at an ambient and high temperature of 45 °C (Sections 6.8 and 6.9; Annexes A.8 and A.9).

The PT specialist company should check the expected conditions for the specific project, in particular, the time of stressing versus the time of peak heat of hydration. The expected peak temperature at the time of stressing and the actual radius of tendon curvature must be within the range of the polymer duct approval testing and this report, if the time of stressing and the time of the peak heat of hydration coincide. Otherwise, the PT specialist company should take appropriate actions for the specific project. If these fall outside of the experience documented through testing in accordance with this report, partial stressing may be considered or further testing of the particular polymer duct at the expected temperature peak of the project.

4.1.3 Start-up meeting

Passing on all the relevant information on the polymer duct system right at the start of the project to the parties involved in the construction of the project and having interfaces with the installation of the polymer duct system is highly recommended. This may best be done in a start-up meeting with the relevant parties. Information to be passed on includes:
the essential features of the polymer duct system
the differences to the installation of standard metal ducts
points to pay particular attention to
what special checks are to be carried out
the clarification of the line of communication in case of problems

If a company other than the PT specialist company carries out a part of the polymer duct installation, the qualifications and the experience of the personnel have to be assessed and, if necessary, the PT specialist company has to organize and carry out the adequate training of the personnel prior to the start of installation. Such training should be properly recorded.

The start-up meeting may also be the opportunity to discuss concrete placing and the time for tendon stressing, if these are found to be critical during the above mentioned review and if they are not resolved earlier.

4.1.4 Transportation and storage of polymer ducts

Flat duct and small diameter round duct (approximately up to 30 millimetres in diameter) may be supplied on reels without the tensile elements installed (i.e. coiled ducts only). The diameter of the reels has to be sufficiently large to avoid permanent deformations of the coiled ducts (Section 6.5 and Annex A.5 for a flexibility test of the polymer duct system).

Larger-diameter round duct should preferably be supplied in straight pieces in a length adapted to the anticipated transportation means. Typical lengths are between 4 and 12 metres, such as to fit into standard containers. Providing straight lengths of duct segment, assembled inside suitable means for transportation, will allow for stacked storage that does not deform the ducts below. The main issue is to avoid the permanent deformation of the duct in the cross section, which could weaken its resistance to lateral loads during installation or to outside pressure during concreting. Particular caution is warranted if polymer duct shipment and/or storage occur over a long period of time.

Polymer ducts should be stored off the ground so that they do not become soiled or contaminated on the inside with earth or other materials. Polymer ducts and components must be protected against damage, exposure and contamination on reception and until they are used in the structure. If necessary, duct ends may be sealed during shipment, storage, and prior to installation with temporary end caps.

Alternatively, tendons in larger round ducts manufactured in a workshop with polymer ducts and pre-installed tensile elements may be taken to the site in coils. The diameter of the coils has to be sufficiently large to avoid permanent deformation of the coiled ducts and damage to the connectors (Section 6.5 and Annex A.5 for the flexibility test of the polymer duct system). This application is covered in this report. However, coiled round duct larger than 30 millimetres in diameter without tensile elements is not covered in this report.

4.1.5 Project specific PT system documentation

For proper construction and documentation, shop drawings should be prepared that show the actual geometry (size and position) of the post-tensioning tendons installed in the structure. Details of anchorages and couplers, if any, should be documented as well as any particular details for the project. For PL2 and, certainly, PL3 tendons, particular details of the
encapsulation at the anchorages, vents, and of the electrical connections for measurements/monitoring should be documented on shop drawings. In addition, method statements/instructions for the correct installation of PL2 and, in particular, PL3 tendons should be available on site to ensure that the tendons will be fully encapsulated and monitorable after the installation and the placing of the concrete.

Some of the aspects that should be covered by the project specific shop drawings are discussed in the following clauses.

4.1.5.1 Tendon/duct supports

• General:

Tendon or duct supports for polymer ducts need to be carefully detailed to provide a firm and smooth support for the ducts within specified installation tolerances along the tendon length and, in particular, in areas of significant curvature. The ducts need to be firmly tied to the supports to prevent both vertical and horizontal duct displacement during concreting. The ducts should preferably be tied to two orthogonal bars or supports to provide rigid support in space. Simply tying the ducts to the vertical legs of stirrups is considered insufficient to safely prevent vertical movement during concrete placing. In some specifications it is recommended that polymer ducts be tied with plastic strips rather than steel wire to avoid damage to the duct.

Polymer duct approved in accordance with the performance requirements and tests of this report are, in general, sufficiently strong to prevent local transverse crushing/deformation at the tendon supports. The lateral-load-resistance performance test for polymer ducts specified in Section 6.4 and Annex A.4 is performed at a minimum radius of curvature for field installation without half shell duct supports. However, some owners and specifications recommend the use of so-called half-shell duct supports in zones of tight curvature. Such half-shell duct supports are placed between the polymer duct and the tendon support on the inside of the tendon curvature. ASTRA (2007) recommends the use of half shell duct supports wherever the tendon curvature is less than twice the minimum radius of the tendon curvature for field installation (condition (1) in Section 3.3.4 above). Experience with EIT tendons has shown that such half-shell duct supports are highly beneficial in real structures to provide some additional margin of safety against local damage at tight tendon curvature and to comply with the specified electrical resistance.

For structures with significant fatigue actions, such as railway bridges, and for tendons that are monitored with EIT technology, ASTRA (2007) requires the use of half-shell duct supports made of polymer material, in other words, non-metallic.

Whenever such half-shell duct supports are provided, the thickness of the half shells needs to be considered when the height of the tendon supports is detailed and specified in the shop drawings.

• Duct support spacing:

While *fib* Bulletin 7 (2000) specified a performance test for the flexural behaviour of polymer ducts, there was insufficient experience at the time to specify acceptance criteria that would have permitted the use of measured performance to determine actual duct support spacing. This report now specifies a performance test for the stiffness of polymer ducts with acceptance criteria (Section 6.2 and Annex A.2). This
allows the PT specialist company to directly determine maximum duct support spacing so as to comply with the specified test performance. Hence, the shop drawings for the specific project should be prepared with due consideration of the actual maximum duct support spacing as determined in the performance testing specified in this report in accordance with Section 6.2 and Annex A.2.

- **Inlets, outlets, valves and plugs:**
  Grout inlets, outlets, valves and plugs should be made of polymers similar to those of the polymer duct. Vent tubes from inlets and outlets should, in general, have a minimum inside diameter of 20 millimetres. Inlets and outlets should have suitable valves or plugs to properly close and seal the flow of the grout. They can be secured to the polymer duct with either mechanical, welded or shrink-wrap connections. The locations of inlets and outlets should be detailed on shop drawings in compliance with *fib* Bulletin 20 (2002) or PTI/ASBI (2012), or similar recommendations.

  The detailing of tendon inlets and outlets, valves and so forth in the structure should be such as to limit/prevent the risk of damage during installation and construction. Consideration should be given to where to place these vents and whether to have them reach the upper surface of the concrete (with the risk of them being damaged by personnel or equipment moving on this surface), to exit on the side, and so forth.

  This report specifies electrical resistance testing for ducts with and without connectors and inlets, outlets, valves and so forth (Section 7.2 and Annex B.2 for sufficient EIT performance).

- **Duct connections:**
  Duct connections include anchorage-to-duct and duct-to-duct connections. Connections need to be designed and detailed to prevent loosening during concrete placement. For PL 2 and PL3 the duct-to-duct connections need to be leak-tight and able to satisfy the duct system leak tightness test along the continuous length of the tendon as defined in Section 6.6 and Annex A.6 of this report. The anchorage-to-duct connections need to pass the assembly leak test for all PLs (Section 7.1 and Annex B.1; Section 7.3 and Annex B.3 for the EIT performance test for PL3).

  Connections can be made to various designs and are typically proprietary system details. For PL 1 the connections need only prevent the ingress of concrete into the duct at the time of concrete placement and connection devices are typically sealed by means of an appropriate tape.

  At connections more space is typically required in cross section than for the duct alone. Sufficient space and tolerance has to be allowed for this in the detailing of the cross section and reinforcement layout.

  Usually, it will be sufficient to show typical connection details in the shop drawings.

### 4.2 During installation and concreting

#### 4.2.1 Duct supports and half shells

Duct supports should be installed as specified in the polymer-duct system approval and as detailed in the project-specific shop drawings and/or method statements (Section 4.1.5.1).
Where specified in the project specification half-shell duct supports are installed and placed between duct supports and polymer ducts at the inside of the duct curvature.

### 4.2.2 Duct installation

For cast-in-place structures, polymer ducts are preferably either assembled in segments inside the formwork or the entire duct length may be pre-assembled outside the formwork and placed without prestressing steel into the formwork and onto the duct supports, or a combination of both methods. In either case, individual duct segments need to be connected with means specified in the polymer duct system documentation and as specified in the shop drawings or method statements. These means may include the mirror welding of adjacent duct segments, the use of specific duct connectors/couplers or heat shrink sleeves. The prestressing steel may be either installed before or after concreting.

Alternatively, complete tendons with polymer duct and prestressing steel may be pre-assembled in a workshop, placed on reels, shipped to the site and lifted from the coils onto the duct supports in the formwork. This method is particularly suitable for small tendons inside round or flat ducts. This method requires suitable lifting means and particular care during handling to avoid damage to the polymer ducts. Particular attention needs to be paid to the temperature at which the pre-assembled tendons are uncoiled from the reels. Uncoiling of tendons at low temperature close to or below freezing may cause the polymer duct to crack. In such cases, the entire tendon on coils should be warmed up to approximately the same temperature at which it was coiled, or to at least 10 °C, before it is carefully uncoiled.

In the case of segmental cast-in-place construction, the duct sections need to protrude from the previously cast segment to permit the connection of the duct sections of the next segment to the previously placed sections. As with metal duct, these protruding duct sections need particularly good protection to prevent damage prior to the connection of the later duct sections.

In the case of precast segmental construction, specific duct couplers need to be installed during segment erection to provide the leak-tight connection of the ducts (the continuity of the ducts across joints) between adjacent concrete segments for all PL2 and PL3 applications. For PL1, the joints may be sealed with epoxy resin to avoid the ingress of aggressive media into the tendon ducts without actual duct continuity.

It is strictly forbidden to place any loads onto polymer ducts or have personnel walk on them. Such transverse loading may pre-deform the polymer duct to such an extent that it cannot completely recover afterwards, specifically in time for concreting. It should be noted that pre-deformed polymer ducts may have significantly lower resistance to transverse loads such as concrete pressure.

Special care also needs to be taken during polymer-duct system assembly to ensure the leak tightness of the connections of the polymer ducts to the tendon anchorage / anchorage trumpets and for grout inlets and vents for all PL2 and PL3 applications.

As soon as practically possible all duct ends (with or without prestressing steel installed) and grout inlets and vents should be sealed to avoid the ingress of water or contaminants into the ducts up to the time when the prestressing tendon is stressed and grouted.

Polymer duct should be firmly fixed to the duct supports in such a way as to avoid movements (up-lift, lateral and longitudinal) of the ducts prior to and during concreting. In some specifications, polymer strips (and never metal wire) are recommended for attaching polymer ducts for PL2 and PL3.
Particular care has to be applied in zones with rebar congestions, such as tendon anchorage zones or where ducts cross rebar planes, to avoid damage to or deformations of the polymer ducts during the installation of the reinforcing steel and the closing of formwork. This is particularly true for cases where parts of the reinforcement are installed after the installation of the ducts. Pre-deformed polymer ducts have a significantly reduced lateral-load resistance and may collapse or be severely deformed during concreting to such a degree that the installation of the prestressing steel may not be possible afterwards.

It is recommended to carefully inspect the polymer ducts for any damage or deformations prior to closing the formwork, while there is still reasonable access. If visual inspection for duct deformations is not feasible, a torpedo/plunger made of steel, timber or plastic may be pulled through the ducts to detect any significant duct deformations prior to concreting. The correct location of the ducts and the installation tolerances of the reinforcement should also be verified at this time to avoid the risk of the ducts being moved or deformed during the closing of the formwork.

Any welding or flame cutting operation close to or above polymer ducts is prohibited or has to be carried out with the adequate protection of the polymer ducts. Welding sparks may damage the polymer ducts and compromise the leak tightness or electrical isolation.

In round polymer ducts the prestressing steel is preferably installed after concreting. This allows the period between the installation of the prestressing steel, the stressing and the permanent corrosion protection to remain short and thus avoids the risk of corrosion prior to grouting. However, flat ducts are less stiff and, therefore, less resistant to concrete pressure, meaning that the long flat sides may deform during concreting. It may be preferable, therefore, to install the prestressing steel prior to concreting in all flat and possibly small-diameter round duct applications.

For all PL2 and PL3 applications, this report requires the verification of the leak tightness of the installed polymer duct systems on site before concreting with an air pressure test. Any leaks in the duct system may thus be detected prior to concreting and repaired where necessary (Section 7.5 and Annex B.5 for polymer duct system testing).

4.2.3 Concreting

Special care must be exercised during the placing of the concrete to avoid damage to the polymer ducts. Concrete placing methods should be planned and executed such as to avoid concrete mass falling onto ducts, concrete pushing ducts laterally, or vibrators damaging the ducts and connections.

Class-I polymer ducts that comply with this report are tested to external (negative) pressures of 0.75 bars when bent to the minimum radius of the curvature for field installation (Section 6.7 and Annex A.7). Flat polymer ducts may either also comply with Class I or be tested to a lower pressure of 0.25 bars, Class II, and still be acceptable for shallow concrete members such as floor slabs if they are declared as Class II in the system documentation. This pressure of 0.75 bars corresponds to an equivalent hydrostatic depth of liquid, normal-weight concrete of about 3 metres. When it comes to typical normal-weight concrete made with Portland cement at a normal ambient temperature and poured at the typical speed, this limit will cover typical site procedures and methods for concrete placement.

However, attention should be paid if self-compacting concrete or concrete with large amounts of retarder is used. Such concretes may cause pressures higher than the specified 0.75 bars in the performance testing in accordance with this report (Section 4.1.2.2).
Polymer ducts may have a fairly high temperature at the time of concreting in warm climates if the ducts were exposed to the sun just prior to concrete placing. Hence, the ducts may be more flexible due to the elevated temperature when concrete placing starts. Again for this reason, concrete placement should be done with care under these conditions. Once the duct is immersed in fresh concrete it will quickly adjust to the temperature of the surrounding concrete.

4.3 After concreting

As soon as practically possible after concreting, a torpedo/plunger made of steel, timber or plastic should be pulled through all the ducts to confirm that the ducts are free of significant deformations and blockages, if prestressing steel has not been installed prior to concreting.

For precast segmental construction an air pressure test of ducts is specified in this report to ensure that all joints between segments are sufficiently leak-tight after segment erection (Section 7.5 and Annex B.5).

The prestressing steel may now be installed if it was not done prior to concreting. All anchorages with tendon tails should be sealed to prevent the ingress of water or contaminants into the tendons up to the time when the prestressing tendons are grouted.

In particular in the cases of the early-age stressing of tendons inside thick concrete members and with tight tendon radii, tendon stressing should be planned so that the time of the peak temperature of the heat of hydration of the concrete can be avoided (Section 4.1.2.3).

Tendons may be stressed when the concrete has reached the minimum compressive strength specified in the PT system approval documentation or the project specification, whichever is higher. The partial stressing of tendons in stages may be necessary if the minimum concrete strength specified in the PT system documentation is larger than the strength at the time of stressing specified for the project. Tendon stressing should proceed in the sequence specified in the shop drawings and to the maximum tendon forces specified in the project specification. Tendon tails may be cut only after the designer has approved the tendon stressing reports and tendon elongations.

As soon as practically possible after the acceptance of the stressed tendons, within the time period specified in the project specification, the permanent corrosion protection should be applied to all tendons. In Europe, EN 13670 (2009) limits the periods between tendon assembly and grouting to 12 weeks, between tendon installation and grouting to 4 weeks, and between tendon stressing and grouting to 4 weeks, for favourable environmental conditions, that is when there are no chlorides due to de-icing salts or seawater present. In the case of unfavourable conditions, these periods are reduced to a maximum of 2 weeks from tendon stressing to grouting. Per PTI/ASBI M50.3-12 (2012), the time limits between prestressing steel installation and grouting are 7 days in a very damp atmosphere (humidity > 70%) or over salt water, 20 days in a moderate atmosphere (humidity 40 to 70%), and 40 days in a very dry atmosphere (humidity < 40%).

When the time between stressing and grouting exceeds the specified limits, the anticipated temporary corrosion protection means need to be implemented (Section 4.1.1).

The application of permanent corrosion protection implies the injection of cementitious grout into the tendon. The pressure during injection should be monitored and the maximum pressure limited in such a way as to avoid any damage to the concrete cover. This is particularly important in cases with flat ducts, low concrete cover and a low amount of surface reinforcement outside the ducts. The concrete cover has occasionally been observed to spall-off during the grouting of building floor slabs with flat ducts and little or no ordinary
surface reinforcement near the tendon high points or low points, that is, where tendons have minimum cover to the concrete surface.

In any case, the injection pressure should be maintained (not increased) at the end of the injection just sufficiently long enough to verify that the duct system is leak-tight. This measure also assures that the polymer duct has a tight fit against the surrounding concrete at the end of the injection.

As soon as the grout has set, typically the day after grouting, all accessible areas of the tendons should be checked for the complete filling of the tendons with grout [fib 20 (2002)], and corrective measures taken when required.

Finishing works on tendons may then be carried out, such as sealing or protection of the anchorage zones and anchorage recesses, and all vent locations, as detailed in the shop drawings or given in the method statements. While the anchorage recesses of PL1 and PL2 tendons are typically filled with non-shrink grout or mortar, the recesses of PL3 tendons may be filled or may be left open for easier access for EIT measurements and inspection.
5 Material requirements

5.1 General

Since the available experience with polymer ducts for internal bonded post-tensioning is limited to PE and PP polyolefin, the present report specifies required characteristics for these two materials only. This chapter gives requirements and acceptance criteria for polyethylene (PE) and for polypropylene (PP) for ducts, and other system components such as connectors or heat shrink sleeves produced by an extrusion or injection moulding process.

Wherever possible this report focuses on the performance of the fabricated duct system components. Therefore, whenever a performance characteristic is verified by a test on the fabricated duct system component no particular requirement for the material is specified. Rather the responsibility is left with the system manufacturer to design the duct system component with polymer properties and system dimensions so as to comply with the duct system performance specifications. The system manufacturer, however, needs to declare the actual material characteristics and properties with which he can consistently demonstrate compliance with the duct system performance specification.

However, there are some duct system performance characteristics that cannot easily be verified by the testing specified in this report. This applies in particular to the long-term durability performance of polymer materials. Therefore, this report specifies some minimum performance requirements for polymer materials related to durability - oxidation induction time (OIT), environmental stress cracking resistance (ESCR), and only for PE, hydrostatic design basis (HDB). In addition, minimum performance values are specified for notched impact resistance. Hence, whatever the actual material composition and duct system design is, these minimum performance characteristics must be complied with. The specified values have been chosen so as to obtain a material class that has proven an excellent durability for pipes manufactured to high standards in other industries, such as gas pipes and pressure pipes.

The specified characteristics, properties and acceptance criteria for polyethylene and polypropylene may serve as guidance for cases where other materials are intended to be used.

5.2 Material specification, properties and acceptance criteria for PP and PE

Tables 5.1 and 5.2 give the material properties for PP and PE respectively, which are considered relevant for the performance of polymer duct system components for internal bonded post-tensioning tendons. There are two groups of properties:

- Those for which a minimum value is specified for the compliance of all materials (duct performance is not verified)
- Those for which the actual values need to be declared by the manufacturer (no minimum value for material specified by this report, but duct performance is verified)

The tables specify which values need to be declared by the manufacturer and which properties need to comply with the specified minimum value.
Tables 5.1 and 5.2 make reference to ISO and ASTM standards for the test procedures of the actual material characteristics. The manufacturer can choose either the ISO or the ASTM standards. Testing needs to be performed only to one standard for each characteristic. It should be noted that the actual test procedure has an effect on the measured performance. Therefore, test methods other than those specified may only be used if the correlation or safe relationship between the results of these other test methods and the methods referenced in this chapter has been established.

Tables 5.1 and 5.2 also specify whether a particular property is determined on one of the following:

- The resin / raw material of PP or PE
- The compound of PP or PE resin with all additives, stabilisers and master batch (colour) mixed in the proportions as intended to be used for the component manufacture (compound test)
- The fabricated duct system component (duct test) or both

Where practically feasible the property is determined on specimens taken from the manufactured duct. Where this is considered not feasible because of the geometry of the specimen and the duct corrugation, material testing on test samples produced from the compound is specified. Only for HDB, testing on the resin is specified.

Tables 5.1 and 5.2 additionally specify what property has to be determined or declared:

- For initial approval of the polymer duct system:
  These properties have to be determined on each compound material batch for the duct system components used in the duct component or system tests. However, test specimens of one particular duct size or component for approval testing should be made from one and the same batch of compound.
- During factory production control (FPC):
  These properties have to be determined on each compound material batch.
- For the polymer duct system delivery certificates:
  For each delivery of polymer duct system components, a material certificate should be prepared that includes the values of the properties from the testing done for FPC or from audit testing (for the particular compound batch) as noted in Tables 5.1 and 5.2. Alternatively, a declaration of conformity by the manufacturer that all the requirements of this report have been met may be provided if permitted in the project specification or under the regulations in the place of use.

Notched impact testing should be performed at both specified temperatures (i.e. 23 °C and 0 °C) independent of the region or climate where the duct is to be used. These tests are considered to confirm the robust behaviour of the material over the specified temperature range.

It should be noted that it may be difficult or impossible to cut test specimens from fabricated polymer duct samples for some types of tests, such as tensile yield strength and
elongation at break testing, because of the specified size and shape of test specimens. This is particularly the case for small diameter ducts and for narrowly spaced duct corrugations. The authors of this report have considered producing samples from manufactured duct by grinding duct material and moulding it into test samples. However, even if done by the same laboratory with identical equipment and procedures the test results are expected to show large scatter and, therefore, to be difficult to compare with tests performed on the compound material or tests performed on such samples at an earlier time. Therefore, this report specifies these tests to be performed on test samples produced from the compound (compound test) either by the injection moulding, extrusion or compression moulding of plates from which the test specimens have been cut. While test specimens produced in this way will not exactly produce the same properties as would be determined on specimens cut from the manufactured duct, the authors believe that this approach will allow good control of the polymer material used for duct manufacture.

In the case of problems on site, where the performance of the polymer duct used on site should be verified and compared with the performance determined during approval, FPC or audit testing, the comparative testing of the performance of the duct system components is recommended. In addition, the grinding of duct material from the site to produce test specimens for material testing may be considered in this case. However, some difference in properties must be expected with such specimens compared to specimens cut from manufactured ducts or produced from the original compound and, therefore, results should be validated by comparative testing.

The authors of this report consider the hydrostatic design basis test (HDB) as not directly related to or relevant for the performance of ducts for internal bonded tendons. In addition, HDB testing takes much time and is expensive. However, it is believed that the materials meeting a certain minimum hydrostatic design basis will have overall good performance and durability. Since this value is readily available for PE, this report specifies a minimum performance for HDB that, however, may be verified based on data sheets of the resin (raw material) for PE only.

Some values of test parameters are not specified in the referenced standards either because these standards refer to product standards (which do not exist for polymer ducts for internal bonded tendons) or because these test standards leave this parameter for agreement between client and laboratory. For notched impact testing, the test parameters are specified in Tables 5.1 and 5.2. For other types of material tests, the actually applied test parameters should be declared in the test reports.

Section 5.5 provides some background information on the specified test methods.
Table 5.1: Properties and acceptance criteria for PP

<table>
<thead>
<tr>
<th>Property</th>
<th>Standard for test procedure</th>
<th>Unit</th>
<th>Acceptance criteria</th>
<th>Duct approval testing ¹⁾ (Section 8)</th>
<th>FPC ²⁾ (Section 9.2)</th>
<th>Audit testing ³⁾ (Section 9.3)</th>
<th>Duct delivery certificate</th>
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<tr>
<td>ESCR (Condition C)</td>
<td>ASTM D 1693</td>
<td>Hours</td>
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<td>Duct test</td>
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<td>Duct test</td>
<td>Declaration of conformity by manufacturer or material certificates with values from FPC</td>
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<td>J/m</td>
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<tr>
<td></td>
<td>ASTM D 256 @0°C</td>
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</tr>
<tr>
<td></td>
<td>ISO 179-1/1eA @23 °C</td>
<td></td>
<td>≥ 22</td>
<td>Compound test</td>
<td>Compound test</td>
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<td><strong>II: Properties for which values need to be declared by manufacturer (plus additional general requirements of Section 5.3)</strong></td>
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<td>g/cm³</td>
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<td>Duct test</td>
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<td>Compound test</td>
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<tr>
<td>Elongation at yield and at break</td>
<td>ASTM D 638</td>
<td>%</td>
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<td>Compound test</td>
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Note: Test frequencies = ¹⁾ for each compound batch used in approval testing; ²⁾ for each production batch of compound; ³⁾ 1/audit
Table 5.2: Properties and acceptance criteria for PE

<table>
<thead>
<tr>
<th>Property</th>
<th>Standard for test procedure</th>
<th>Unit</th>
<th>Acceptance criteria</th>
<th>Duct approval testing</th>
<th>FPC</th>
<th>Audit testing</th>
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<td>ESCR (Condition C)</td>
<td>ASTM D 1693</td>
<td>Hours</td>
<td>≥ 600</td>
<td>Duct test</td>
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<td>Notched impact</td>
<td>ASTM D 256 @23 °C</td>
<td>J/m</td>
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<td>Compound test</td>
<td>Compound test</td>
<td>Declaration of conformity by manufacturer or material certificates with values from FPC</td>
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<td>HDB (hydrostatic design basis) or MRS</td>
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<td>Density</td>
<td>ASTM D 1505</td>
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<td>Elongation at yield and at break</td>
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<td>%</td>
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<td>Not required</td>
<td>Not required</td>
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</tbody>
</table>

Note: Test frequencies = ¹ for each compound batch used in approval testing; ² for each production batch of compound; ³ 1/audit5.3
5.3 Additional general material requirements

The following additional general requirements apply to all polymers used for ducts for internal bonded tendons and need to be certified by the manufacturer:

- Material to be produced from virgin resins only:
  The manufacturer should certify compliance with this requirement for each supply of duct system components.

- Material to be stable against UV for intended use:
  It is assumed that the manufactured ducts and components are sufficiently resistant against UV during transport and storage. If left unprotected over extended periods, the question of UV stability may have to be addressed [e.g. EOTA TR 010 (2004)]. For black ducts, a carbon content of $\geq 2\%$ has proved to provide sufficient durability. For other colours, other means of UV protection or stabilization will be required.

The following additional requirements are often specified for the polymers used for duct system components:

- Material to be corrosion-resistant and durable:
  This requirement is complied with when using PE and PP materials as specified in this report.

- Material to be free from chlorine and chlorides:
  This requirement is complied with when using PE and PP materials as specified in this report. Note that PVC is not permitted since it may release chlorine in elevated temperature.

- Material to be non-reactive with prestressing steel, grout and concrete:
  This requirement is complied with when using PE and PP materials as specified in this report.

5.4 Material specifications for other polymers

The use of any other material than those covered under this report should be governed by a specific agreement between the owner of a project or his representative and the duct system manufacturer. The duct system manufacturer should submit the general material characteristics, performance requirements and acceptance criteria to be complied with for approval to the owner or his representative. The above specified characteristics, properties and acceptance criteria for polyethylene and polypropylene may serve as guidance for such other materials (as may the performance requirements contained in this report). Other materials may include composites, polyamides, and so forth. However, compliance and conformity to this fib report cannot be claimed for such other materials.
5.5 Background information on specified test methods

This section provides some general information on the test methods specified in this chapter. The interested reader is referred to the referenced standards for more specific information on the actual test method, test specimen, test procedure and measurements.

- OIT – oxidation induction time:
  A valuable characterization test for assessing the long-term stability of polyolefin materials; oxidative degradation, oxidation stability; the effectiveness of anti-oxidant agents. Differential scanning colorimeter (DSC) equipment measuring the heat flow into and out of the heated specimen provides test results that can be evaluated. Test results may include: glass-transition temperatures $T_g$, DSC peak melting temperatures $T_m$, crystallinity and specific heat capacity.

- ESCR – environmental-stress cracking resistance:
  Environmental-stress cracking is the formation in a material of cracks caused by relatively low tensile-stress and environmental conditions. The test result is the number of hours at which 50% of the specimens tested exhibit stress cracks. Excellent polyolefin material reaches results in excess of 1,000-1,500 test hours. All PE material is required to be tested for ESCR and although some types of PP are considered to be non-sensitive to environmental-stress-cracking testing, it is nevertheless recommended to cover all types of PP and possible blends. Please note that parties should consider in the project logistics that the specified acceptance criteria result in a testing duration of 600 hours, in other words, a minimum of 25 days after duct fabrication. Hence, ESCR results may be supplied at the earliest one month after duct fabrication.

- ESCR testing to ASTM F 2136 has been proposed in some recent specifications as a more rigorous test method, giving more reproducible results and a significantly shorter test duration than testing to ASTM D 1693. However, the authors of this report had no experience with this standard and, therefore, were unable to specify acceptance criteria. As mentioned in Section 5.2, test methods other than those specified in Tables 5.1 and 5.2 may be used if the correlation or safe relationship between the results of these other test methods and the methods referenced in this chapter has been established. This concept may be applied to ESCR testing to ASTM F 2136.

- Notched impact:
  The Charpy impact test, also known as the Charpy V-notch test, is a standardized high strain-rate test that determines the amount of energy absorbed by an injection-moulded specimen (Note: specimens produced by extrusion or compression moulding are also considered acceptable for the intent of this report) during fracture. This absorbed energy is a measure of a given material's notch toughness and acts as a tool to study temperature-dependent ductile-brittle transition. It is widely applied in industry since it is easy to prepare and conduct, and can give results quickly. A disadvantage is that some results are only comparative.

- Izod impact testing is a method of determining the impact resistance of an injection moulded specimen (Note: specimens produced by extrusion or compression moulding are also considered acceptable for the intent of this report). An arm held at a specific height (constant potential energy) is released. The arm hits the sample and breaks it. From the energy absorbed by the sample, its impact energy is determined. A notched sample is generally used to determine impact energy and notch sensitivity.
The test is similar to the Charpy impact test but the sample is held in a cantilevered beam configuration, as opposed to a three-point bending configuration in the Charpy impact test.

- **HDB – hydrostatic design basis:**
  It offers valuable confirmation of the stability of thermoplastic pipes against constant internal pressure, under constant temperature in the range of 20 to 80 °C. This is a typical property and value to be determined by the raw material supplier for the material classification rating of a new raw-material type prior to market introduction. According to ISO, this method is called MRS.

- **MFR – melt mass-flow rate (also MVR – melt volume-flow rate):**
  MFR and MVR are a measure of the ease of flow of the melt of a thermoplastic polymer at a certain temperature. It is defined as the mass of polymer, in grams or cm³, flowing in ten minutes through a capillary of a specific diameter and length by a pressure applied via prescribed alternative gravimetric weights for alternative prescribed temperatures. MFR and MVR are very commonly used for polyolefins, polyethylene being measured normally at 190 °C and polypropylene normally at 230 °C. The manufacturer should choose a material with a melt index so high that he/she can easily form the polymer in the molten state into the article intended, but on the other hand so low that the mechanical strength of the final component will be sufficient for its use.

- **Density:**
  Density is the mass per unit volume. Density provides a quality control measurement to verify the raw-material manufacturer-data-sheet value against the delivered raw material. It is also a quality-control measurement to verify that the final duct product value is close to the delivered raw-material value. A small variation versus the delivered raw-material value confirms a good production process with small material property variations. There are three methods given in ISO 1183-1. Method A (immersion method) seems to be particularly suitable for polyolefin.

- **Flexural modulus:**
  Flexural modulus is an essential factor in the determination of the stiffness of injection-moulded specimens (Note: specimens produced by extrusion or compression moulding are also considered acceptable for the intent of this report). The flexural test measures the force required to bend a beam under 3-point-loading conditions and hence provides the flexural stiffness. The data is often used to select materials even for parts that will not support flexural loading. The flexural test result is a plot of load versus displacement or stress versus strain. From this data, a number of properties can be calculated such as flexural modulus, flexural strength, flexural yield strength and flexural yield strain.

- **Tensile yield strength, elongation at yield and at break:**
  Tensile properties are an important aspect of qualifying a compound or polymer resin. The tensile tests measure the force required to yield a specimen and the extent to which the specimen stretches or elongates at yield and at the breaking point. Tensile tests produce a stress-strain diagram that is used to determine the tensile modulus. Specimens are injection moulded from compound (Note: specimens produced by extrusion or compression moulding are also considered acceptable for the intent of this report) into a special form of bars or strips, gripped in the test equipment and pulled under specified loading speed until failure. An extensometer is
applied in the test equipment to determine the elongation. Data that can be derived from this test include: tensile strength (at yield and at break); modulus of elasticity; elongation and percentage elongation at yield and at break. The tensile test result is a load-versus-deformation or stress-versus-strain curve.

- Thermal expansion coefficient:

  The thermal expansion is the change in length of an injection-moulded specimen (Note: specimens produced by extrusion or compression moulding are also considered acceptable for the intent of this report) exposed to a given temperature change. The thermal expansion coefficient is the ratio of the reversible expansion caused by the applied temperature variation divided by the original length of the specimen and the applied temperature variation.

As mentioned in Section 5.2, some test standards offer several options for test methods. Where the option/method to be used is not specified in Tables 5.1 and 5.2, the duct manufacturer should declare the actually used test method/option in the test report.
6 Component requirements

This chapter presents requirements, reasons, and explanations for the essential aspects of the polymer-duct-system testing including components. Assessment (testing) procedures for duct and duct components are shown in Annex A. These assessment procedures should preferably be used as part of a system approval process as accepted by an approval body and can be adapted into future testing standards. Additionally, project engineers may require some of the testing procedures for project specific acceptance/suitability requirements.

Each of the following sections discusses one essential aspect of polymer-duct-system testing and corresponds to an assessment procedure in Annex A. Material properties and dimensions, in particular, duct thicknesses, must be consistent and uniform throughout the complete range of tests; future auditing must confirm that the material properties and dimensions used in production conform to those used for testing. The discussion will centre on the requirements, reasons and explanations showing why the aspect is important for assessment. These sections give designers, and others, information for a better understanding of the essential aspects to be evaluated prior to approving any polymer-duct system.

6.1 Dimensional requirements

Assessment (testing) procedures are shown in Annex A.1.

Duct and connectors including connection details must be completely defined in terms of geometry, tolerances, and materials, just like any part of a post-tensioning system. Key dimensions of duct and connectors, as applicable, should be declared in the manufacturer’s documentation. Tolerances of parts should be adequately limited to assure proper fit over the design range of temperature variations and should be within the range specified on the duct manufacturer’s drawings.

Duct and connector design should be suitable for the proper assembly, installation, stressing, and grouting of the post-tensioning system. For a particular post-tensioning application, the internal dimensions of the duct and connectors should comply with minimum area requirements based upon a ratio of a cross-sectional area of prestressing steel to duct or a minimum clearance from the prestressing steel to the duct as identified in applicable codes.

Confirmation is required for all the assessment procedures in Annex A that test specimens used in testing conform to the stated dimensional tolerances of the manufacturer’s drawings. Material properties and dimensions/thicknesses must be consistent and uniform throughout the complete range of tests and must be identified for each test. The procedures shown in Annex A.1 can be used to confirm that the production material received meets the tolerances shown in manufacturer’s drawings.

When preparing the test specimens one should be aware that cross sections may deform after the cutting of the duct due to residual stresses. Such possible effects have to be taken into account.

There may be critical or important dimensions for certain components other than those specified for ducts in Annex A.1. Such other critical or important dimensions should then be identified and included in the test programme according to Annex A.1.
6.2 Stiffness of duct

Assessment (testing) procedures are shown in Annex A.2.

The stiffness of the duct is used to determine the maximum permissible spacing of duct supports. Duct supports establish the profile of the tendon that, in theory, should be a smooth curve for draped tendons or a smooth line for straight tendons. Workers installing tendons would like the supports as far apart as possible to save time and costs while designers want supports closely spaced to make sure that tendon forces meet the design requirements, in other words, so that friction losses are within the assumptions made by the designer.

Ducts will deflect between supports. This deflection becomes part of the wobble coefficient that designers use to determine tendon forces. The straighter and smoother the tendon profile is, the less actual wobble. Limiting support spacing to values resulting in a maximum allowable net duct deflection of L/500 between supports will provide the design professional with assurance that the wobble created by the duct deflection between supports is controlled.

There is a trade-off to be considered when designing polymer ducts for post-tensioning. By making the duct stiffer, fewer supports are needed; however, this possibly makes the duct more costly or affects other performance criteria [the increased wall thickness may reduce the compressive strength of members with ducts and bond strength (Sections 3.2.8 and 3.2.9 respectively)]. If the duct is less stiff, there may be duct cost benefits but more installation costs because of more supports. Duct stiffness can be affected by material properties, dimensions/thickness and the spacing and magnitude of corrugations.

Applied loads that include the weight of the duct and duct buoyancy between supports will cause the duct to deflect. Duct deflection will reduce with increased duct stiffness. Mainly due to the effect of corrugations, the stiffness of a corrugated polymer duct may not be determined accurately enough based on the nominal duct diameter and specified material properties. It is therefore proposed to measure the actual flexural stiffness (EI) of the duct in a test under well-defined conditions. This measured duct stiffness is then used to determine a maximum duct support spacing such as to limit the duct deflection under a nominal load to an acceptable value. This report uses the duct buoyancy when immersed in concrete as the applied load and limits the deflection to 1/500 of the duct support spacing in the end span of a 4-span continuous beam, uniformly loaded in all spans. Another factor is the pre-loading of prestressing steel. When prestressing steel is installed in the duct prior to concreting, its weight can counterbalance some or all of the duct buoyancy forces and it stiffens the duct. However, testing in accordance with this report is done without consideration of the pre-loading of prestressing steel unless the duct to be used EXCLUSIVELY with pre-loaded strands (this may for example apply to flat ducts).

The maximum permissible duct support spacing may be determined in two steps as follows, based on the flexural stiffness $(E*I)_{eff}$ determined according to Annex A.2:

Step 1: Determination of net duct force (DF) – *Note that duct corrugations are ignored for net duct force calculations.*

- Net duct force per unit length ‘DF’ shall be determined by the following equation for round duct:
  \[
  DF = \left( \pi * r^2 * w_c \right) - w_d - w_{pre}
  \]
  Where:
  \[
  r = \text{radius of outside diameter of duct}
  \]
• Net duct force per unit length ‘DF’ shall be determined by the following equation for flat/oval duct:

$$DF = (A \times w_c) - w_d - w_{pre}$$

Where:
- $A$ = area of duct
- $w_c$ = unit weight of normal weight concrete
- $w_d$ = mass of duct per length
- $w_{pre}$ = mass of pre-loaded prestressing steel per length (zero if not pre-loaded prestressing steel).

**Step 2:** Determination of maximum support spacing (SS) – *Note that maximum allowable deflection between supports is $L/500$.*

• Maximum support spacing ‘SS’ shall be determined by the following equation:

$$SS = \left[\frac{(154 \times (E \times I)_{eff}}{(500 \times |DF|)}\right]^{1/3}$$

Where:
- $(E \times I)_{eff}$ = Effective stiffness (as determined in Annex A.2, Clause A.2.3.5)
- $|DF|$ = Absolute value of net duct force per unit length.

In practice, the maximum spacing of duct supports has often been limited to about 10 to 12 duct diameters in cases where the prestressing steel is not preloaded even for ducts with a larger SS as determined above. In cases where the prestressing steel is preloaded, a slightly larger maximum spacing of duct supports may be acceptable.

**6.3 Longitudinal load resistance of duct system**

Assessment (testing) procedures are shown in Annex A.3.

There are two situations that this test examines:

- duct systems for tendons assembled on site
- prefabricated tendons (polymer ducts with tensile elements) assembled in the workshop and shipped in coils.

All applications must comply with the requirements for the first situation; prefabricated tendons must comply with the requirements for both situations.

All applications of duct systems must have adequate longitudinal load resistance to maintain continuity and integrity prior to concrete placement. The duct, and in particular
connectors between duct segments, and connections between duct and anchorage trumpets (see system tests in Chapter 7 and Annex B for the testing of connections to anchorages), should be sufficiently strong to resist restraint and movement caused by temperature variations that will occur on site after the field installation of duct and prior to the concrete placement.

To confirm the adequacy of the duct system assembled on site, the duct and connectors are stretched to achieve an elongation equal to 40 °C in temperature difference multiplied by the coefficient of the linear expansion of the actual polymer used multiplied by the specimen length. Prefabricated tendons (ducts with tensile elements) are in addition tested under a specified load when supplied on coils. The intent of the stretching and load application is to simulate the temperature movement and effects of coiling and, ultimately, to confirm that the connectors remain leak-tight (Annex A.6 for assessment procedure).

Assessment procedures for the longitudinal load resistance of the duct system determine whether the duct system can maintain the applied elongation and/or the specified load during the test period without the failure of the duct or the slippage of the connection.

It should be noted that the mirror-welding of ducts is not considered a ‘connector’ in this report and, hence, is not considered a part of the duct system approval process. Mirror-welded duct connections may be assessed as part of the project quality control in accordance with stay cable recommendations by the PTI and the fib or in accordance with DVS 2207 or equivalent standards and recommendations.

6.4 Lateral load resistance of duct

Assessment (testing) procedures are shown in Annex A.4.

The duct should be sufficiently strong to resist damage due to curvature and concrete loads at the support points. When tying the duct into a profile, a load is typically applied at the support points due to the bending of the duct. Additionally, the pressure of concrete on the duct will force the duct against the supports. If the duct deforms around the support (local indentation), there may be issues when installing prestressing steel or stressing the tendon.

Assessment procedures for the lateral load resistance of the duct confirm that the duct will not sustain irreversible transverse deformations of 10% of the duct diameter or 5 millimetres, whichever is smaller, after the release of the specified load. This is the same performance criterion that is used in EN 523 (2003) for flexible metal duct without stiffeners.

In addition, assessment procedures for the lateral load resistance of the duct now also confirm that the duct will not immediately deform excessively under an applied load, namely no more than 35% of duct diameter. Since it is recognized that the loads specified in EN 523 (2003) are rather high for small diameter ducts (even for metal ducts without stiffeners), the performance for deformation under an applied load is verified at 50%, 67% and 100% of the specified load for duct diameters < 85 millimetres, 85 to 100 millimetres, and > 100 millimetres respectively.

6.5 Flexibility of duct system

Assessment (testing) procedures are shown in Annex A.5.

The duct should be flexible enough to allow bending to a radius of curvature that will be used during shipping or in the field. The duct must be able to be bent to the radius of the curvature for the profiling of the tendon during installation on site. Where post-tensioning
ducts will be preassembled with prestressing steel in the factory for shipping to the jobsite, the duct must be flexible enough to allow coiling on reels to occur and to fit onto a truck for shipping. Duct connectors must also remain intact when the duct system is bent to the radius on the coil or on site.

When the duct system is bent to the specified radius of curvature (either in coil or on site), the deformation of the duct cross-section should not exceed 5% of the internal duct diameter to allow for the installation of prestressing steel in the field and to confirm that the tendon will remain within the profile envelope for the tendon. **Note that flat or oval ducts are tested in the direction for which they are conceived to be bent on site or during shipping in coils.**

Assessment procedures for the flexibility of the duct system confirm that the deformation of the duct cross section does not exceed 5% for a specified radius of curvature for shipping or field use, thus confirming that the duct system does not collapse in on itself. Additionally, assessment is made at room, low and high temperatures. At low temperatures polymers can become brittle and bending can fracture the duct or connectors and at high temperatures the polymer duct may not maintain its shape.

### 6.6 Leak tightness of duct system

Assessment (testing) procedures are shown in Annex A.6.

The duct system when in its final condition for PL1 applications must be mortar tight (similar to steel duct) and for PL2 and PL3 applications must be leak-tight. This means that after exposure to shipping, jobsite handling, installation and concreting the duct and connectors should be mortar/leak-tight. Thus, assessment for mortar/leak tightness is performed on the same test specimen that has successfully passed longitudinal load, lateral load and flexibility testing. Leak tightness is an important feature of polymer duct systems and is an essential requirement for PL2 and PL3 applications.

For mortar tightness, the duct system is bent to the specified minimum radius of curvature for field installation and a positive pressure is applied to a water column within the duct for a specified duration with a minimum amount of water leakage.

For leak tightness, the duct system is bent to the specified minimum radius of curvature for field installation and a positive pressure is applied to the specimen in a water tank for a specified duration. Then the same specimen is exposed to negative pressure in a water tank for a specified duration. These tests are to simulate field conditions and no water expulsion or infiltration is allowed.

Assessment procedures for the leak tightness of the duct system confirm that the duct and connectors remain mortar-tight for PL1 applications and leak-tight for PL2 and PL3 applications.

### 6.7 Concrete pressure on duct

Assessment (testing) procedures are shown in Annex A.7.

Post-tensioning ducts are exposed to pressure that can collapse the duct when concrete is placed. The duct system when in its final condition must be able to withstand this concrete pressure so that the tendons can be properly placed and/or tensioned. This assessment is required for all tendon protection levels.

The concern is that the polymer-duct system may collapse in on itself and not allow prestressing steel to be installed and tensioned or, in the case of pre-installed tendons, not
allow tensioning. This report specifies two performance classes, I and II. Performance Class I applies to polymer ducts for general use and specifies that the duct system should maintain a minimum of a 3.0 metres in normal-weight concrete head pressure for all types of duct and sizes when bent to the specified minimum radius of curvature for field installation. The 3.0-metre dimension is the commonly accepted maximum height for hydrostatic pressure in conventional normal-weight concrete placed at an ambient temperature and for a relatively slow placement. Concrete further away from the placement front will start to harden and thus not apply hydrostatic pressure on the duct (Chapter 4). The specified 3.0-metre hydrostatic pressure may, however, be exceeded at a low temperature and/or high speed of concrete placement and/or with the use of self-compacting concrete, that is, the specified concrete pressure in Annex A.7 may be insufficient for some applications in practice.

Performance Class II applies to polymer ducts used exclusively in shallow concrete members such as floor slabs and specifies that the duct system should maintain a minimum of 1.0 metre in normal weight concrete head pressure. It is believed that this Class II may apply primarily to some types of flat polymer ducts. The relevant performance class shall be declared in the polymer duct system documentation.

Assessment procedures for concrete pressure on a duct system confirm that the duct will not collapse in upon itself when exposed to a specified concrete head pressure when bent to the specified minimum radius of curvature for field installation.

6.8 Wear resistance of duct

Assessment (testing) procedures are shown in Annex A.8.

The duct should be sufficiently resistant to wear caused by prestressing steel during the stressing of the tendon when bent to the minimum specified radius of curvature for field installation. This is extremely important for the long-term performance of the duct and the durability of the post-tensioning tendon. If the prestressing steel wears through the duct wall, friction coefficients used in design may be non-conservative. The wear of the duct will be affected by material properties and blends. Temperature also affects the wear of polymer ducts and must be evaluated. If the prestressing steel should wear through the duct during stressing, the integrity of the tendon’s protective envelope will be destroyed. There may also be a risk of fretting fatigue for the tendon if the prestressing steel comes into contact with metal at the worn duct section (either because it is in contact with a metallic duct support or reinforcing steel).

In order to maintain the integrity of the duct envelope, a minimum residual duct wall thickness must remain in place after the stressing of the tendon. The minimum residual wall thickness varies based upon the tendon protection level and is specified so that there is an inherent safety factor. The following identifies the minimum residual duct wall thickness after simulated stressing of the tendon:

- For PL1, minimum residual wall thickness after testing is 1.0 millimetres
- For PL2 and PL3, minimum residual wall thickness after testing is 1.5 millimetres

A profiled tendon will apply a force and relative displacement to the duct at points of tendon curvature. During testing a specified force is applied as a clamping force on a single strand to a duct specimen and the single strand is moved on the polymer duct to simulate the
stressing of the tendon. The clamping force is gradually increased with the strand movement to reach the specified force \( Q \) when the full strand movement will be attained.

The clamping force applied to the single strand in the test may be related to the actual size of the tendon (number of strands), the stressing force and the tendon radius of curvature according to the following method:

- Clamping force \( Q \) is given by the following equation:
  \[
  Q = 0.7 \times F_{pk} \times A_p \times k \times l / R_{min}
  \]
  Where:
  \( F_{pk} \) = specified 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 (strand) inside one duct, according to Figure 6.1 [Oertle (1988)]
  \( n \) = number of tensile elements in tendon
  \( l \) = length of test specimen (duct strips)
  \( R_{min} \) = manufacturer’s declared minimum radius of tendon curvature for field installation.

![Fig. 6.1: Cable factor according to Oertle (1988)](image)

- Alternatively, the clamping force \( Q \) may be considered according to Weiher (2008):
  \[
  Q = 0.7 \times F_{pk} \times A_p \times (2 \times n \times \varnothing / d_1) \times l / R_{min}
  \]
  Where:
  \( \varnothing \) = nominal diameter of strand
  \( d_1 \) = internal duct diameter
  All other terms are as given above for the Oertle method.
It should be noted that when using a tendon with a filling ratio outside of range 0.35 to 0.45 the cable factor as proposed by Weiher (2008) is recommended. It should also be noted that Figure 6.1 may provide non-conservative values for the cable factor for small tendon sizes in round duct with less than about 5 tensile elements because of several possible configurations for the staggering of the individual tensile elements on top of each other.

Based on successful wear testing having applied an actual clamping force \( Q \), the suitability in an actual project of polymer ducts that are not completely filled with the maximum possible number of tensile elements can be confirmed by maintaining the calculated clamping force of the project smaller or equal to the actual clamping force \( Q \) in the test.

Testing must confirm that the minimum residual wall thickness remains after stressing at the specified normal and high temperatures that the duct may experience during stressing. Elevated temperature can significantly affect the wear of polymer duct. These elevated temperatures can occur because of early stressing while the concrete may still be at an elevated temperature due to the heat of hydration or due to the environment in which the structure is located.

Assessment procedures for the wear resistance of duct confirm that a minimum residual wall thickness remains after a simulation of the stressing movement of 750 millimetres, which is the approximate extension of a 125-metre long tendon made of strands during a test where stressing occurs from one end. Supplemental testing can be performed to simulate a shorter or longer tendon and/or a different temperature.

The specified test is performed with a strand of 15.2 or 15.7 millimetres in nominal diameter; however, it is also valid for smaller diameter strand. The minimum radius for tendons with smaller diameter strand should be assumed to be the same as that which is determined for specified strand diameters of the same nominal ultimate tendon strength.

While the specified test is performed with strand, it is also valid for wire tendons. The minimum radius for wire tendons should be assumed to be the same as that which is determined for strand tendons of the same nominal ultimate tendon strength.

Bar tendons are not covered by this report since there are several differences, such as lower typical extension, different clamping forces due to bending stiffness of bars and more aggressive wear by ribbed bars. However, in practice straight bar has been used successfully in polymer ducts in several countries.

6.9 Wear resistance of duct under sustained load

Assessment (testing) procedures are shown in Annex A.9.

The duct should be sufficiently resistant to the wearing through caused by prestressing steel during the time between the stressing and grouting of the tendon, when it is bent to the minimum specified radius of curvature. Again, this is extremely important to the long-term performance of the duct and the durability of the post-tensioning tendon. The wearing through of the duct will be affected by material properties and blends. Temperature also affects the wearing through of polymer ducts and must be evaluated. If the prestressing steel should wear through the duct prior to grouting, the integrity of the tendon’s protective envelope is destroyed.

In order to maintain integrity of the duct envelope, a minimum residual duct wall thickness must remain in place prior to the grouting of the tendon. The minimum residual wall thickness varies based on the tendon protection level and is specified so that there is an inherent safety factor. The following identifies the minimum residual duct wall thickness after the simulated
stressing of the tendon and the maintenance of the tendon force for the specified period of time:

- For PL1, minimum residual wall thickness after testing is 0.5 millimetres
- For PL2 and PL3, minimum residual wall thickness after testing is 1.0 millimetres

Tendons are typically grouted within 14 days of stressing; however, prior to the grouting of the tendon, the prestressing steel continues to apply a sustained force to the duct at points of tendon curvature. This sustained force $Q$ is the same as that used for wear testing and is applied to the same test specimen for 14 days. Temperature continues to play a role in the wearing through and test specimens are tested at a specified normal and high temperature.

Assessment procedures for the wear of the duct under a sustained load confirm that a minimum residual wall thickness remains after simulation of a stressed tendon being in place for 14 days prior to grouting for a specified minimum radius of curvature and a specific material blend at a specified temperature.

6.10 Bond behaviour of duct

Assessment (testing) procedures are shown in Annex A.10.

The duct should have the ability to provide sufficient bond with the concrete outside and the grout inside the duct. The designed duct should allow a structural engineer to design post-tensioned members for particular applications of the structure under service and ultimate conditions using the conventional design assumptions for bonded tendons. Based on experience, this may be assumed if the tendon-force increase from effective force to ultimate force (about 40% of tendon ultimate strength) can be transferred within a length of 16 duct diameters.

For the testing in accordance with Annex A.10, the duct system supplier declares a minimum tendon bond force that the duct is able to transfer in a length of 16 times the internal duct diameter. This minimum tendon bond force (capacity) may then be related to an actual number of strands inside the particular duct size, and the actual stress increase between the effective and the ultimate tendon force for a specific project design. Typically, this stress increase may be assumed to be 40% of the strand tensile strength and the maximum number of strands for a particular duct size is used (if known) or alternatively, a duct filling ratio of $(\text{cross sectional area of prestressing steel}) / (\text{duct cross sectional area based on internal diameter}) = 0.45$ may be considered.

The assessment procedures for the bond behaviour of duct confirm the ability of a duct to maintain bond when a load of 40% of the tendon ultimate tensile force is applied from the prestressing steel across the duct into the concrete in a maximum length of 16 duct diameters.

6.11 Precast segmental duct coupler system

Assessment (testing) procedures are shown in Annex A.11.

Precast segmental duct coupler systems are used to provide the continuity of the tendon envelope across segment joints in precast segmental construction. Joints can allow entry points for water (possibly contaminated with corrosive agents) to attack prestressing steel.
Segmental duct couplers and polymer duct provide protection against water borne contaminants by enclosing the prestressing steel in a continuous leak tight enclosure.

The field performance of precast segmental duct coupler systems is paramount to the long-term durability of precast segmental bridges. Constructability is a significant consideration for the builders of segmental bridges and the purchaser should evaluate the proposed systems for the individual characteristics related to constructability. The essential functions of all precast segmental duct couplers include: gasket (seal) compression at a force lower than the temporary prestressing force for segment erection so that the gasket (seal) does not act like a shim; maintaining pressure to prevent the intrusion of possibly contaminated water and the efflux of grout; a system remaining intact without failure and free of epoxy inside the encapsulation, wherever it is used during segment erection; and components remaining properly attached without crushing, tearing, or other signs of failure.

Assessment procedures for precast segmental duct coupler systems confirm that the gasket (seal) does not act as a shim, that the system maintains pressure and that it remains intact, free of epoxy intrusion, and without crushing or tearing.

6.12 Fracture resistance of duct system (optional test)

Assessment (testing) procedures are shown in Annex A.12.

The designer may want to specify an option in which the duct system within a structure remains intact for the complete encapsulation and corrosion protection for certain applications during the design life of the structure (PL2). This may be of particular interest for cracked structures in aggressive environment, for example, where de-icing salts are present or splash zones exist, and for electrically isolated tendons (PL3). It has been shown that corrugated steel duct will fracture at cyclically opening cracks across the duct (Section 3.2.10). Polymer duct has been shown to perform significantly better under similar conditions.

If such an option is specified by the designer, the manufacturer of the duct system must verify the performance by testing three representative sizes of the duct system. Note that the assessment procedures shown in Annex A.12 follow cyclic crack opening tests (CCOT) presented in Cordes (1996) and M. Abel (1996), and should be considered for the verification of the performance.

The objective of the CCOT is to initiate a crack at the mid-height of a test specimen and then cycle the width of the crack opening between 0.2 millimetres and 0.5 millimetres for 2 million cycles. The completed test thereby simulates a design lifetime of cyclic demand placed on a polymer duct that passes through a structural crack. The cracking or the excessive wear of the polymer duct during the simulation would imply that the complete encapsulation and corrosion protection provided by the duct may not remain intact for the design life of the structure.

Assessment procedures for the fracture resistance of the duct system confirm that the duct system remains intact with no cracks or perforations during the CCOT.

Note that CCOTs are optional and not required for the basic acceptance of a duct system. It is the manufacturer who decides to test this option and, hence, obtains an approval that includes this option. Alternatively, the test may be performed for a specific project when required by the designer in the project specification. However, for typical construction programmes, the time for project specific testing may not be sufficient.
6.13 Summary

A summary of all the requirements, methods of verification, and acceptance criteria for the polymer duct system together with components and material is given in Annex C.
7 System requirements

This chapter presents requirements and acceptance criteria for the performance of partially or fully assembled polymer duct systems. The corresponding test methods and procedures are given in Annex B. The proposed tests may be carried out at an independent qualified laboratory or by the system manufacturer or by the PT specialist company on his/her premises, when witnessed and confirmed by a qualified third party inspection agency.

These system tests should demonstrate that the partially or fully assembled components, previously successfully tested in the component tests, act as a complete system and that the system complies with the performance requirements for the intended use. In particular the following aspects should be verified on the assembled polymer duct system:

- leak tightness of anchorage-duct assembly
- EIT performance of duct system
- EIT performance of anchorage-duct assembly
- full-scale assembly of system
- leak tightness of assembled system.

The tests should document the suitability of the system for practical applications and, therefore, be performed as a representative scale test. It is considered sufficient to test one representative size of the system since it is assumed that the duct and components are designed as a series. If this assumption does not apply, testing several sizes may need to be considered. However, for the EIT performance of a duct system, all the sizes of the entire series are tested to obtain actual electrical resistance values for each size of duct and component.

The installation of the polymer duct system should follow the method statement prepared for the system. The method statement should be adjusted, if required, until the system tests meet the specified requirements.

The proposed tests are meant as system approval tests and, therefore, need to be carried out only once for the approval or certification of the system.

The strict adherence of installation methods used on site to the method statement used for system approval, the installation of the system by well trained and qualified personnel, the application of quality plans, and the independent checking by the engineer on site will ensure that the performance confirmed in the approval testing will also be obtained on construction sites.

*fib* Bulletin 7 (2000) also specified a/an:

- stressing/friction test
- grouting test
- electrical resistance test.
The authors of this report have come to the conclusion that after more than 20 years of experience with the use of polymer ducts these tests should not form part of the approval process anymore but may rather be carried out site specifically, if at all, for the following reasons:

- The friction parameters of polymer ducts are sufficiently well known and in fact more reliable than for metal ducts. Hence, an approval test with a nominal general tendon profile is not considered to provide any new and relevant information. For particular tendon layouts on a project or structures/members that are particularly sensitive to the typical variations of tendon forces, it is recommended to perform site-specific friction tests on the particular tendon(s) before the start of or early on in construction. Such tests can be done either on a mock-up of the tendon or on an actual tendon in the structure. Since this reproduces the actual tendon profile, the actual tendon properties, installation and equipment, this will provide the most valuable and meaningful results for the actual project.

- Experience has shown that, in general, the quality of the grouting of tendons in polymer ducts is not different to that of tendons in metal duct. If any difference exists, it may be that one may observe slightly larger air bubbles inside corrugations on top of polymer ducts since there are typically fewer corrugations in a given duct length than in similar metal ducts over which the air entrapped inside the duct is distributed. However, these air bubbles are small and do not leave prestressing steel exposed. Hence, they are of no particular concern to the performance and durability of the tendons. For particular tendon layouts on a project or particularly critical structures, site-specific grouting tests are recommended on a mock-up of the particular tendon(s) before the start of construction. Since such tests reproduce the actual tendon profile, the actual grout mix, grouting equipment and grouting procedures, they will provide the most valuable and meaningful results for the actual project and also offer excellent training for the personnel involved.

- Electrical resistance testing (EIT) in accordance with this report is now performed on polymer duct sections with connectors and vents and an anchorage/duct assembly. Hence, an approval test with a nominal general tendon profile is not considered to provide any new and relevant information. EIT testing is typically performed on site on all or a specified number of the EIT tendons as part of the PT contract. A proposed testing method and acceptance criteria may be found in ASTRA (2007) (also see Section 3.3.8 of this bulletin). Hence, on-site tests provide the desired feedback on the quality of installation for the actual tendons in the project.

### 7.1 Leak tightness of anchorage-duct assembly

Assessment (testing) procedures are shown in Annex B.1.

The anchorage-duct assembly, when in its final condition for PL1 applications, must be mortar-tight (similar to steel duct) and for PL2 and PL3 applications must be leak-tight. Thus, the assessment for mortar/leak tightness is performed on an assembly of anchorages with trumpets, as applicable, and ducts. Leak tightness is an important feature for the anchorage-duct assembly and is a requirement for PL2 and PL3 applications since these parts of the tendons are often subjected to the most severe exposure conditions on the structure.
For mortar tightness, the anchorage-duct assembly is subjected to positive pressure by using a water column inside the anchorage-duct assembly for a specified duration, with a minimum amount of water leakage.

For leak tightness, the anchorage-duct assembly is subjected to positive pressure by using air inside the anchorage-duct assembly for a specified duration. Then the same specimen is exposed to negative pressure from the outside side when submerged in a water tank for a specified duration. Alternatively, the outside negative pressure may be simulated by a vacuum from inside. These tests are to simulate field conditions and no air expulsion or water infiltration is allowed.

Assessment procedures for the leak tightness of the anchorage-duct assembly confirm that the duct-to-trumpet connections and the trumpet-to-bearing plate connections, as designed for the polymer duct system and anchorages, remain mortar-tight for PL1 applications and leak-tight for PL2 and PL3 applications.

### 7.2 EIT performance of the duct system

Assessment (testing) procedures are shown in Annex B.2.

The actual electrical isolation that can be achieved by the polymer duct system in PL3 applications depends on the characteristics and performance of the individual components, namely duct, duct connectors and vents, on eventual defects in the polymer duct system and on the quality of the assembly and installation on site. The characteristics and performance of the individual components and ducts, and connectors with/without vents, as well as their assembly are assessed with the EIT performance testing of the duct system described in this section and Annex B.2. The quality of the anchorage-duct assembly is assessed by the EIT performance of anchorage-duct assembly (Section 7.3 and Annex B.3). The EIT performance of the installed tendons (PL3) that may include potential defects are finally assessed through the project-specific testing of the electrical resistance of the installed tendons, for example, in accordance with the procedures specified in ASTRA (2007).

A polymer duct without any defects is electrically characterised by its geometry (length, diameter, wall thickness) and its material properties (specific resistance \( \rho \), dielectric constant \( \varepsilon \)). For a duct of length \( L \), the capacitance is \( C = 2*\pi*L*\varepsilon_0*\varepsilon/\ln[d_{\text{ext}}/d_1] \) where \( d_1 \) is the internal diameter of the duct, \( d_{\text{ext}} \) is the outside diameter of the duct, \( \varepsilon_0 \) is the vacuum constant and \( \varepsilon \) is the dielectric constant of the polymer used. This capacitance results in a frequency-dependent capacitive impedance \( Z_c = 1 / (2*\pi*f*C) \) that decreases with the increasing measuring frequency \( f \) and with the length \( L \) of the duct. Further information, for example, on the effect of defects on the above properties, can be found in Elsener/Büchler (2011).

For the assessment of the EIT performance of duct systems, first a metre-long sample of the polymer duct without connectors, followed by one with connectors and finally one with connectors and vents is submerged in a basin filled with tap water. The inside of the duct is also filled with tap water. The electrical resistance, the capacitance and the loss factor are then measured between a reinforcing steel bar inside the duct and a reinforcing steel mesh outside the duct with an LCR meter (\( L = \) Inductance, \( C = \) Capacitance, \( R = \) Resistance).

The assessment procedures for the EIT performance of duct system confirm the theoretically achievable electrical isolation properties of the polymer duct system components. These values should be declared in the polymer-duct-system documentation.
7.3 EIT performance of anchorage-duct assembly

Assessment (testing) procedures are shown in Annex B.3.

Anchorage-duct assembly, when in its final condition for PL3 applications, must provide sufficient electrical isolation to qualify, together with the polymer-duct system, as an electrically isolated tendon. The duct and connector assembly is separately tested for EIT performance, as part of component testing (Section 7.2).

For EIT performance, the anchorage-duct assembly is filled with an electrolyte [saturated Ca(OH)$_2$] on the inside and submerged in the electrolyte on the outside. The electrical resistance is then measured between the inside and the outside of the anchorage-duct assembly. The anchorage-duct assembly remains submerged over a period of three months to verify the initial EIT performance and its durability over time. It should be noted that the alkaline environment is provided in this test to verify the stability of eventual coatings on metallic anchorage surfaces.

The assessment procedures for the EIT performance of the anchorage-duct assembly confirm that the duct-to-trumpet connections, the trumpet-to-bearing-plate connections and the anchorage-cap-to-bearing-plate interfaces, as designed for the polymer-duct system and anchorages, provide sufficient electrical isolation to qualify for PL3 applications.

7.4 Full scale duct system assembly

Assessment (testing) procedures are shown in Annex B.4.

The components of duct systems for PL2 and PL3 tendons must fit together at full scale to comply with the geometrical restraints that may be found on actual sites. The duct system with anchorage-duct assembly and all its accessories must be able to be properly assembled, according to the method statement, into the specified typical tendon geometry after shipment, storage and handling, as specified in the method statement for the system. In particular, the extreme geometrical conditions (e.g. minimum radius of curvature) that are stipulated in the system documentation should be verified in this full-scale assembly test. The assembled duct system must be able to maintain the specified geometry over a period of time.

The assessment procedures for the full-scale duct system assembly for PL2 and PL3 tendons confirm that all the components can be installed as specified in the method statement, and that the duct profile and length comply with the specified profile and length within specified tolerances, without any apparent tendon profile kinks or discontinuities, and without excessive duct deformations and restraints, over a period of time. Since this is a large-scale test, it is carried out outside at the ambient temperature. For applications in extreme climates, either cold or hot, project-specific testing at the expected extreme temperature(s) may be taken into consideration prior to the start of the project.

7.5 Leak tightness of assembled duct system

Assessment (testing) procedures are shown in Annex B.5.

The components of the duct systems for PL2 and PL3 tendons must fit together at full scale to form a sufficiently leak-tight encapsulation for the prestressing steel. The assessment for leak tightness is performed on the full-scale duct-system assembly, as per Section 7.4 above. The front side of the bearing plate, where the anchor head sits, is sealed with the specified anchorage cap.
For leak tightness verification, the full-scale duct-system assembly is subjected to positive air pressure inside the duct assembly for a specified duration.

The assessment procedures for the leak tightness of the duct system assembly for PL2 and PL3 tendons confirm that the assembled components form a sufficiently leak-tight encapsulation (limited loss of air pressure).

7.6 Summary

A summary of all the requirements, methods of verification, and acceptance criteria for the polymer duct system together with components and material is given in Annex C.
8 Approval

As mentioned in Chapter 1, polymer duct systems and products still differ in material properties, geometrical design, connection details, installation procedures and use on site. Therefore, they have not been standardized as was done for corrugated steel ducts or smooth PE pipes. It is the opinion of the task group and the commission that these polymer ducts should, therefore, still be subjected to a ‘system approval’ process until product standards are developed. This chapter provides some brief information about how such an approval process may be set up, in particular for countries which and owners who have little experience with such processes. This information is based on the process applied in European Technical Approvals [see ETAG 013 (2002)].

8.1 Approval process

The process is started by the applicant, typically a polymer-duct manufacturer or a PT specialist company, who wishes to obtain technical approval for a polymer-duct system. The applicant selects an approval body that is accepted (notified) and that is qualified to perform such an approval for polymer-duct systems. The two parties, applicant and approval body, then sign an agreement that defines the conditions and terms for the approval process. The scope of the approval is then confirmed between the parties. This scope specifically includes the extent of the polymer-duct system (number of sizes of ducts, components, etc.) and the required types and the extent of testing. Also at that time the applicant and approval body should agree on the laboratory(ies) to be used for the required tests. The applicant then performs the required testing and prepares all the required documentation for the polymer-duct system. Once all the test reports and other documentation are ready the applicant submits these to the approval body for its evaluation against the requirements of this report or other specifications valid in the particular country. The approval body may then have further questions or may require further documentation. Once the approval body confirms that all the requirements of this report or the specifications valid in the particular country are satisfied the approval is granted. Typically such an approval is valid for a period of five years. Upon the expiration of this period, the approval may be renewed. Typically, renewal will be granted based on the experience collected by the certification body during the five-year validity of the approval. If any relevant details, likely affecting the performance of the polymer-duct system, have changed, a new assessment by the approval body will be made before renewing the approval.

Before using the polymer-duct system in the market, the applicant needs to contract an independent body / certification body that will verify the compliance of the product with the specifications and conditions under which approval was granted. The independent control of the polymer-duct system by the independent body is carried out during the entire period of the validity of the approval. The tasks of this independent body and the required testing of the polymer-duct system under the certification scheme are defined in Chapter 9.

If any serious problem with the polymer-duct system is detected within the period of validity of approval that cannot be corrected within the terms specified by the certification body, the approval body may suspend the approval until the problem is solved or may withdraw the approval.
8.2 Approval body

In Europe the governments of the countries designate approval bodies for the technical approval of specific systems or kits. If such a system of designation does not exist, owners or professional organizations may designate such approval bodies for specific tasks as well. The approval body needs to be independent and qualified for the task of assessing such polymer duct systems.

Such a system was created in Switzerland for post-tensioning systems in the early 1990s and operated until the European Technical Approval process was adopted. The requirement for the technical approval of post-tensioning systems was specified in the Swiss Concrete Standard. The Swiss Highways Administration and Swiss National Railways as the two major owners got together and decided to launch an approval process and organization for the post-tensioning systems and prestressed ground anchor systems used in all their projects. They agreed between them on the specifications for technical approval and created an approval committee consisting of the representatives of the two owners, the laboratories and the experts. The expert(s) assessed the submitted documentation and reported their findings and conclusions to the approval committee. Once all the conditions were satisfied the approval committee granted approval. All granted approvals were published on a website accessible to the public. Hence, anybody could easily check at any time whether a specific system was approved or not. A similar system has been operating in France since the 1970s. In Germany technical approvals have been required by law for specific building products and systems for many years and a special organization, DIBT (German Institute for Building Technology), was created for all German technical approvals.

Other set-ups for approval bodies and approval committees may be possible.

8.3 Basis for assessment

The polymer-duct systems should be assessed during the approval process on the basis of a technical performance specification for materials, systems and use on site. Unless national specifications exist, it is recommended to use this report as a basis for the technical assessment of polymer-duct systems. For the aspects of qualification of the PT specialist companies who install the polymer-duct systems and for the training and qualification of personnel, the CEN Workshop Agreement [CWA 14646 (2003)] is recommended as a basis for assessment. The basis for assessment must be publically available and must be accessible to possible future applicants for technical approvals.

8.4 Documentation for approval

The documentation as basis for the assessment for technical approval should consist at least of the following:

- Public documentation:
  - Technical documentation of polymer duct system:
    This documentation provides users of the system with all the information necessary to allow (i) the correct design and detailing of the structure or the member with these systems, (ii) the specification of the system in the project specification and (iii) the installation of the system on site. It should contain the intended use of the system, the main dimensions, the relevant performance
characteristics of the system, and aspects relevant to the design, detailing and use of the system on site.

- Proprietary documentation:
  - The fabrication drawings of and the material specifications for all duct types and sizes, and main components such as coupling devices/connectors
  - Manufacturing method of polymer duct system components
  - Technical data of specific equipment for installation, if any
  - Particular methods or equipment for transport and storage of polymer-duct-system components
  - Basic method statements for installation of the polymer duct system components.
    This may include such aspects as a recommendation for the installation of half shells in tight tendon curvature.
  - Specific procedures for maintenance of the polymer duct system, if any
  - Reports for all testing performed or required for approval
  - Documentation for compliance with requirements for qualification of PT specialist companies which install the polymer duct systems and for training and qualification of personnel, e.g. in accordance with CWA (2003)
  - Declaration that the polymer-duct-system components do not contain dangerous substances
  - Brief description of quality management system, including factory production control (FPC) for polymer duct system components

The technical documentation referenced above is a public document that is made available to the users of the polymer-duct system. The other documents listed above are at least partly proprietary and confidential information that is provided to the approval body for the assessment. The entire documentation will be kept at the approval body for future reference, if there should be any questions later.

### 8.5 Testing for approval

The following testing is proposed as a basis for the assessment for technical approval of the polymer-duct system (Table 8.1).

<table>
<thead>
<tr>
<th>Type of test</th>
<th>Components tested</th>
<th>Testing frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) Material</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Material tests</td>
<td>Polymer resin or compound and/or</td>
<td>Material testing according to Tables 5.1 and 5.2 of all batches of polymer ducts</td>
</tr>
<tr>
<td>(Sections 5.2 and 5.3)</td>
<td>duct</td>
<td>used for approval testing</td>
</tr>
</tbody>
</table>
### (2) Components

<table>
<thead>
<tr>
<th>Component Description</th>
<th>Material(s)</th>
<th>Testing Details</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Dimensional tolerance</strong>&lt;br&gt;(Section 6.1 and Annex A.1)</td>
<td>Duct and duct connectors</td>
<td>3 each – perform on all sizes of ducts and connectors tested at room temperature</td>
</tr>
<tr>
<td><strong>Stiffness of duct</strong>&lt;br&gt;(Section 6.2 and Annex A.2)</td>
<td>Duct</td>
<td>1 each – perform on all duct sizes at room and high temperature</td>
</tr>
<tr>
<td><strong>Longitudinal load resistance of duct system</strong>&lt;br&gt;(Section 6.3 and Annex A.3)</td>
<td>Duct and duct connectors</td>
<td>1 each – perform on all duct sizes with each connector at room temperature</td>
</tr>
<tr>
<td><strong>Lateral load resistance of duct</strong>&lt;br&gt;(Section 6.4 and Annex A.4)</td>
<td>Duct</td>
<td>1 each – perform on all duct sizes at room and high temperature</td>
</tr>
<tr>
<td><strong>Flexibility of duct system</strong>&lt;br&gt;(Section 6.5 and Annex A.5)</td>
<td>Duct and duct connectors</td>
<td>1 each – perform on all duct sizes with each connector at room, low and high temperature</td>
</tr>
<tr>
<td><strong>Leak tightness of duct system</strong>&lt;br&gt;(Section 6.6 and Annex A.6)</td>
<td>Duct and duct connectors</td>
<td>1 each – perform on all duct sizes with each connector at room temperature</td>
</tr>
<tr>
<td><strong>Concrete pressure on duct system</strong>&lt;br&gt;(Section 6.7 and Annex A.7)</td>
<td>Duct</td>
<td>1 each – perform on all duct sizes at room temperature</td>
</tr>
<tr>
<td><strong>Wear resistance of duct</strong>&lt;br&gt;(Section 6.8 and Annex A.8)</td>
<td>Duct</td>
<td>1 each – perform on all duct sizes at room and high temperature</td>
</tr>
<tr>
<td><strong>Wear resistance of duct under sustained load</strong>&lt;br&gt;(Section 6.9 and Annex A.9)</td>
<td>Duct</td>
<td>1 each – perform on all duct sizes at room and high temperature</td>
</tr>
<tr>
<td><strong>Bond behaviour of duct</strong>&lt;br&gt;(Section 6.10 and Annex A.10)</td>
<td>Duct</td>
<td>1 each – perform on small, medium and largest size of round ducts plus on largest size of flat ducts at room temperature</td>
</tr>
<tr>
<td><strong>Precast segmental duct coupler system</strong>&lt;br&gt;(Section 6.11 and Annex A.11)</td>
<td>Precast segmental duct coupler</td>
<td>1 each – perform on all sizes of precast segmental duct coupler at room temperature</td>
</tr>
<tr>
<td><strong>Fracture resistance of duct</strong>&lt;br&gt;(Section 6.12 and Annex A.12)&lt;br&gt;Note: Optional for approval</td>
<td>Duct</td>
<td>1 each – perform on small, medium and largest duct size at room temperature</td>
</tr>
</tbody>
</table>

### (3) System

<table>
<thead>
<tr>
<th>Component Description</th>
<th>Material(s)</th>
<th>Testing Details</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Leak tightness of anchorage-duct assembly</strong>&lt;br&gt;(Section 7.1 and Annex B.1)</td>
<td>Assembly of PT anchorage, trumpet, duct and connector</td>
<td>1 each – perform on one representative medium duct size at room temperature 2)</td>
</tr>
<tr>
<td><strong>EIT performance of duct system</strong>&lt;br&gt;(Section 7.2 and Annex B.2)</td>
<td>Duct and duct connectors and vents</td>
<td>1 each – perform on all duct sizes with each connector and vent at room temperature for PL3 tendons only</td>
</tr>
<tr>
<td>EIT performance of anchorage-duct assembly (Section 7.3 and Annex B.3)</td>
<td>Assembly of PT anchorage, trumpet, duct and connector</td>
<td>1 each – perform on one representative medium duct size at room temperature for PL3 tendons only 2)</td>
</tr>
<tr>
<td>----------------------------------------------------------</td>
<td>------------------------------------------------</td>
<td>------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Full-scale duct system assembly (Section 7.4 and Annex B.4)</td>
<td>Full-scale assembly of PT anchorages, duct, connectors and accessories</td>
<td>1 each – perform on one representative medium duct size at ambient temperature 2)</td>
</tr>
<tr>
<td>Leak tightness of assembled duct system (Section 7.5 and Annex B.5)</td>
<td>Full scale assembly of PT anchorages, duct, connectors and accessories</td>
<td>1 each – perform on one representative medium duct size at ambient temperature 2)</td>
</tr>
</tbody>
</table>

Notes:
1) For systems intended for PL2 and PL3 only
2) Testing of one representative medium size applies if the entire duct and component series have the same design concept. Testing of several or all sizes may be required if this does not apply.

The material, component and system tests listed in Table 8.1 apply for polymer duct systems intended to be used for PL2 and PL3. For polymer duct systems to be used for PL1, the system tests do not apply. Chapter 6 and Annexes A and B provide information on which tests apply to PL1, PL2 and PL3, and give the acceptance criteria for each test as a function of the specified PL.

When the testing frequency of performance tests in Table 8.1 does not identify ‘all’ sizes to be tested, the specified number of tests in Table 8.1 assumes that all the components of the polymer-duct system form a series, that is, are made of identical material, have the same type of cross section and same form of corrugation, and follow a steady trend in the design of dimensions for all sizes throughout the series (e.g. consistent ratios of size and spacing of corrugations and of wall thickness). If these assumptions do not apply, a larger number of sizes, and in the extreme case the testing of all the sizes, may be required. It is the responsibility of the approval body to verify whether or not the above assumption of a series applies.
9 Evaluation of conformity

9.1 General

Traditional internal post-tensioned tendons come with corrugated metal ducts made of sheet metal strips. Metal duct, although required to have certain mechanical properties (stiffness and durability) and chemical properties (stability and non-reactiveness with other elements of the post-tensioning tendon), cannot be considered a real corrosion barrier by itself. The traditional post-tensioning tendon with corrugated metal duct can only be categorized as tendon type PL1.

Nowadays post-tensioning tendon type PL1 is considered insufficient for a medium to high aggressiveness of the environment and/or with medium to low structural protection layers (Section 3.1). A now well accepted requirement is that the duct become an additional corrosion barrier, which has led to tendon types PL2 and PL3.

The polymer duct manufacturer is responsible for ensuring that the polymer duct system is in conformity with the requirements specified in this technical recommendation and that it is fit for its intended use (tendon type PL1, PL2 or PL3). Therefore, establishing a proper system of conformity attestation is necessary to prove polymer-duct system compliance.

The proposed systems of attestation of conformity for the different tendon types are given in Table 9.1.

<table>
<thead>
<tr>
<th>Product</th>
<th>Tendon type</th>
<th>Attestation of system conformity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polymer-duct system</td>
<td>PL1</td>
<td>1+</td>
</tr>
<tr>
<td></td>
<td>PL2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>PL3</td>
<td></td>
</tr>
</tbody>
</table>

The above-mentioned 1+ system of conformity attestation is based on European regulations. According to these regulations, the manufacturer of a product is responsible for the attestation that his/her products conform to the requirements of the relevant technical specification. Conformity needs to be established by means of testing and/or other evidence, on the basis of the technical specifications. Different levels are specified depending on whether the product’s attestation of conformity is provided by an approved certification body or independent body or by the manufacturer.

For a 1+ level of conformity attestation the following applies: the responsibility for product conformity certification is given to an independent body or third party. It is normal practice that various parties – the producer, the certification body, the inspection body and the laboratory – carry out the individual tasks required to enable product certification to take place. The certification body is responsible for assembling all of the relevant information, verifying that tasks have been carried out according to the technical specification and assessing and certifying the conformity of the product. Product certification can therefore be considered to be an umbrella activity, making use of information from various sources.
Under 1+ systems the responsibility for product sampling lies with the certification body (often delegated to an inspection body), rather than with the manufacturer.

9.1.1 1+ system of attestation of conformity

The 1+ system of attestation of conformity for a polymer-duct system requires the following tasks:

- Tasks for the manufacturer:
  - factory production control (permanently)
  - further testing of samples taken at the factory by the manufacturer of the polymer-duct-system components
- Tasks for the independent body:
  - initial type-testing of the polymer-duct-system components
  - initial inspection of factory and factory production monitoring
  - continuous surveillance, assessment and approval of factory production control (at least once in 5 years)
  - audit testing of samples taken at the factory (at least once in 5 years)

9.2 Tasks and responsibilities of the manufacturer

9.2.1 Factory-production control

The polymer-duct-system manufacturer has to implement and continuously maintain a factory production monitoring system. The factory production monitoring system shall ensure that the polymer-duct system (polymer duct, connectors, etc.) conforms to the technical specification.

All the elements, requirements and provisions adopted by the polymer-duct-system manufacturer shall be documented systematically in the form of written operating and processing instructions.

The results of factory production monitoring have to be recorded and evaluated. The records have to at least include the following information:

- designation of the products and the basic materials
- type of verification or testing
- date of manufacture of the products and date of testing of the products or basic materials or components
- results of verification and testing and, if appropriate, comparison with requirements
- name and signature of the person responsible for the factory production control

Each delivery of raw material shall be checked to ensure that it is in compliance with the properties that are required for the intended use of the polymer-duct system. The
The manufacturer of the polymer-duct system must carry out the checks and tests described in Table 9.2. The applicable standards for all tests are given in Chapter 5, Tables 5.1 and 5.2.

**Table 9.2: Minimum factory production monitoring for material used for polymer ducts**

<table>
<thead>
<tr>
<th>Component</th>
<th>Item</th>
<th>Test / Check</th>
<th>Trace-ability</th>
<th>Minimum frequency</th>
<th>Documentation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw material (Resin)</td>
<td>HDB (for PE only)</td>
<td>Check</td>
<td>Full</td>
<td>100%</td>
<td>Data sheet</td>
</tr>
<tr>
<td>Raw material (Compound)</td>
<td>Notched impact</td>
<td>Test</td>
<td>Full</td>
<td>1/batch</td>
<td>yes</td>
</tr>
<tr>
<td></td>
<td>MFR</td>
<td>1)</td>
<td>yes</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Flexural modulus</td>
<td>Test</td>
<td>1)</td>
<td>yes</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Tensile yield strength</td>
<td>1)</td>
<td>yes</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Elongation at yield and at break</td>
<td>1)</td>
<td>yes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Raw material (Duct)</td>
<td>OIT</td>
<td>Test</td>
<td>Full</td>
<td>1/ batch</td>
<td>yes</td>
</tr>
<tr>
<td></td>
<td>ESCR (Condition C)</td>
<td>1)</td>
<td>yes</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>MFR</td>
<td>1)</td>
<td>yes</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Density</td>
<td>1)</td>
<td>yes</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Notes:**
1) *At each change of batch of raw material of resin and compound*
2) *Certificate of specific values of tested raw material.*

In addition to the checks on the material as per Table 9.2, the manufacturer must carry out tests and monitoring on the fabricated polymer ducts and components in accordance with Table 9.3. Table 9.3 specifies the kind and frequency of tests that have to be carried out by the manufacturer during production. The tests specified in Table 9.3 apply to all tendon types, from PL1 to PL3. The test methods are those specified in Annex A. However, the FPC testing of polymer-duct systems takes place at 23 °C ± 5 °C only.

**Table 9.3: Minimum factory production control for polymer ducts used for all tendon types**

<table>
<thead>
<tr>
<th>Component</th>
<th>Item</th>
<th>Test / Check</th>
<th>Trace-ability</th>
<th>Minimum frequency</th>
<th>Documentation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polymer-duct-system components</td>
<td>Visual inspection</td>
<td>Check</td>
<td>Full</td>
<td>100 %</td>
<td>no</td>
</tr>
<tr>
<td></td>
<td>Dimensional tolerance</td>
<td>Test</td>
<td>Full</td>
<td>2 at start of production plus ≥ 2 specimens per working shift</td>
<td>yes</td>
</tr>
<tr>
<td></td>
<td>Longitudinal mass</td>
<td>Test</td>
<td>Full</td>
<td>2 at start of production plus ≥ 2</td>
<td>yes</td>
</tr>
</tbody>
</table>
### Table

<table>
<thead>
<tr>
<th>Polymer-duct-system components</th>
<th>Test</th>
<th>Full</th>
<th>specimens per working shift</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stiffness of duct 5)</td>
<td></td>
<td></td>
<td>1 per batch of duct; plus</td>
</tr>
<tr>
<td>Longitudinal load resistance of duct system 5)</td>
<td></td>
<td></td>
<td>1 for every new material batch; plus 1 for every additional new month of continuous duct production</td>
</tr>
<tr>
<td>Lateral load resistance of duct 5)</td>
<td></td>
<td></td>
<td>yes 4)</td>
</tr>
<tr>
<td>Flexibility of duct system 5)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Leak tightness of duct system 5)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wear resistance of duct 5)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Notes:

1) Material batch refers to the compound of the polymer duct and not to the raw material of connector and other ancillaries

2) Number of tests per size of duct or connector

3) Visual inspection includes: correct size and shape, smoothness, fins, kinks, cavities, correct marking or labelling as detailed in the prescribed test plan

4) On top of the internal documentation of FPC, a ‘duct delivery certificate’ should be prepared for each shipment, indicating the actual results of FPC testing for the particular batch(es) contained in the shipment. Alternatively, a declaration of conformity by the manufacturer that all requirements of this report are met may be provided if permitted in the project specification or under the regulations in the place of use

5) FPC testing is at 23 °C ± 5 °C only.

The polymer-duct-system manufacturer must keep all records/documentation of factory production monitoring for a period of at least 10 years or as the law requires.

### 9.2.2 Non-compliance with specifications

If the tests performed during production (Tables 9.2 and 9.3) deliver unsatisfactory results, the polymer-duct-system manufacturer should immediately quarantine the product and implement measures to correct the defects. After the correction of the defects, the respective test – if verification is required for technical reasons – should be repeated.

### 9.3 Tasks and responsibilities of independent body

#### 9.3.1 Initial type testing of the products

For the initial type testing, the results of the tests performed as part of the technical approval/assessment of the polymer-duct system, described in Section 8.5, may be used
unless there are changes in the production processes of the manufacturing plant. In such cases, the independent body should propose the necessary re-testing.

9.3.2 Initial inspection of factory and factory production control

During an initial visit and inspection the independent body should ascertain that the manufacturing plant(s) and in particular the personnel and equipment, as well as factory production monitoring, are suitable to ensure a continuous and orderly manufacturing of the polymer-duct system.

9.3.3 Continuous surveillance

The independent body should inspect the polymer-duct-system manufacturer at least once every five years. The independent body should verify that the system of factory production monitoring, including the testing equipment and execution, the test results obtained and the specified manufacturing process are maintained, and that the test values determined during FPC comply with the requirements.

9.3.4 Audit testing of samples taken at the factory

At least once within 5 years, during surveillance inspection (Section 9.3.3), the independent body has to take samples of the polymer raw material (resin and compound) and the polymer-duct-system components for independent testing. Table 9.4 summarizes the minimum procedures that should be implemented by the independent body. The test methods for duct systems should be those specified in Annex A. However, the audit testing of polymer duct systems takes place at 23 °C ± 5 °C only.

<table>
<thead>
<tr>
<th>Component (resin)</th>
<th>Item</th>
<th>Test/check</th>
<th>Sampling – number per visit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw material (resin)</td>
<td>HDB (for PE only)</td>
<td>Check</td>
<td>1 1)</td>
</tr>
<tr>
<td>Raw material (compound)</td>
<td>Notched impact</td>
<td>Test</td>
<td>1 1)</td>
</tr>
<tr>
<td></td>
<td>MFR</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Flexural modulus</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Tensile yield strength</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Elongation at yield and at break</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Raw material (duct)</td>
<td>OIT</td>
<td>Test</td>
<td>1 1)</td>
</tr>
<tr>
<td></td>
<td>ESCR (condition C)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>MFR</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Density</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plastic-duct system</td>
<td>Visual inspection 2)</td>
<td>Check</td>
<td>Test 2 3)</td>
</tr>
<tr>
<td>---------------------</td>
<td>----------------------</td>
<td>-------</td>
<td>-----------</td>
</tr>
<tr>
<td></td>
<td>Dimensional tolerance 2) of duct and components</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Longitudinal mass 2)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Stiffness of duct 2) 4)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Longitudinal load resistance of duct system 2) 4)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Lateral load resistance of duct 2) 4)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Flexibility of duct system 2) 4)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Leak tightness of duct system 2) 4)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Wear resistance of duct 2) 4)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Notes:

1) 1 sample from running duct production every 5 years

2) Test may be performed as witness testing (e.g. during corresponding yearly FPC testing)

3) Random 2 duct sizes and 2 components (as applicable) for testing and comparison against values of FPC and approval testing

4) Audit testing is at 23 °C ± 5 °C only.
10 References and standards


CWA 14646 (2003) “Requirements for the installation of post-tensioning kits for prestressing of structures and qualification of the specialist company and its personnel”, CEN Workshop Agreement CWA 14646, European Committee for Standardization, Brussels


FDOT (2013) “Standard specifications for road and bridge construction”, Florida Department of Transportation (FDOT), Section 462 Post-Tensioning and Section 960 Post-Tensioning Components, Tallahassee, Florida (2013)


Matt (1990) P. Matt: “Qualitätsgesicherte und überwachbare Spannysteme im Brückenbau“ (Quality assured and inspectable prestressing systems for bridge construction), Eidg. Verkehrs- und Energiewirtschaftsdepartement, Bundesamt für Strassenbau, Froschungsauftrag Nr. 81/89 (1990)


Annex A  Component assessment procedures

This annex presents assessment (testing) procedures for duct and other components for the essential aspects of polymer duct systems for post-tensioning. The intent of each of these tests is explained in Chapter 6. Each procedure identifies the objective/purpose, performance requirements, testing methods, acceptance criteria and reporting for the specific essential aspects. The results of these tests prove whether a specific polymer-duct system is able or unable to fulfil the essential performance requirements that are identified for and form the basis of duct system performance.

Each procedure begins by describing the objective or purpose of the test. Performance requirements identify what is essential, what has to be tested, what sizes have to be tested, how often the tests are required or updated, and the type of testing and number of tests. The testing methods define test specimens, measuring and testing equipment, test specimen temperatures, specific test procedures, and calculations, if necessary. Acceptance criteria are identified for each tendon protection level (PL). Specific reporting requirements will allow for the consistency of test reports.

Connectors used with polymer duct systems are identified as heat-seal connections, slip-on couplers, mechanical couplers, combinations of the previous, or any other external method to attach a duct to another duct or trumpets. Butt-fusion-welded joining (mirror welding of ducts) is not considered a connector for these assessment tests. Mirror-welded duct connections may be assessed as part of project quality control in accordance with stay cable recommendations by the PTI and the fib, or in accordance with DVS 2207 (2005).

The specified assessment procedures apply for approval testing, factory production control (FPC) where specified, and for audit testing where specified. The reasons for testing and the number of required tests are given in Chapter 8 for approval testing and in Chapter 9 for FPC and audit testing. However, for ease of use, the number of required tests is also given in Annex A. In the case of any inconsistency, the numbers given in Chapters 8 and 9 prevail.

Test specimen temperatures for approval testing are generally grouped into three areas due to the essential aspects of each assessment and are to be considered the temperature of the duct specimen throughout testing. Different regions will have different temperature ranges; actual site conditions should be considered. The temperature ranges below are considered to be minimum requirements for testing. Duct manufacturers can declare other temperature ranges if these go beyond the values specified below:

- room temperature: 23 °C ± 5 °C
- low temperature: at no more than -15 °C
- high temperature: at no less than 45 °C

However, FPC and audit testing is performed at 23 °C ± 5 °C only.

Tendon protection levels as identified in fib Bulletin 33 (2006) and PTI-ASBI M50.3-12 (2012) play an important role in identifying necessary polymer-duct-system requirements for the long-term durability of a structure and are included in the acceptance criteria for each assessment procedure. The successful testing of the duct system to a higher tendon PL, confirms the ability of the duct system when utilizing the same details to meet lower tendon PL requirements without additional testing.
The consistency of the materials and the geometry of duct-system components (in particular, the thickness of the duct) between tests are crucial for the future confirmation that the manufactured products can achieve the tested results. Therefore, the material and the thicknesses of polymer ducts or components must be consistent throughout the testing. Confirmation of the actual material properties of all the batches used in approval testing is to be included in all test reports in accordance with Chapter 5. All duct samples of one particular duct size for approval testing should be made from the same material batch. The actual thicknesses of all the duct and component samples used for testing must be determined and recorded and the mass of these components measured. All the samples of the components used for testing should be randomly selected from production batches.

Approval testing may preferably be performed in an independent and qualified laboratory. However, testing by the manufacturer in his/her own laboratory is acceptable if witnessed and confirmed by a qualified independent third party. The test reports should be prepared and confirmed by the laboratory or the third party. All FPC testing is performed by the designated internal QC. All audit testing is performed under the responsibility of the auditing authority. The auditing authority may perform these tests and prepare the test reports themselves or subcontract these tasks to a qualified independent third party or to the manufacturer and have them witnessed by the third party.

The test reports for approval testing should provide full details, as listed in Annexes A.1 to A.12. The results of FPC testing may be recorded in standardized summary sheets. However, the test equipment, test methods, calibrations of testing and measuring equipment must be described either by reference to a corresponding approval test report (if the testing means are identical) or by reference to a separate report that gives all the testing means and is updated every time a testing means has changed. The test reports for audit testing may be similar in style and content to FPC test reports; however, they need to be either prepared or at least checked and signed by the independent third party.
A.1 Dimensional requirement

A.1.1 Objective/purpose

A.1.1.1 To confirm duct and duct connectors are fabricated within specified tolerances for all samples used for any of the component tests.

A.1.2 Performance requirements

A.1.2.1 What is essential:
- Geometry (dimensions and tolerances)

A.1.2.2 What is tested:
- Duct
- Duct connectors

A.1.2.3 How often are tests required or updated:
- Initially
- If there is a change of design and/or manufacturing process
- For each type of material used

A.1.2.4 Type of testing, number of tests, size of test specimens:
- Approval testing: 3 tests of each size of duct and connector, performed on all sizes (see Section 8.5)
- FPC testing: 2 tests at the start of production plus a minimum of 2 / work shift (see Section 9.2)
- Audit testing: 2 duct sizes and 2 components randomly selected (see Section 9.3).

A.1.3 Testing methods

A.1.3.1 Test specimens:
- Duct – approximately 500 mm sample should be used
- Connectors – actual connector

A.1.3.2 Measuring and testing equipment:
- Vernier caliper (accuracy 0.1 mm) Note that the caliper points should be rounded not sharp or pointed
- Thermometer (accuracy ± 0.5 °C)
- Scale for weighing duct or components

A.1.3.3 Test specimen temperature:
- 23 °C ± 5 °C

A.1.3.4 Test procedure / Measuring of duct specimens
- Figure A.1-1 defines base measurements
- Measurements should be taken at both ends of the specimen in two directions at right angles to one another – see Fig. A.1-1(a) and (b) for round duct and A.1-1(c) for flat or oval duct
- Measure and record:
  1. Test specimen temperature
  2. Internal diameter (d₁) for round duct
  3. Internal perpendicular dimensions (d₁) for flat ducts
  4. Wall thickness (t)
  5. External diameter (d₂) for round duct
  6. External perpendicular dimensions (d₂) for flat ducts
  7. All ‘critical’ dimensions as defined in component drawings
  8. Mass of specimens
A.1.3.5 Test procedure / Measuring of connector specimens

- Measurements are similar to those shown above for duct
- Measure and record:
  1. Test specimen temperature
  2. Internal diameter ($d_1$)
  3. Wall thickness (t)
  4. All ‘critical’ dimensions as defined on component drawings
  5. Mass of specimens

A.1.3.6 Record actual and average values

![Figures A.1-1: Duct dimensions](image)

Figure A.1-1  Duct dimensions

A.1.4 Acceptance criteria

A.1.4.1 Same for all tendon Protection Levels (PL)

A.1.4.2 Manufacturer should designate in component drawings:

- Internal diameter ($d_1$) for round duct
- Internal perpendicular dimensions ($d_{i1}$) for flat ducts
- Wall thickness (t)
- External diameter ($d_2$) for round duct
- External perpendicular dimensions ($d_{i2}$) for flat ducts
- ‘Critical’ dimensions, if any, and specified tolerances

A.1.4.3 Duct dimensions:

- Actually measured dimensions or, where applicable, average dimensions should be within the dimensions and tolerances specified in the manufacturer’s drawings or specifications
- However, in any case:
  - Average value of internal diameter $d_1$ should be within +/- 1% or +/- 1 mm, whichever is greater
• Average value of external diameter $d_2$ should be within +/- 1% or +/- 1 mm, whichever is greater
• Average value of wall thickness should be within -0 / +0.5 mm, checked at (i) the middle between adjacent corrugations and (ii) next to a corrugation. However, any individual recorded value of wall thickness no less than specified wall thickness

A.1.4.4 Connector dimensions:
• Actually measured dimensions or, where applicable average dimensions, should be within the dimensions and tolerances specified in the manufacturer’s drawings or specifications.

A.1.5 Reporting

A.1.5.1 Approval test report should contain at a minimum:
• Date and location of testing
• Name of laboratory and individuals who performed and/or witnessed the testing
• Tested material properties and type/ batch or lot numbers /designation of duct and connectors tested
• Table containing test specimen temperature, recorded measurements, averages, acceptance criteria, and pass/fail designation
• Pictures of actual test specimens
• Manufacture’s component drawings (confidential information provided to authorized parties only)
• Any hand written field notes used in preparing final report
• Certified calibration reports of measuring and testing equipment

A.1.5.2 FPC and audit test reports should contain at a minimum:
• Date and location of testing
• Name of individuals who performed and/or witnessed the testing
• Tested material properties and type/ batch or lot numbers /designation of duct and connectors tested
• Table containing test specimen temperature, recorded measurements, averages, acceptance criteria, and pass/fail designation.
A.2 Stiffness of duct

A.2.1 Objective/purpose
A.2.1.1 To determine duct stiffness based on actual deflection over a specified duct length
A.2.1.2 To establish maximum support spacing of duct at normal and high temperatures with a maximum allowable net mid span deflection of L/500 between supports of a continuous duct over multiple spans of identical length L.
  • Spacing and magnitude of corrugations affect the overall stiffness of the duct
  • Duct buoyancy is a significant determining factor for support spacing of duct
  • Pre-loading of prestressing steel is an important determining factor for support spacing of duct. However, this is considered only if the ducts are used EXCLUSIVELY with pre-loaded prestressing steel
  • Deflections between supports must be minimized to reduce wobble effect.

A.2.2 Performance requirements
A.2.2.1 What is essential:
  • Performance
A.2.2.2 What is tested:
  • Duct
A.2.2.3 How often are tests required or updated:
  • Initially
  • If a change of design and/or manufacturing process
  • For each type of material used
A.2.2.4 Type of testing, number of tests, size of test specimens:
  • Approval testing: 1 test per size, performed on all duct sizes (see Section 8.5)
  • FPC testing: 1 per batch of duct manufacture, plus 1 for every new batch of compound, plus 1 for every additional month of continuous production (see Section 9.2)
  • Audit testing: 2 duct sizes randomly selected (see Section 9.3)

A.2.3 Testing methods
A.2.3.1 Test specimens:
  • Total length 1100 mm
A.2.3.2 Measuring and testing equipment:
  • Gauge or LVDT (accuracy 0.1 mm)
  • Thermometer (accuracy ± 0.5 °C)
  • Load cell for alternative test method (accuracy 1 N or ± 1% of maximum test load whichever is larger)
  • Scale for weighing duct or components
A.2.3.3 Test specimen temperature:
  • 23 °C ± 5 °C
  • At least 45 °C for approval testing only
A.2.3.4 Test procedure
  • Test set-up (see Fig. A.2-1):
    • Two supports should be placed so there is 1,000 mm clear span between support points
    • Each support should have a flat surface for the duct to rest on that is able to revolve around the support point, thus maintaining a flat surface as the duct deflects
Measurements of duct deflection should be taken at mid span  
*Note: Since the duct deflections to be measured are small, particular care has to be taken in the set-up and actual measuring of deflections. It is recommended to install a reference level (wire or bar) connected over the supports at the centre line of the duct and measure duct deflection at mid span against this reference level. The deflection measuring system should be kept independent of the load application system*

- Duct specimen should be placed on supports  
- Duct should overlap support points 50 mm on each side  
- Confirm test specimen temperature  
- Record duct deflection at mid span (reference deflection)  
- Gradually apply a load F at mid span to increase mid span deflection from reference deflection to the target deflection Δ = 5.0 mm (loading speed not exceeding 100 N/minute) and record duct deflection against applied load immediately when reaching the target deflection  
- Maintain target deflection for a minimum of 2 minutes, and record corresponding applied load. The load measured after 2 minutes at the target deflection of Δ = 5.0 mm deflection is $F_{eff}$  
- Measure and record:  
  1. Test specimen temperature  
  2. Load immediately when reaching the target deflection and after 2 minutes  
  3. Applied load $F_{eff}$ after holding 5.0 mm target deflection for minimum of 2 minutes  
  4. Mass of specimen  
  5. Observations

**A.2.3.5 Determination of effective stiffness**

- Effective duct stiffness $(E \times I)_{eff}$ is the secant stiffness in the load-deflection test, between 0 and 5.0 mm deflection, with the load $F_{eff}$ measured after 2 minutes holding the target deflection $Δ = 5.0 \text{ mm}$. It should be determined by the following equation:

$$ (E \times I)_{eff} = \frac{F_{eff} \times L^3}{48 \times Δ} $$

Where:  
- $F_{eff}$ = applied load after 2 minutes holding target deflection $Δ = 5.0 \text{ mm}$  
- $L$ = span  
*Note: $E$ = modulus of elasticity of duct material; the actual value of $E$ is not required for the assessment of this test.*
A.2.4 Acceptance criteria

A.2.4.1 Same for all tendon Protection Levels (PL)
A.2.4.2 Record effective duct stiffness (E * I)_{eff} as determined under A.2.3.5:

*Note: Maximum duct support spacing (SS) may be determined as given in Section 6.2*

A.2.4.3 For FPC and audit testing:
Effective stiffness (E * I)_{eff} should be within ± 10% of value determined for approval testing.

A.2.5 Reporting

A.2.5.1 Test report should contain at a minimum:
- Date and location of testing
- Name of laboratory and individuals who performed and/or witnessed the testing
- Tested material properties and type/ batch or lot numbers /designation of duct tested
- Documentation that test specimens confirm to dimensional tolerances
- Mass of duct specimens
- Table containing test specimen temperature, measured test deflection and load, calculated duct effective stiffness based on testing
- Pictures of testing
- Manufacture’s component drawings (confidential information provided to authorized parties only)
- Any hand written field notes used in preparing final report
- Certified calibration reports of measuring and testing equipment

A.2.5.2 FPC and audit test reports should contain at a minimum:
- Date and location of testing
- Name of individuals who performed and/or witnessed the testing
- Tested material properties and type/ batch or lot numbers /designation of duct and connectors tested
- Table containing test specimen temperature, recorded measurements, calculated duct effective stiffness based on testing.
A.3 Longitudinal load resistance of duct system

A.3.1 Objective/purpose

A.3.1.1 To confirm duct system has adequate longitudinal load resistance to maintain continuity prior to concrete placement

A.3.1.2 To confirm duct and duct connectors are strong enough to resist restraint and movement caused by temperature variations that will occur on site after field installation of duct and prior to concrete placement

A.3.1.3 To confirm that duct and duct connector are strong enough to resist loads caused by coiling of prefabricated tendons.

Note that prefabricated tendons need to comply with both test methods to imposed deformation and to applied load.

A.3.2 Performance requirements

A.3.2.1 What is essential:
- Performance

A.3.2.2 What is tested:
- Duct and duct connectors

A.3.2.3 How often are tests required or updated:
- Initially
- If a change of design and/or manufacturing process
- For each type of material used
- When a new connector is proposed for use

A.3.2.4 Type of testing, number of tests, size of test specimens:
- Approval testing: 1 test per size, performed on all duct sizes with each connector (see Section 8.5)
- FPC testing: 1 per batch of duct manufacture, plus 1 for every new batch of compound, plus 1 for every additional month of continuous production (see Section 9.2)
- Audit testing: 2 duct sizes with corresponding connectors randomly selected (see Section 9.3).

A.3.3 Testing methods

A.3.3.1 Test specimens:
- Two pieces of duct
  - First piece is 1100 mm in length
  - Second piece is 550 mm in length
  - An anchorage trumpet can be substituted for second piece of duct
- Connector – actual connector used
- Figure A.3-1 shows layout of a test specimen. Dimension from base to top of connector (D) is dependent on attachment method and should be at least 1100 mm (1,000 mm with fusion butt weld connection)

Note that this test specimen will also be used for lateral load resistance of duct (assessment procedure Annex A.4), Flexibility of Duct System (Assessment Procedure Annex A.5), and leak tightness of duct system (assessment procedure Annex A.6) without re-assembly of duct connection

A.3.3.2 Measuring and testing equipment:
- Thermometer (accuracy ± 0.5 °C)
- Load cell (accuracy 1 N or ± 1% of maximum test load whichever is larger
Annex A: Component assessment procedures

- Gauge or LVDT (accuracy 0.1 mm)
- Scale for weighing duct or components

A.3.3.3 Test specimen temperature:
- \(23 \, ^\circ C \pm 5 \, ^\circ C\)

A.3.3.4 Test loads:
- All types of tendons: The applied longitudinal load for duct should be the load \(F_1\) required to achieve an elongation \(\Delta\) of the duct length \(L\) equal to 40 °C times the coefficient of linear expansion \(\alpha_T\) of polymer used times the relevant length \(L\):
  \[
  \Delta = 40 \times \alpha_T \times L
  \]
- For prefabricated tendons which are supplied on coils: The longitudinal load \(F_1\) valid for all types of tendons should not be smaller than the following \(F_{pre}\):

<table>
<thead>
<tr>
<th>Duct diameter (mm)</th>
<th>Applied load (F_{pre}) (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\leq 25)</td>
<td>250</td>
</tr>
<tr>
<td>(25 &lt; d_1 \leq 35)</td>
<td>400</td>
</tr>
<tr>
<td>(35 &lt; d_1 \leq 45)</td>
<td>600</td>
</tr>
<tr>
<td>(45 &lt; d_1 \leq 55)</td>
<td>900</td>
</tr>
<tr>
<td>(55 &lt; d_1 \leq 65)</td>
<td>1,100</td>
</tr>
<tr>
<td>(65 &lt; d_1 \leq 75)</td>
<td>1,400</td>
</tr>
<tr>
<td>(75 &lt; d_1 \leq 85)</td>
<td>1,600</td>
</tr>
<tr>
<td>(85 &lt; d_1 \leq 100)</td>
<td>1,900</td>
</tr>
<tr>
<td>(100 &lt; d_1 \leq 130)</td>
<td>2,200</td>
</tr>
<tr>
<td>(130 &lt; d_1 \leq 160)</td>
<td>2,400</td>
</tr>
</tbody>
</table>

A.3.3.5 Test procedure:
- Prepare test specimen
- Install test specimen into apparatus to apply load/maintain elongation
- Take initial measurements as noted in Fig. A.3-1:
  - Pull plate to pull plate prior to applying loads (A)
  - Free length (B)
  - Length of connector (C)
  - Base to top of connector (D)
  - Length from base to connector measurement point (E)
  - Outside of connector measurement points (F)
- Confirm test specimen temperature
- Duct for all types of tendons:
  - Gradually apply a longitudinal load to achieve an elongation of the duct length (E) equal to \(\Delta = 40 \times \alpha_T \times E\) (as per A.3.3.4) – confirmed by measuring additional length between base and connector measurement point
  - Once elongation is achieved, record applied load and length from base to connector (E) and outside of connector (F) measurement points
  - Maintain required elongation for 10 minutes
  - After maintaining required elongation for 10 minutes, record applied load and length from base to connector (E) and outside of connector (F) measurement points
• Duct for prefabricated tendons supplied in coils:
  ▪ Same procedure as for ducts for all types of tendons. However, the longitudinal load $F$ should be the larger of the two values $F_1$ and $F_{\text{pre}}$ according to A.3.3.4

• Measure and record:
  1. Test specimen temperature
  2. Test specimen lengths
  3. Applied elongation and corresponding longitudinal force $F_1$ and for prefabricated tendons $F_{\text{pre}}$
  4. Applied/sustained loads and corresponding elongation
  5. Mass of duct specimens
  6. Any unusual observations.

![Test specimen for longitudinal load test](image)

**Fig. A.3-1: Test specimen for longitudinal load test**

### A.3.4 Acceptance criteria

#### A.3.4.1 Tendon Protection Level (PL):

• Required for PL1:
  ▪ Maintain specified longitudinal load $F_{\text{pre}}$ for at least 10 minutes for ducts intended to be used with prefabricated tendons supplied on coils

• Required for PL2 and PL3:
  ▪ Maintain required elongation $\Delta = 40 \times \alpha \times L$ of the duct length for at least 10 minutes for ducts for all tendon applications
  ▪ Maintain specified longitudinal load $F_1$ for at least 10 minutes for ducts intended to be used with prefabricated tendons supplied on coils
  ▪ No visual slippage of connector
  ▪ No unusual observations that would indicate failure of duct system.

### A.3.5 Reporting

#### A.3.5.1 Test report should contain at a minimum:

• Date and location of testing
• Name of laboratory and individuals who performed and/or witnessed the testing
• Tested material properties including type/batch or lot numbers/designation of duct and connectors tested and coefficient of linear expansion of polymer used for duct
• Documentation that test specimens confirm to dimensional tolerances
• Mass of duct specimens
• Table containing test specimen temperature, measurements, applied elongation and applied/sustained loads, acceptance criteria and pass/fail designation for each sample tested
Annex A: Component assessment procedures

- Pictures of testing
- Manufacture’s component drawings (confidential information provided to authorized parties only)
- Any handwritten field notes used in preparing final report
- Certified calibration reports of measuring and testing equipment

A.3.5.2 FPC and audit test reports should contain at a minimum:
- Date and location of testing
- Name of individuals who performed and/or witnessed the testing
- Tested material properties and type/ batch or lot numbers /designation of duct and connectors tested
- Table containing test specimen temperature, recorded measurements, acceptance criteria, and pass/fail designation
A.4 Lateral load resistance of duct

A.4.1 Objective/purpose
A.4.1.1 To confirm lateral load resistance of duct at normal and high temperatures
A.4.1.2 To confirm duct is strong enough to resist damage due to curvature and load of concrete at the support point.

A.4.2 Performance requirements
A.4.2.1 What is essential:
• Performance
A.4.2.2 What is tested:
• Duct
A.4.2.3 How often are tests required or updated:
• Initially
• If a change of design and/or manufacturing process
• For each type of material used
A.4.2.4 Type of testing, number of tests, size of test specimens:
• Approval testing: 1 test per size, performed on all duct sizes (see Section 8.5)
• FPC testing: 1 per batch of duct manufacture, plus 1 for every new batch of compound, plus 1 for every additional month of continuous production (see Section 9.2)
• Audit testing: 2 duct sizes randomly selected (see Section 9.3).

A.4.3 Testing methods
A.4.3.1 Test specimens:
• Total length 1100 mm
• Do not use stiffeners between duct and duct support for testing

Note that this is the long end of test specimen from successful completion of testing for longitudinal load resistance of duct system (assessment procedure Annex A.3) with connector attached without re-assembly of duct connection and will also be used for flexibility of duct system (assessment procedure Annex A.5) and Leak Tightness of Duct System (Assessment Procedure Annex A.6)
A.4.3.2 Measuring and testing equipment:
• Vernier caliper (accuracy 0.1 mm)
• Thermometer (accuracy ± 0.5 °C)
• Load cell (accuracy ± 1 N or ± 1% of maximum test load whichever is larger)
• Scale for weighing duct or components
A.4.3.3 Test specimen temperature:
• 23 °C ± 5 °C
• At least 45 °C for approval testing only
A.4.3.4 Test loads:
• For round duct, the following lateral loads F should be applied to the specimens:
### Annex A: Component assessment procedures

<table>
<thead>
<tr>
<th>Duct diameter (mm)</th>
<th>Applied load $F_1$ (N) for residual duct deformation</th>
<th>Load $F_d$ (N) for immediate duct deformation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\leq 25$</td>
<td>500</td>
<td>250</td>
</tr>
<tr>
<td>$25 &lt; d_1 \leq 35$</td>
<td>600</td>
<td>300</td>
</tr>
<tr>
<td>$35 &lt; d_1 \leq 55$</td>
<td>750</td>
<td>375</td>
</tr>
<tr>
<td>$55 &lt; d_1 \leq 85$</td>
<td>950</td>
<td>475</td>
</tr>
<tr>
<td>$85 &lt; d_1 \leq 100$</td>
<td>1,050</td>
<td>700</td>
</tr>
<tr>
<td>$100 &lt; d_1 \leq 130$</td>
<td>1,050</td>
<td>1,050</td>
</tr>
<tr>
<td>$130 &lt; d_1 \leq 160$</td>
<td>1,050</td>
<td>1,050</td>
</tr>
</tbody>
</table>

- For flat or oval duct, the applied lateral load $F$ is based on the internal diameter in the short direction.

**A.4.3.5 Test procedure:**
- **Test set-up** (see Fig. A.4-1):
  - Place test specimen on a firm 500 mm long base
  - A plunger provided with a cylindrical end with a diameter of 12 mm (simulating reinforcing steel across duct) is used to apply load
  - Each test specimen should be loaded twice in two different locations between the ribs
  - The locations of loading should be situated in the middle third of the test specimen and should be no closer than 150 mm from each other
  - Flat duct should be tested/loaded on the shortest dimension
- **Test procedure**
  - Confirm test specimen temperature
  - Gradually apply specified lateral load to the test specimen over a period of at least 30 seconds. The maximum load $F_1$ should be held for two minutes
  - Release lateral load from test specimen
  - Data recording should be at lateral load $F_d$ (immediately after reaching lateral load $F_d$), at full lateral load $F_1$ (immediately after reaching lateral load $F_1$ and two minutes after), immediately after lateral load release and two minutes after lateral load release
  - Perform test procedure at two locations
- **Measure and record:**
  1. Test specimen temperature
  2. Record data at each of the two applied load locations
  3. At applied load $F_d$ – depth of indentation/deflection (immediately after reaching load)
  4. At full applied load $F_1$ – depth of indentation/deflection (immediate and after two minutes)
  5. Immediately after load release – depth of indentation/deflection
  6. Two minutes after load release – depth of indentation/deflection
  7. Mass of duct specimen
  8. Any visual damage.
A.4.4 Acceptance criteria

A.4.4.1 Same for all tendon Protection Levels (PL)
A.4.4.2 No deformations exceeding 35% of duct internal diameter immediately when reaching the specified lateral load $F_d$
A.4.4.3 No deformations exceeding 10% of duct internal diameter or 5 mm whichever is smaller two minutes after release of load $F_1$
A.4.4.4 No visual damage of test specimen.

A.4.5 Reporting

A.4.5.1 Test report should contain at a minimum:
- Date and location of testing
- Name of laboratory and individuals who performed and/or witnessed the testing
- Tested material properties and type/batch or lot numbers/designation of duct tested
- Documentation that test specimens confirm to dimensional tolerances
- Mass of duct specimens
- Table containing test specimen temperature; applied lateral loads $F_d$ and $F_1$; indentation/deflection at applied load $F_d$ (immediately after reaching load), indentation/deflection at applied load $F_1$ (immediately after two minutes), immediately after load release, and two minutes after load release; acceptance criteria; and pass/fail designation for each sample tested
- Pictures of testing
- Manufacture’s component drawings (confidential information provided to authorized parties only)
- Any hand written field notes used in preparing final report
- Certified calibration reports of measuring and testing equipment

A.4.5.2 FPC and audit test reports should contain at a minimum:
- Date and location of testing

Fig. A.4-1: Lateral load test set-up
• Name of individuals who performed and/or witnessed the testing
• Tested material properties and type/batch or lot numbers/designation of duct and connectors tested
• Table containing test specimen temperature, recorded measurements, acceptance criteria, and pass/fail designation
A.5 **Flexibility of duct system**

A.5.1 **Objective/purpose**

A.5.1.1 To confirm duct and duct connectors stay connected when bent to a radius of curvature that will be used during shipping or in the field

A.5.1.2 To confirm duct and duct connectors do not collapse in on themselves when bent to a radius of curvature that will be used during shipping or in the field

A.5.1.3 To confirm flexibility of the duct system at normal, low and high temperature

A.5.2 **Performance requirements**

A.5.2.1 What is essential:

- Performance

A.5.2.2 What is tested:

- Duct and duct connectors

A.5.2.3 How often are tests required or updated:

- Initially
- If a change of design and/or manufacturing process
- For each type of material used
- When a new connector is proposed for use

A.5.2.4 Type of testing, number of tests, size of test specimens:

- Approval testing: 1 test per size, performed on all duct sizes with each connector (see Section 8.5)
- FPC testing: 1 per batch of duct manufacture, plus 1 for every new batch of compound, plus 1 for every additional month of continuous production (see Section 9.2)
- Audit testing: 2 duct sizes with corresponding connectors randomly selected (see Section 9.3).

A.5.3 **Testing methods**

A.5.3.1 Test specimens:

- Total length 1,100 mm
- Connector placed at approximate centre of sample
- Duct – two sample lengths of approximately 550 mm
- Connector – actual connector used

\*Note that this is the test specimen from successful completion of testing for longitudinal load resistance of duct system (assessment procedure Annex A.3) and lateral load resistance of duct (assessment procedure Annex A.4) without re-assembly of duct connection, and will also be used for leak tightness of duct system (assessment procedure Annex A.6) without re-assembly of duct connection\*

\*Note that the long end of the previously tested specimen is cut to a length of 550 mm for a total length of 1100 mm\*

A.5.3.2 Measuring and testing equipment:

- Plunger (accuracy ± 0.5 mm)
- Thermometer (accuracy ± 0.5 °C)
- Scale for weighing duct or components
- Curved templates (accuracy ± 3% of specified radius)

- For prefabricated tendons only and flat and round ducts intended to be coiled:
### Duct diameter (mm) | Radius (mm)
--- | ---
≤ 85 | 750
> 85 and ≤ 100 | 900
> 100 and ≤ 130 | 1,000

- For all tendons: Radius = Manufacturer’s declared minimum radius of curvature for field installation

#### A.5.3.3 Test specimen temperature:
- 23 °C ± 5 °C
- At no more than -15 °C for approval testing only
- At least 45 °C for approval testing only

#### A.5.3.4 Test procedure:
- Prepare templates
  - Manufacture curved templates – see Fig. A.5-1.
    *Note that a recess may be installed in the template to accommodate connector*
  - Two curved templates should be held firmly in position
  - Space curved templates so that duct fits firmly between the curved templates at the base
- Prepare plunger
  - Manufacture plunger – see Fig. A.5-2 for generic dimensions
  - Diameter of plunger is 95% of duct internal diameter
  - Plunger for flat duct has a diameter of 95% of smallest dimension
  - Each size duct should have a unique plunger
    *Note that a ball is not to be substituted for the plunger*
- Confirm test specimen temperature
- Insert test specimen between curved templates
- Test specimen should be bent slowly (at least 5 seconds each) around the template twice in each direction (total of four bends) – see Fig. A.5-3
- Hold the duct in the last bent position for two minutes
- After two minutes and while in the last bent position, a plunger is inserted and should easily pass the whole length of test specimen
- Measure and record:
  1. Test specimen temperature
  2. Actual plunger dimensions
  3. Mass of specimen
  4. Whether plunger easily passes the whole length of the test specimen while in the final bent position
  5. Any visual damage or deformation.
A.5.4 Acceptance criteria

A.5.4.1 Same for all tendon Protection Levels (PL)
A.5.4.2 No deformations exceeding 5% of duct internal diameter while test specimen is in final bent position – confirmed by easy passage of plunger
A.5.4.3 No visual damage of test specimen.

A.5.5 Reporting

A.5.5.1 Test report should contain at a minimum:
• Date and location of testing
• Name of laboratory and individuals who performed and/or witnessed the testing
• Tested material properties and type/batch or lot numbers/designation of duct and connectors tested
• Documentation that test specimens confirm to dimensional tolerances
• Table containing test specimen temperature, test radius, acceptance criteria and pass/fail designation for each sample tested
• Mass of duct specimens
• Pictures of testing
• Manufacture’s component drawings (confidential information provided to authorized parties only)
• Any hand written field notes used in preparing final report
• Certified calibration reports of measuring and testing equipment

A.5.5.2 FPC and audit test reports should contain at a minimum:
• Date and location of testing
• Name of individuals who performed and/or witnessed the testing
• Tested material properties and type/ batch or lot numbers /designation of duct and connectors tested
• Table containing test specimen temperature, recorded measurements, acceptance criteria, and pass/fail designation.
A.6 Leak tightness of duct system

A.6.1 Objective/purpose

A.6.1.1 To confirm duct system maintains mortar/leak tightness when exposed to project conditions
A.6.1.2 To confirm duct and duct connectors maintain mortar/leak tightness when bent to minimum specified field installation radius of curvature after the system is subjected to longitudinal load, lateral load and flexibility tests.

A.6.2 Performance requirements

A.6.2.1 What is essential:
• Performance
A.6.2.2 What is tested:
• Duct and duct connectors
A.6.2.3 How often are tests required or updated:
• Initially
• If a change of design and/or manufacturing process
• For each type of material used
• When a new connector is proposed for use
A.6.2.4 Type of testing, number of tests, size of test specimens:
• Approval testing: 1 test per size, performed on all duct sizes with each connector (see Section 8.5)
• FPC testing: 1 per batch of duct manufacture, plus 1 for every new batch of compound, plus 1 for every additional month of continuous production (see Section 9.2)
• Audit testing: 2 duct sizes with corresponding connectors randomly selected (see Section 9.3)

A.6.3 Testing methods

A.6.3.1 Test specimens:
• Total length 1100 mm
• Connector placed at approximate centre of sample
• Connector – actual connector used
• Template for minimum specified field installation radius of curvature

Note that this is the test specimen from successful completion of testing for longitudinal load resistance of duct system (assessment procedure Annex A.3), lateral load resistance of duct (assessment procedure Annex A.4) and flexibility of duct system (assessment procedure Annex A.5) without re-assembly of duct connection

A.6.3.2 Measuring and testing equipment:
• Thermometer (accuracy ± 0.5 °C)
• Pressure gauge [accuracy ± 0.01 bar (0.001 N/mm²)]
• Scale for weighing duct or components
• Curved template for minimum specified radius of curvature (accuracy ± 3% of radius)
A.6.3.3 Test specimen temperature:
• 23 °C ± 5 °C
A.6.3.4 Test procedure:
• Prepare test specimen
• Seal both ends of test specimen
• Attach test specimen to curved template and maintain radius throughout test
• Confirm test specimen temperature
• Positive pressure test for PL1:
  ▪ Fill test specimen with water
  ▪ Measure quantity of water in test specimen prior to test
  ▪ Replace water in test specimen prior to applying test pressure
  ▪ Apply positive pressure of 0.5 bar (0.050 N/mm²)
  ▪ Maintain pressure throughout test
  ▪ Test duration is 5 minutes
  ▪ Capture any water that leaks out of test specimen
  ▪ Measure quantity of water remaining at completion of test
• Positive pressure test for PL2 and PL3:
  ▪ Apply positive pressure of 0.5 bar (0.050 N/mm²)
  ▪ Maintain pressure throughout test
  ▪ Submerge into water tank
  ▪ Hold submerged for duration of test
    ▪ For PL2 duration is 5 minutes
    ▪ For PL3 duration is 30 minutes
  ▪ Look for air expulsion during duration of test
  ▪ Remove from water tank
• Negative pressure test (vacuum) for PL2 and PL3:
  ▪ Apply negative pressure of 0.5 bar (0.050 N/mm²)
  ▪ Maintain pressure throughout test
  ▪ Submerge into water tank
  ▪ Hold submerged for duration of test
    ▪ For PL2 duration is 5 minutes
    ▪ For PL3 duration is 30 minutes
  ▪ Remove from water tank
  ▪ Look for water penetration inside of duct
• Measure and record:
  1 Test specimen temperature
  2 Tested pressure
  3 Tested radius or radii
  4 Test duration
  5 Mass of duct specimens
  6 Observations for PL1:
    ▪ Quantity of water in test specimen prior to test
    ▪ Quantity of water in test specimen at completion of test
  7 Observations for PL2 and PL3:
    ▪ Note any air expulsion during duration of positive pressure test and record location
    ▪ Note any water penetration inside of duct during negative pressure test.

A.6.4 Acceptance criteria
A.6.4.1 Required for PL1:
  • Less than 1.5% loss of water
A.6.4.2 Required for PL2 and PL3:
  • For PL2 duration is 5 minutes
• For PL3 duration is 30 minutes
• No visibly detectable leaks with positive pressure
• No visibly detectable leaks with negative pressure

A.6.5 Reporting

A.6.5.1 Test report should contain at a minimum:
• Date and location of testing
• Name of laboratory and individuals who performed and/or witnessed the testing
• Tested material properties and type/batch or lot numbers/designation of duct and connectors tested
• Documentation that test specimens confirm to dimensional tolerances
• Mass of duct specimens
• Confirmation that test specimen used herein successfully completed testing for longitudinal load resistance of duct system A.3, lateral load resistance of duct A.4 and flexibility of duct system A.5
• Table containing test specimen temperature, radius of curvature, tendon protection level tested, test pressure, duration of test and pass/fail designation for each sample tested
• Pictures of testing
• Manufacturer’s component drawings (confidential information provided to authorized parties only)
• Any handwritten field notes used in preparing final report
• Certified calibration reports of measuring and testing equipment

A.6.5.2 FPC and audit test reports should contain at a minimum:
• Date and location of testing
• Name of individuals who performed and/or witnessed the testing
• Tested material properties and type/batch or lot numbers/designation of duct and connectors tested
• Table containing test specimen temperature, recorded measurements, acceptance criteria, and pass/fail designation.
A.7 Concrete pressure on duct

A.7.1 Objective/purpose

A.7.1.1 To confirm duct will not collapse or compress more than 10% when exposed to hydrostatic pressure of 3.0 m (Class I) or 1.0 m (Class II) of normal weight concrete and bent to the minimum radius of tendon curvature for field installation.

A.7.2 Performance requirements

A.7.2.1 What is essential:

• Performance. Two performance Classes I and II are considered. Class I is for general use of polymer ducts, Class II is for use in shallow concrete members up to 1 m in depth only

A.7.2.2 What is tested:

• Duct

A.7.2.3 How often are tests required or updated:

• Initially
• If a change of design and/or manufacturing process
• For each type of material used

A.7.2.4 Type of testing, number of tests, size of test specimens:

• Approval testing: 1 test per size, performed on all duct sizes (see Section 8.5)
• FPC testing: Not required (see Section 9.2)
• Audit testing: Not required (see Section 9.3)

A.7.3 Testing methods

A.7.3.1 Test specimens:

• Total length 1,000 mm

A.7.3.2 Measuring and testing equipment:

• Thermometer (accuracy ± 0.5 °C)
• Pressure gauge [accuracy ± 0.01 bar (0.001 N/mm²)]
• Scale for weighing duct or components
• Curved template for minimum specified radius of curvature (accuracy ± 3% of radius)

A.7.3.3 Test specimen temperature:

• 23 °C ± 5 °C

A.7.3.4 Test procedure:

• Prepare test specimen
• Seal both ends of test specimen
• Bend test specimen on template to manufacturer’s declared minimum radius of curvature for field installation (see A.5 flexibility of duct system) and hold in bent position for at least 30 minutes
• Confirm test specimen temperature
• Negative pressure test (vacuum):
  • Apply negative pressure of 0.75 bar (0.075 N/mm²) or 0.25 bar (0.025 N/mm²) for Class I or Class II, respectively
  • Maintain pressure for at least 5 minutes
  • During test look for duct deformation (collapse in on itself) and measure duct diameter in plane of template and at right angle to plane before bending, immediately after bending, 30 minutes after bending, after application of pressure and just before releasing the pressure
Note that the test may be performed with positive pressure from the outside of the duct

- Measure and record:
  1. Test specimen temperature
  2. Tested pressure
  3. Radius of curvature of template for duct specimen
  4. Mass of specimens
  5. Test duration
  6. Dimensions of outside of duct:
     i. Prior to bending of duct specimen
     ii. In bent position 30 minutes after bending prior to application of test pressure
     iii. After five minutes of holding test pressure
     iv. Just before release of test pressure
     v. Five minutes after release of test pressure
  7. Observations:
     i. Note any changes in geometry of duct, such as indentations, ovalizing or collapsing.

A.7.4 Acceptance criteria

A.7.4.1 Same for all tendon Protection Levels (PL)
A.7.4.2 Tested at negative pressure of 0.75 bar (0.075 N/mm$^2$) or 0.25 bar (0.025 N/mm$^2$) for five minutes for Class I or Class II, respectively
A.7.4.3 No changes in geometry/duct diameter of more than 10% in plane of template and at right angle to plane:
   - For round duct, average diameter prior to application of test pressure versus at five minutes of applied pressure
     *Note: consider absolute values of change for average*
   - For flat duct, average long and short dimension prior to application of test pressure versus at five minutes of applied pressure
     *Note: consider absolute values of change for average*
A.7.4.4 No collapse of duct.

A.7.5 Reporting

A.7.5.1 Test report should contain at a minimum:
   - Date and location of testing
   - Name of laboratory and individuals who performed and/or witnessed the testing
   - Tested material properties and type/batch or lot numbers/designation of duct tested
   - Documentation that test specimens confirm to dimensional tolerances
   - Mass of duct specimens
   - Table containing test specimen temperature, radius of curvature of duct in test, test pressure, duration of test, measured dimensions, observations and pass/fail designation for each sample tested
   - Declaration of performance Class I or Class II as applicable
   - Pictures of testing
   - Manufacture’s component drawings (confidential information provided to authorized parties only)
   - Any hand written field notes used in preparing final report
• Certified calibration reports of measuring and testing equipment
A.7.5.2 FPC and audit test reports should contain at a minimum:
• Date and location of testing
• Name of individuals who performed and/or witnessed the testing
• Tested material properties and type/ batch or lot numbers /designation of duct and connectors tested
• Table containing test specimen temperature, recorded measurements, acceptance criteria, and pass/fail designation.
A.8 Wear resistance of duct

A.8.1 Objective/purpose

A.8.1.1 To confirm that a minimum residual wall thickness can be maintained during stressing at a given maximum clamping force on a strand
A.8.1.2 To confirm the minimum bend radius for duct at normal and high temperature
A.8.1.3 To confirm the minimum residual wall thickness for different tendon Protection Levels (PL)
A.8.1.4 To allow for supplemental testing for project specific criteria such as temperature adjustments or movement distance (current movement is 750 mm representing single end stressing of a 125 m long tendon consisting of strand or wire)

A.8.2 Performance requirements

A.8.2.1 What is essential:
- Performance

A.8.2.2 What is tested:
- Duct subjected to wearing action of strand:
  - For each temperature
  - For manufacturer’s declared maximum clamping force representing conditions for minimum radius of curvature for field installation

  *Note: The proposed test method is performed with strands of 15.2 or 15.7 mm nominal diameter. The test is considered valid for tendons with smaller diameter strand also.*

  *Note: The proposed test method using strand does apply equally for tendons with wire. However, the test method does not apply for tendons with bars.*

A.8.2.3 How often are tests required or updated:
- Initially
- If a change of design and/or manufacturing process
- For each type of material used

A.8.2.4 Type of testing, number of tests, size of test specimens:
- Approval testing: 1 test per size, performed on all duct sizes, (see Section 8.5)
- FPC testing: 1 per batch of duct manufacture, plus 1 for every new batch of compound, plus 1 for every additional month of continuous production (see Section 9.2)
- Audit testing: 2 duct sizes randomly selected (see Section 9.3)
- Supplemental testing to satisfy project specific criteria as per project specifications.

A.8.3 Testing methods

A.8.3.1 Test specimens:
- Two strips cut from actual production polymer duct

  *Note that for flat duct this is on long side or the side that the strand will bear against*

- Each duct strip should be cut such as to consist of approximately 1/8 of the duct circumference (45 of 360 degrees)

  *Note that for large diameter duct less than 1/8 of the duct circumference will need to be used so as not to restrict wear by binding the two duct pieces in the test apparatus. Note that for flat duct strips the width should be at least 30 mm*
• Each duct strip should have a length of twice the rib/corrugation spacing but not less than 100 mm total length with the ribs placed symmetrically over the length of the specimen
• Wall thickness of each duct strip should be measured in at least six locations, in the longitudinal axis of the strips, spaced equally in about the middle half of specimen length, at locations which will likely be in contact with the prestressing steel, and the location and values recorded
• Measure the mass of duct specimen from which the strips are cut
• Each duct strip should be mounted in a supporting body
• See Figure A.8-1 for sample test specimen

Fig. A.8-1: Test Specimen

A.8.3.2 Test apparatus:
• A testing machine or suitable test frame with the capability to maintain one element of clean, 7-wire prestressing strand (15.2 or 15.7 mm) with at least one meter of free length in a stressed condition of 70% of its tensile strength
• A device to move the test specimen along the prestressing steel in a controlled manner
• A hydraulic jack or mechanical device to press the test specimen consisting of two duct strips against the prestressing steel with the specified clamping force
• A load cell to confirm the clamping force
• See Figure A.8-2 for sample test set-up
• Two supporting bodies compatible with the outer duct surface
A.8.3.3 Measuring and testing equipment:
- Thermometer (accuracy ± 0.5 °C)
- Vernier caliper (accuracy 0.1 mm)
  Note that the caliper points should be rounded not sharp or pointed
- Load cells (accuracy ± 1 N or ± 1% of maximum test load whichever is larger)
- Scale for weighing duct or components

A.8.3.4 Test specimen temperature:
- Normal temperature, 23 °C ± 5 °C
- High temperature, at least 45 °C for approval testing only

A.8.3.5 Identification of clamping force Q:
- Identify and declare clamping force Q between strand and duct samples for wear testing
  Note: Identified clamping force Q may be related to tendon force, duct size and filling degree and tendon radius of curvature according to Section 6.8

A.8.3.6 Test procedure:
- Prepare test specimen
- Prepare test apparatus
- The prestressing strand should be stressed to (or maintained at) a force F of 70% of its tensile strength
- Confirm test specimen temperature, and maintain test specimen temperature throughout testing
- Test specimen consisting of two duct strips mounted in supporting bodies should be installed on opposite sides across the diameter of the prestressing strand
Annex A: Component assessment procedures

- Test specimen consisting of the two duct strips should then be clamped by means of a hydraulic jack or mechanical device to the prestressing strand with an initial clamping force of 10% of Q as per A.8.3.5
- Test specimen should then be moved along the prestressing strand over a total distance of 750 mm while increasing the clamping force proportionally to the movement so as to reach Q as per A.8.3.5 when the total movement of 750 mm is attained, without allowing the specimen to rotate around the strand
- Movement should be accomplished in a time frame of two minutes ± 30 seconds after applying initial clamping force of 10% of Q
- Hold the test specimens in final position while maintaining clamping force Q for an additional 2 minutes
- Clamping force Q should then be released
- Remove duct strips from supporting bodies
- Immediately measure and record the residual wall thickness at the same longitudinal locations where initial thickness measurements were made, however, in transverse direction at these locations where the wall thickness is deemed to be lowest
- Measure and record:
  1. Test specimen temperature
  2. Mass of duct prior to cutting duct strips
  3. Tested clamping force Q
  4. Actual movement and time for movement
  5. Wall thickness:
     i. Initial wall thickness at six locations spaced equally in about the middle half of each duct strip
     ii. Residual wall thickness at conclusion of testing at same six longitudinal locations on each duct strip however, in transverse direction at these locations where the wall thickness is deemed to be lowest.

A.8.4 Acceptance criteria

A.8.4.1 For PL1, minimum residual wall thickness after testing is 1.0 mm at all sections
A.8.4.2 For PL2 and PL3, minimum residual wall thickness after testing is 1.5 mm at all sections.

A.8.5 Reporting

A.8.5.1 Test report should contain at a minimum:
- Date and location of testing
- Name of laboratory and individuals who performed and/or witnessed the testing
- Tested material properties and type/batch or lot numbers/designation of duct tested
- Documentation that test specimens confirm to dimensional tolerances
- Mass of duct specimens prior to cutting of duct strips
- Table containing test specimen temperature, type of strand, clamping force Q and how applied, actual measurement locations on test specimens, individual measurements of initial wall thickness, individual measurements of residual wall thickness after testing, and pass/fail designation for each sample tested per tendon PL
- Pictures of testing and test samples before and after testing
• Manufacture’s component drawings (confidential information provided to
  authorized parties only)
• Any hand written field notes used in preparing final report
• Certified calibration reports of measuring and testing equipment

A.8.5.2 FPC and audit test reports should contain at a minimum:
• Date and location of testing
• Name of individuals who performed and/or witnessed the testing
• Tested material properties and type/batch or lot numbers/designation of duct and
  connectors tested
• Table containing test specimen temperature, recorded measurements, acceptance
  criteria, and pass/fail designation

A.8.5.3 Supplemental testing:
• Requirements, testing methods, acceptance criteria and reporting are identical to
  Section A.8.5.1 above
A.9 Wear resistance of duct under sustained load

A.9.1 Objective/purpose

A.9.1.1 To confirm that a minimum residual wall thickness can be maintained in a stressed tendon over a period of time (14-days) at a given clamping force prior to grouting of the tendon

A.9.1.2 To confirm the minimum bend radius for duct at normal and high temperature

A.9.1.3 To confirm the minimum residual wall thickness for different tendon protection levels (PL).

A.9.2 Performance requirements

A.9.2.1 What is essential:
- Performance

A.9.2.2 What is tested:
- Duct subjected to sustained wearing action of strand:
  - For each temperature
  - For manufacturer’s declared maximum clamping force representing conditions for minimum radius of curvature for field installation
  
  Note: The proposed test method is performed with strands of 15.2 or 15.7 mm nominal diameter. The test is considered valid for tendons with smaller diameter strand also
  
  Note: The proposed test method using strand does apply equally for tendons with wire. However, the test method does not apply for tendons with bars

A.9.2.3 How often are tests required or updated:
- Initially
- If a change of design and/or manufacturing process
- For each type of material used

A.9.2.4 Type of testing, number of tests, size of test specimens:
- Approval testing: 1 test per size, performed on all duct sizes (see Section 8.5)
- FPC testing: Not required (see Section 9.2)
- Audit testing: Not required (see Section 9.3)

A.9.3 Testing methods

A.9.3.1 Test specimens:
- Test specimens from successful completion of wear resistance of duct testing (assessment procedure Annex A.8) are used for this test

A.9.3.2 Test apparatus:
- Test apparatus is similar to that used in wear resistance of duct testing (assessment procedure Annex A.8)
- A testing machine or suitable test frame with the capability to maintain one element of clean, 7-wire prestressing strand (15.2 or 15.7 mm) with at least one meter of free length in a stressed condition of 70% of its tensile strength
- A hydraulic jack or mechanical device to press the test specimen consisting of two duct strips against the prestressing strand with the specified clamping force
- A load cell to confirm the clamping force
- Scale for weighing duct or components
- Two supporting bodies compatible with the outer duct surface
A.9.3.3 Measuring and testing equipment:
• Thermometer (accuracy ± 0.5 °C)
• Vernier caliper (accuracy 0.1 mm)
• Load cells (accuracy ± 1 N or ± 1% of maximum test load whichever is larger)

A.9.3.4 Test specimen temperature:
• Normal temperature, 23 °C ± 5 °C
• High temperature, at least 45 °C for approval testing only

A.9.3.5 Determination of clamping force Q
• Clamping force Q should be the same as used in wear resistance of duct testing (assessment procedure Annex A.8) for these test specimens

A.9.3.6 Test procedure:
• Prepare test apparatus
• The prestressing strand should be stressed to (or maintained at) a force F of 70% of its tensile strength
• Confirm test specimen temperature, and maintain test specimen temperature throughout testing
• On successful completion of wear resistance of duct testing (assessment procedure Annex A.8):
  ▪ Immediately replace tested duct strips back into their supporting bodies
  ▪ Mount the supporting bodies on opposite sides across the diameter of the prestressing strand
• Test specimen consisting of the two duct strips should then be clamped by means of a hydraulic jack or mechanical device to the prestressing strand with a clamping force Q as per A.9.3.5
• Clamping force Q should be maintained for 14 days
• After 14 days, clamping force Q should be released
• Remove duct strips from the supporting body
• Immediately measure and record the residual wall thickness at the same longitudinal locations where initial thickness measurements were made, however, in transverse direction at these locations where the wall thickness is deemed to be lowest
• Measure and record:
  1. Test specimen temperature over duration of test
  2. Mass of duct prior to cutting duct strips
  3. Tested clamping force Q over duration of test
  4. Wall thickness:
     i. Initial wall thickness at six locations spaced equally in about the middle half of each duct strip
     ii. Residual wall thickness at conclusion of testing at same six longitudinal locations on each duct strip however, in transverse direction at these locations where the wall thickness is deemed to be lowest

A.9.4 Acceptance criteria
A.9.4.1 For PL1, minimum residual wall thickness after testing is 0.5 mm at all sections
A.9.4.2 For PL2 and PL3, minimum residual wall thickness after testing is 1.0 mm at all sections.
A.9.5 Reporting

A.9.5.1 Test report should contain at a minimum:

- Date and location of testing
- Name of laboratory and individuals who performed and/or witnessed the testing
- Tested material properties and type/batch or lot numbers/designation of duct tested
- Documentation that test specimens confirm to dimensional tolerances
- Mass of duct specimens prior to cutting of duct strips
- Table containing test specimen temperature, type of strand, clamping force Q and how applied, actual measurement locations on test specimens, individual measurements of initial wall thickness, individual measurements of residual wall thickness after testing, and pass/fail designation for each sample tested per tendon PL
- Pictures of testing and test samples before and after testing
- Manufacture’s component drawings (confidential information provided to authorized parties only)
- Any hand written field notes used in preparing final report
- Certified calibration reports of measuring and testing equipment

A.9.5.2 Supplemental testing:

- Requirements, testing methods, acceptance criteria and reporting are identical to Section A.9.5.1 above.
A.10 Bond behaviour of duct

A.10.1 Objective/purpose

A.10.1.1 To confirm bond characteristics between duct/grout and duct/concrete
A.10.1.2 To confirm the ability of duct to transfer a load of 40% of the ultimate tensile force of the tendon over a duct length of not more than 16 duct diameters.

A.10.2 Performance requirements

A.10.2.1 What is critical:
• Performance
A.10.2.2 What is tested:
• Duct subjected to bond action with strands

Note: Since the test addresses the bond capacity of the duct to grout or surrounding concrete, this test is performed with strand only even if the duct is intended to be used with wire

A.10.2.3 How often are tests required or updated:
• Initially
• If a change of design and/or manufacturing process
• For each type of material used

A.10.2.4 Type of testing, number of tests, size of test specimens:
• Approval testing: 1 test per size, performed on 3 duct sizes, i.e. small, medium and largest (see Section 8.5)
• FPC testing: Not required (see Section 9.2)
• Audit testing: Not required (see Section 9.3).

A.10.3 Testing methods

A.10.3.1 Test specimens:
• Identify and declare minimum tendon bond force $F_{bu}$ for the duct size being tested which may be based on consideration of:
  ▪ Maximum number of tensile elements (strand) inside actual duct size or alternatively, based on a filling ratio of (cross sectional area of prestressing steel) / (duct cross sectional area based on internal diameter) = 0.45 (number of strands rounded up to next full number)
  ▪ Use the highest characteristic tensile strength of strand for use with the duct
  ▪ Multiply the area of maximum number of strand times its highest characteristic tensile strength to determine the relevant ultimate tensile force for the tendon in the duct being tested
  ▪ Minimum bond test load $F_{bu}$ is 40% of relevant ultimate tensile force
• Identify length of duct to transfer test load $F_{bu}$ of 40% of ultimate tensile force:
  ▪ No more than 16 internal duct diameters ($d_1$)
• Dimensions of test beam (refer to Fig. A.10.1):
  ▪ Grouted bond length ‘l’ is no more than 16 times the internal diameter $d_1$ of the duct
  ▪ Maximum cross sectional width ‘a’ should be no more than the minimum centre to centre spacing of anchorages for the particular tendon size as per the PT system approval but not more than $a = 1.2 \sqrt{P_u / f_{cm,0}}$ where $P_u$ is the ultimate capacity of the tendon and $f_{cm,0}$ is the concrete strength at which stressing of the tendon to full load is permitted
Note that a circular test specimen of diameter $a$ is acceptable

- Skin reinforcement should be provided by internal reinforcing steel, 1% by volume (approximately 50 kg/m³ in form of closed stirrups and 30 kg/m³ in form of longitudinal bars)
- Duct should be installed in the centre of test specimen
- Concrete:
  - Cylinder compressive strength at the start of test = 30 - 40 N/mm² (determined as average of 3 cylinders)
  - Slump = 100 ± 20 mm
  - Maximum size of coarse aggregate = 20 mm
- Prestressing strand
  - Place a sufficient number of strands such as to reach the minimum bond test load $F_{bu}$ without exceeding a tensile stress of about 75% of the ultimate tensile strength in the strand
  - Length of strand should extend the length of the duct and, on the loaded end, a free length (for installation of stressing equipment, pull heads, jack chairs, etc.) and on the unloaded end for access to strand tails
- Grout:
  - PT Grout may either comply with PTI M55.1-12, Specification for Grouting of Post-Tensioned Structures or EN 447 or fib Bulletin 20
  - Compressive strength at the start of test = 30 - 40 N/mm² (determined as average of 3 tests on halves of prisms or cubes)

Fig. A.10.1: Bond test specimen

A.10.3.2 Measuring and testing equipment:
- Thermometer (accuracy ± 0.5 °C)
- Load cell or calibrated stressing ram (accuracy ± 1 N or ± 1% of maximum test load whichever is larger)
- Extensometer or dial gauge (accuracy ± 0.01mm)
- Scale for weighing duct or components

A.10.3.3 Test temperature:
- 23 °C ± 5 °C

A.10.3.4 Test procedure:
- Prepare test specimen:
  - Form test specimen
  - Place skin reinforcement in formwork
  - Place duct into centre of formwork
  - Place concrete in formwork
i. Air cure test specimen
ii. Take concrete specimens for compressive testing – air cure next to bond test specimen

- Remove formwork
- Place required number of strands into duct prior to grouting and centre inside duct
- Grout test specimen over grouted length l once concrete has attained sufficient strength to resist any grouting pressures. Grouting may be done by gravity with the test specimen in vertical position
  i. Air cure test specimen
  ii. Take grout specimens for compressive testing – air cure next to bond test specimen

- Required compressive strength prior to testing:
  - Concrete = 30 - 40 N/mm² at start of test (cylinder strength)
  - Grout = 30 - 40 N/mm² at start of test (cube strength)
- Prepare test specimen for testing:
  - At the unloaded end of test specimen, set up extensometers / dial gauges to enable continuous, relative movement measurements of:
    i. A minimum of four strands or all strands if less than four
    ii. Grout column
    iii. Duct
  - At the loaded end of test specimen, set up stressing equipment, pull heads, jack chair, load cell and any other apparatus necessary to stress the test specimen
- Testing:
  - Test load is F_{bu} according to A.10.3.1
  - Test specimen should be loaded gradually in increments of force in a minimum of four load steps until test load F_{bu} is achieved or bond failure of tendon occurs
  - Load should be held at each load step for a minimum duration of 2 minutes
- Measure and record:
  1. Test specimen designation
  2. Test temperature
  3. Mass of duct specimen
  4. Concrete (cylinder) and grout (cube) strength at start of testing
  5. Measurements:
     i. Force at each load step
     ii. Duration force is held at each load step
     iii. Displacement at each load step of all instrumented strands, grout column, and duct
  6. Location and mode of failure if any
  7. Any unusual observations.

A.10.4 Acceptance criteria

A.10.4.1 Same for all tendon protection levels (PL)
A.10.4.2 Maintain full test load F_{bu} for at least two (2) minutes duration without excessive strand slippage, grout column to duct failure, or duct to concrete failure:
• The relative movement of tendon and grout versus concrete should stabilize within the 2 minutes. If it does not, the full test load $F_{bu}$ should be maintained until the relative movement has stabilized.

• Excessive strand slippage is defined as movement of any strand greater than 5mm.

• Grout column to duct failure is defined as movement of grout column greater than 5mm.

• Duct to concrete failure is defined as movement of duct greater than 5mm.

Note: Invalid test results do not need to be reported, i.e. do not represent a failed test. A test in which excessive strand slippage occurs is considered an invalid test since the investigated failure mode of bond failure of duct to grout or to concrete did not occur.

A.10.5 Reporting

A.10.5.1 Test report should contain for valid tests only at a minimum:

• Date and location of testing

• Name of laboratory and individuals who performed and/or witnessed the testing

• Tested material properties and type/batch or lot numbers/designation of duct tested

• Mass of duct specimens prior to testing

• Calculations and information including documentation that duct test specimens confirm to dimensional tolerances; calculations for ultimate tensile force of tendon for duct size being tested; declared minimum tendon bond force $F_{bu}$; calculations of length of duct and test beam dimensions; concrete mixture, slump, and strength at testing; and grout material, mixture, flow time, and strength at testing

• Table containing test temperature; test specimen designation; force at each load step (begin and end of holding force); duration force is held at each load step; time until relative movement of tendon and grout versus concrete stabilizes; recorded displacement of strands, grout column and duct at each load step; observations and pass/fail designation for each specimen tested

• Pictures of testing (rebar cage, duct installed in formwork, unloaded tendon end)

• Manufacture’s component drawings (confidential information provided to authorized parties only)

• Any hand written field notes used in preparing final report

• Certified calibration reports of measuring and testing equipment.
A.11 Precast segmental duct coupler system

A.11.1 Objective/purpose

A.11.1.1 To confirm precast segmental coupler will perform in the field
A.11.1.2 To confirm precast segmental coupler gasket (seal) compresses at a force lower than segment erection temporary prestressing force without acting as a shim
A.11.1.3 To confirm precast segmental coupler system maintains pressure so as to prevent intrusion of possibly contaminated water and efflux of grout
A.11.1.4 To confirm precast segmental coupler system remains intact without failure, free of epoxy during segment erection, and components remain properly attached without crushing, tearing, or other signs of failure.

A.11.2 Performance requirements

A.11.2.1 What is essential:
• Performance
A.11.2.2 What is tested:
• Precast segmental coupler system
A.11.2.3 How often are tests required or updated:
• Initially
• If a change of design and/or manufacturing process
• For each type of material used
A.11.2.4 Type of testing, number of tests, size of test specimens:
• Approval testing: 1 test per size, performed on all segmental duct coupler sizes (see Section 8.5)
• FPC testing: Not required (see Section 9.2)
• Audit testing: Not required (see Section 9.3)

A.11.3 Testing methods

A.11.3.1 Test specimens:
• All final components necessary for a complete precast segmental duct coupler system
• Temporary components such as caps, load plugs, fixing devices, etc. that are not part of the final system may be used in their capacity but are not tested
A.11.3.2 Measuring and testing equipment:
• Thermometer (accuracy ± 0.5 °C)
• Pressure gauge [accuracy ± 0.01 bar (0.001 N/mm²)]
• Load cell (accuracy ± 1 N or ± 1% of maximum test load whichever is larger)
• Scale for weighing duct or components
A.11.3.3 Test specimen temperature:
• 23 °C ± 5 °C
A.11.3.4 Test procedure:
• Cast the precast segmental duct coupler with duct and connectors (assembly) into a two part concrete test block (at least 300 mm x 300 mm x 300 mm) using match cast techniques
• After the concrete has hardened, separate the blocks and clean the joining surface of any bond breaker material
• Sealing gasket required compressive force:
  • Hold a piece of paper between test blocks
Using an external apparatus, apply a compressive force to the concrete test blocks to compress the sealing gasket to its final position
- Confirmation of final position is when paper cannot be removed
- Record compressive force

• Precast segmental duct coupler air pressure test:
  - Do not apply epoxy between the test blocks during this test
  - Seal ends of duct where they exit the test blocks
  - Using an external apparatus, clamp the test blocks together and maintain a force to produce a 0.275 N/mm² (2.75 bar) stress (segment erection temporary force) on the test block cross-section during this test
  - Pressurize the assembly within the test blocks to test pressure according to A.11.4.2 for tendon protection level (PL) being tested and lock-off the outside air force
  - Record test pressure:
    i. Initially
    ii. After 5 minutes

• Assembly toughness test:
  - Place a 1.6 mm (1/16 inch) layer of typical segmental epoxy on the face of both test blocks
  - Using an external apparatus, clamp the test blocks together and maintain a force to produce a 0.275 N/mm² (2.75 bar) stress (segment erection temporary force) on the test block cross-section for 24 hours
  - Remove the clamping force
  - Carefully demolish the test blocks
  - Record observations:
    i. Did precast segmental duct coupler assembly (with duct and connectors) remain intact during testing
    ii. Did any epoxy leak into system during clamping
    iii. Did components remain properly attached without crushing, tearing, or other signs of failure
    iv. Any additional observations
  - Measure and record:
    1. Test specimen temperature
    2. Sealing gasket compressive force
    3. Air pressure results:
      i. Initial air pressure
      ii. Final air pressure after five minutes
    4. Assembly toughness test observations.

A.11.4 Acceptance criteria

A.11.4.1 For all tendon Protection Levels (PL), maximum force to compress gasket to its final compressed position should not be greater than 0.175 N/mm² (1.75 bar) times the area enclosed by the gasket

A.11.4.2 For different tendon Protection Levels (PL):
  - PL1, precast segmental duct coupler assembly must sustain a 1.50 bar (0.150 N/mm²) internal test pressure for a minimum of five minutes with no more than a 0.15 bar (0.015 N/mm²) reduction in pressure
  - PL2 and PL3, precast segmental duct coupler assembly must sustain a 3.5 bar (0.350 N/mm²) internal test pressure for a minimum of five
minutes with no more than a 0.35 bar (0.035 N/mm²) reduction in pressure.

A.11.4.3 For all tendon Protection Levels (PL), precast segmental duct coupler assembly (with duct and connectors) should be intact, free of epoxy infiltration into the inside of the encapsulation, and properly attached without crushing, tearing or other signs of failure.

A.11.5 Reporting

A.11.5.1 Test report should contain at a minimum:

- Date and location of testing
- Name of laboratory and individuals who performed and/or witnessed the testing
- Tested material properties and type/batch or lot numbers/designation of components of the precast segmental duct coupler system tested
- Documentation that test specimens confirm to dimensional tolerances
- Table containing test specimen temperature, sealing gasket compressive force, initial and final air test pressure, toughness observations, and pass/fail designation for each sample tested per tendon PL
- Pictures of testing at all phases
- Manufacture’s component drawings (confidential information provided to authorized parties only)
- Any hand written field notes used in preparing final report
- Certified calibration reports of measuring and testing equipment.
A.12 Fracture resistance of duct (optional test)

A.12.1 Objective/purpose

A.12.1.1 To confirm fracture resistance of duct for use in tendons of PL2 and PL3
A.12.1.2 To confirm the ability of duct to remain intact (no cracks, perforations or excessive wear) for a minimum of 2 million cycles of crack openings between 0.2 mm and 0.5 mm for use in tendons of PL2 and PL3.

A.12.2 Performance requirements

A.12.2.1 What is critical:
- Performance
A.12.2.2 What is tested:
- Duct
A.12.2.3 How often are tests required or updated:
- Approval – if declared as option of polymer duct system, this test should be performed as part of the polymer duct system approval
- Project specific – if not part of system approval but required for a specific project
A.12.2.4 Type of testing, number of tests, size of test specimens:
- Approval testing: 1 test per size, performed on 3 duct sizes, i.e. small, medium and largest (see Section 8.5) for PL2 and PL3 only
- FPC testing: Not required (see Section 9.2)
- Audit testing: Not required (see Section 9.3)
- Project specific testing: As per project specification.

A.12.3 Testing methods

A.12.3.1 Test specimens, refer to Figure A.12-1:
- Identify three, i.e. small, medium and largest, sizes of duct series
  - Duct should be installed in the centre of test specimen
- General dimensions of test specimen:
  - Width ‘b’ is no more than two times the outside diameter of the duct
  - Length ‘h’ is no less than two times ‘b’
- A shallow notch should be placed at mid-height of the concrete prism to function as a point of crack initiation (crack former)
- High-strength reinforcement (deformed bar):
  - One at each end of specimen within duct
  - Connected through the use of a slip connection (alignment pin)
  - To be used as a means by which to impose axial deformation and consequentially crack opening
  - Size is based on required axial force to generate cracking and required displacement
- Unbonded high-strength reinforcement (threaded rod):
  - Used to control crack opening at reasonable force generated during the course of the cyclical testing
  - Placed in the four corners of the test specimen
  - Size to be determined for each test specimen
- Peripheral steel confinement:
  - To preclude the development of splitting cracks in concrete prism due to load application by deformed bar
• Provide steel bearing plates and a peripheral steel confinement at each end of concrete prism
• Size to be determined for each test specimen
• No internal reinforcing steel is used
• **Concrete:**
  • Cylinder compressive strength = 40 N/mm² maximum at start of test
  • Self-consolidating or conventional
  • High slump for proper consolidation
  • Maximum size of coarse aggregate = 20 mm
• **Grout:**
  • PT Grout may comply either with PTI M55.1-12, Specification for Grouting of Post-Tensioned Structures or EN-447 or *fib* Bulletin 20
  • Compressive strength (cube) = 40 N/mm² maximum at start of test

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Fig. A.12-1: Fracture resistance test set-up

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**A.12.3.2 Measuring and testing equipment:**

- Thermometer (accuracy ± 0.5 °C)
- Load cell (accuracy ± 1 N or ± 1% of maximum test load whichever is larger)
- Displacement transducers (accuracy ± 0.01mm)
- Scale for weighing duct or components
- Test frame

**A.12.3.3 Test temperature:**

- 23 °C ± 5 °C

**A.12.3.4 Test procedure:**

- Prepare test specimen:
• Form test specimen
• Place duct into centre of formwork and longitudinally align the crack former with a duct section between two adjacent ribs
• Place plastic block-outs for threaded rods
• Place concrete in formwork:
  i. Air cure test specimen
  ii. Take concrete specimens for compressive testing – air cure
• Formwork should be removed
• After adequate cure, install deformed bar and alignment pin assembly (including slip connection) in centre of duct and secure in position
• Grout test specimen by gravity in vertical position:
  i. Air cure test specimen
  ii. Take grout specimens for compressive testing – air cure next to test specimen
• Once grout has hardened:
  i. Steel bearing plates are secured into position at each end using high-strength steel (threaded rods) and nuts
  ii. Peripheral steel confinement is clamped around the periphery of the concrete prism at each end
• Required compressive strength prior to testing:
  ▪ Concrete = 40 N/mm² maximum (cylinder strength) at start of test
  ▪ Grout = 40 N/mm² maximum (cube strength) at start of test
  ▪ Testing should start before either one of the maximum compressive strengths is achieved
• Prepare test specimen for testing:
  ▪ Install test specimen in test frame
  ▪ Place four displacement transducers on each side of the concrete prism across the crack former
• Testing
  ▪ Perform a static test to crack specimen at crack former:
    i. Create a crack of 0.5 mm
    ii. Cycle equipment manually to set displacements at 0.2 mm and 0.5 mm
    iii. Make adjustments to rod forces and measurements to confirm even crack opening from 0.2 mm to 0.5 mm on the four sides
  ▪ Begin cyclic crack opening test:
    i. Maximum frequency is no more than 4 Hz
    ii. Total of two million cycles required
  ▪ At least every 24 hours suspend cyclic testing:
    i. Conduct a static test to verify displacements corresponding to crack widths of 0.2 mm to 0.5 mm
    ii. Make necessary adjustments to equipment
  ▪ Test specimen autopsy:
    i. Remove test specimen from test frame
    ii. Remove instrumentation and unbonded high-strength steel (threaded rods)
    iii. Document condition of test specimen with pictures
    iv. Carefully remove concrete to expose polymer duct
    v. Inspect duct for cracks, perforations and signs of wear over the entire length, with particular attention to the region in direct proximity to the mid-height crack
• Measure and record:
  1. Test temperature
  2. Concrete and grout strengths prior to testing
  3. Mass of duct specimens prior to testing
  4. Measurements:
     i. Cycle count
     ii. Frequency
     iii. Minimum and maximum crack widths
     iv. Force and displacement of test frame for 0.2 mm crack opening
     v. Force and displacement of test frame for 0.5 mm crack opening
  5. Documentation of condition of duct test specimen
  6. Documentation of duct conditions by inspection for cracks, perforations and signs of wear
  7. Location and mode of failure if any
  8. Any unusual observations.

A12.4 Acceptance criteria
A.12.4.1 Same for tendon Protection Levels PL2 and PL3
A.12.4.2 After two million cycles of crack opening between 0.2 mm and 0.5 mm, there should be no cracks, perforations or excessive wear in the polymer duct.

A.12.5 Reporting
A.12.5.1 Test report should contain at a minimum:
  • Date and location of testing
  • Name of laboratory and individuals who performed and/or witnessed the testing
  • Tested material properties and type/batch or lot numbers/designation of duct tested
  • Calculations and information including documentation that duct test specimens confirm to dimensional tolerances; documentation of condition of test specimen after testing; and documentation of inspection for cracks, perforations and signs of wear
  • Mass of duct specimens prior to testing
  • Table containing test temperature; concrete and grout strengths prior to testing; cycle count, frequency, minimum and maximum crack opening, force and displacement of test frame for 0.2 mm and 0.5 mm crack opening; observations and pass/fail designation for each specimen tested
  • Pictures of duct specimen prior to concreting and after testing
  • Manufacture’s component drawings (confidential information provided to authorized parties only)
  • Any hand written field notes used in preparing final report
  • Certified calibration reports of measuring and testing equipment
Annex B  
System assessment procedures

Polymer system tests are performed on an assembly of selected polymer duct system components combined with post-tensioning system components such as anchorages or grouting accessories. Often the components of polymer duct and post-tensioning systems are provided by different companies and made of different materials and, therefore, their proper assembly and geometrical compatibility must be confirmed in a system test.

These system assessment tests are intended to serve as a verification of the design concept of an entire series of tendon sizes with a polymer-duct system in combination with other post-tensioning system components. Therefore, it is best to confirm the design concept and compatibility of the polymer-duct system with the post-tensioning system in a single test done on a medium-sized tendon that is representative for the design concept of the entire series. However, the testing of several sizes may be appropriate if the series of tendon sizes of a particular system should use several different design concepts, that is, not form a single series. An exception in this concept is made for the EIT performance of polymer-duct systems for which each size is tested since the actual values of electrical resistance are verified for each size.

This annex presents assessment (testing) procedures for the duct system for selected aspects of polymer ducts for post-tensioning. Each procedure identifies the objective/purpose, performance requirements, testing methods, acceptance criteria and reporting for the specific essential aspects. The results of these tests prove whether a specific polymer-duct system is able or unable to fulfil the essential performance requirements that are identified for and form the basis of duct system performance.

Each procedure begins by describing the objective or purpose of the test. Performance requirements identify what is essential, what has to be tested, what sizes have to be tested, how often the tests are required or updated, and the type of testing and number of tests. The testing methods define test specimens, measuring and testing equipment, test specimen temperatures, specific test procedures and calculations, if necessary. Acceptance criteria are identified for each tendon protection level (PL) as applicable. Specific reporting requirements will allow for the consistency of test reports.

The specified assessment procedures are required for approval testing only. The necessity for testing and the number of required tests are given in Chapter 8 for approval testing.

Polymer-duct-system tests are performed at room temperature, if performed in a laboratory, or at ambient temperature if performed outside. If the polymer-duct system is to be used in a climate that is very different from the testing conditions, additional project-specific testing may be appropriate.

The consistency of materials and the geometry of the duct-system components (in particular, duct thickness) between tests is crucial for the future confirmation that manufactured products can achieve the tested results. Therefore, the material and thicknesses of polymer ducts or components must be consistent throughout the testing. The confirmation of the actual material properties of all the batches used in approval testing is to be included in all test reports in accordance with Chapter 5. The actual thicknesses of all the duct and component samples used for testing must be recorded and the mass of these components measured. All the samples of the components used for testing should be randomly selected from production batches.

Approval testing should preferably be performed in an independent and qualified laboratory. However, testing by the manufacturer in his/her own laboratory or premises is
acceptable, in particular for full-scale outdoor tests, if witnessed and confirmed by a qualified independent third party. The test reports should be prepared and confirmed by the laboratory or the third party.
B.1 Leak tightness of anchorage-duct assembly

B.1.1 Objective/purpose

B.1.1.1 To confirm anchorage-duct assembly maintains mortar or leak tightness when exposed to project conditions for tendons PL1 or PL2 / PL3, respectively.

B.1.2 Performance requirements

B.1.2.1 What is essential:
- Performance

B.1.2.2 What is tested:
- Anchorage-duct assembly

B.1.2.3 How often are tests required or updated:
- Initially
- If a change of design and/or manufacturing process of polymer ducts, trumpets or connectors, anchorage components
- For each type of duct material, trumpet and anchorage components used
- When a new anchorage or trumpet is proposed for use

B.1.2.4 Type of testing, number of tests, size of test specimens:
- Approval testing: 1 test per size, performed on 1 medium representative duct size (see Section 8.5) for all PL1 to PL3
- FPC testing: Not required (see Section 9.2)
- Audit testing: Not required (see Section 9.3).

B.1.3 Testing methods

B.1.3.1 Test specimens, see Fig. B.1-1:
- Polymer duct length of at least 300 mm
- Trumpet / transition to anchorage
- PT anchorage (bearing plate, anchor head and cap)
- Connector between duct and trumpet as applicable
- Any other component which forms part of the anchorage-duct assembly as per the PT system documentation

B.1.3.2 Measuring and testing equipment:
- Thermometer (accuracy ± 0.5 °C)
- Pressure gauge [accuracy ± 0.01 bar (0.001 N/mm²)]
- Scale for weighing duct or components
- Container/tank large enough to place anchorage-duct assembly inside
- Test frame which serves to apply a nominal pre-compression between anchor head and bearing plate

B.1.3.3 Test specimen temperature:
- 23 °C ± 5 °C

B.1.3.4 Test procedure:
- Prepare anchorage-duct test specimen assembly
- Install steel rod and apply the nominal pre-compression between anchor head and bearing plate of 1 kN total force
- Confirm test specimen temperature
- Positive pressure test for PL1:
  - Fill inside of anchorage-duct assembly test specimen with water
  - Measure quantity of water in test specimen prior to test
- Replace water in test specimen prior to applying test pressure
- Apply positive pressure of 0.5 bar (0.050 N/mm²)
- Maintain pressure throughout test
- Test duration is 5 minutes
- Capture any water that leaks out of test specimen
- Measure quantity of water remaining at completion of test

- **Positive pressure test for PL2 and PL3:**
  - Apply positive air pressure of 0.5 bar (0.050 N/mm²)
  - Maintain air pressure throughout test
  - Submerge into water tank
  - Hold submerged for duration of test
    - i. For PL2 duration is 5 minutes
    - ii. For PL3 duration is 30 minutes
  - Look for air expulsion during duration of test
  - Remove from water tank

- **Negative pressure test (vacuum) for PL2 and PL3:**
  - Apply negative pressure (vacuum) of 0.5 bar (0.050 N/mm²)
  - Maintain pressure throughout test
  - Submerge into water tank
  - Hold submerged for duration of test
    - i. For PL2 duration is 5 minutes
    - ii. For PL3 duration is 30 minutes
  - Remove from water tank
  - Look for water penetration inside of anchorage-duct assembly

**Measure and record:**
1. Test specimen temperature
2. Tested pressure
3. Applied pre-compression between anchor head and bearing plate
4. Test duration
5. Mass of polymer duct system components
6. **Observations for PL1:**
   - i. Quantity of water in test specimen prior to test
   - ii. Quantity of water in test specimen at completion of test
7. **Observations for PL2 and PL3:**
   - i. Note any air expulsion during duration of positive pressure test and record location
   - ii. Note any water penetration inside of anchorage-duct assembly during negative pressure test.
B.1.4 Acceptance criteria

B.1.4.1 Required for PL1:
• Less than 1.5% loss of water

B.1.4.2 Required for PL2 and PL3:
• For PL2 duration is 5 minutes
• For PL3 duration is 30 minutes
• No visibly detectable leaks with positive pressure
• No visibly detectable leaks with negative pressure

B.1.5 Reporting

B.1.5.1 Test report should contain at a minimum:
• Date and location of testing
• Name of laboratory and individuals who performed and/or witnessed the testing
• Tested polymer material properties and type/batch or lot numbers/designation of duct and connectors tested
• Documentation that all components of test specimens confirm to dimensional tolerances
• Mass of polymer duct system components prior to testing
• Table containing test specimen temperature, applied pre-compression load between anchor head and bearing plate, tendon protection level tested, test pressure, duration of test and pass/fail designation for each sample tested
• Pictures of testing
• Manufacture’s component drawings (confidential information provided to authorized parties only)
• Any hand written field notes used in preparing final report
• Certified calibration reports of measuring and testing equipment

Fig. B.1-1: Anchorage-duct assembly test set-up
B.2  EIT performance of duct system

B.2.1  Objective/purpose

B.2.1.1  To confirm the electrical resistance properties of the polymer duct system components, i.e. duct, duct with connector, and duct with connector and vents intended to be used for tendons PL3.

B.2.1.2  To establish a basis that the polymer duct system components may achieve sufficient electrical resistance to meet the assembled duct system EIT test requirement on site for tendons PL3.

B.2.2  Performance requirements

B.2.2.1  What is essential:
• Performance

B.2.2.2  What is tested:
• Duct
• Duct with connectors
• Duct with connectors and vents

B.2.2.3  How often are tests required or updated:
• Initially
• If a change of design and/or manufacturing process of polymer duct or connectors and vents
• For each type of material used
• When a new connector or vent is proposed for use

B.2.2.4  Type of testing, number of tests, size of test specimens:
• Approval testing: 1 test per size, performed on all duct sizes with each connector and vent (see Section 8.5) for PL3 only
• FPC testing: Not required (see Section 9.2)
• Audit testing: Not required (see Section 9.3).

B.2.3  Testing methods

B.2.3.1  Test specimens:
• Total length 1100 mm
• Types of specimens:
  ▪ Duct only
  ▪ Duct with connector placed at approximate centre of sample
  ▪ Duct with connector and vent placed at approximate centre of sample

B.2.3.2  Measuring and testing equipment:
• Thermometer (accuracy ± 0.5 °C)
• Scale for weighing duct or components
• LCR meter (inductance, capacitance, resistance)
  Note: A suitable LCR meter is the product ELC-131 D, or CMT-437 or equivalent

B.2.3.3  Test specimen temperature:
• 23 °C ± 5 °C

B.2.3.4  Test procedure (see Fig. B.2-1):
• Prepare test specimen
• Install steel rod concentrically into test specimen
• Fill test specimen with tap water
- Seal both ends of test specimen
- Prepare water basin:
  - Assemble water basin as per Fig. B.2-1
  - Install reinforcing steel mesh on either side of basin, separated by spacer from basin walls, and fix in place
- Install test specimen into water basin and seal ends against basin walls
- Fill basin with tap water up to 250 mm height
- Keep test specimen immersed in water basin for two weeks
- Connect steel rod inside duct to one input of LCR meter, and the two connected reinforcing steel meshes to the other input of LCR meter
- Confirm test specimen temperature
- Perform electrical measurements on test specimen at suggested electrical current test frequency of 1 kHz, once every two hours over test period of 24 hours:
  - Measure electrical AC resistance \( R \) (ohm)
  - Measure capacitance \( C \) (nF/m)
  - Measure loss factor \( D \) (-)
- Measure and record:
  1. Test specimen temperature
  2. Tested electrical AC resistance \( R \): Individual values and average of last 3 readings
  3. Tested capacitance \( C \): Individual values and average of last 3 readings
  4. Tested loss factor \( D \): Individual values and average of last 3 readings
  5. Mass of duct specimens

**Fig. B.2-1: EIT performance of duct system - test set-up**

**B.2.4 Acceptance criteria**

B.2.4.1 Required for PL3:
- All three specimens (i.e. duct, duct with connector, duct with connector and vent) should reach an electrical AC resistance of \( R \geq 2,000 \text{ kOhm} \)
• The capacitance C and loss factor D for all test specimens should be declared and should be consistent with the material and duct diameter.

B.2.5 Reporting

B.2.5.1 Test report should contain at a minimum:
• Date and location of testing
• Name of laboratory and individuals who performed and/or witnessed the testing
• Tested material properties of duct, designation of material for connectors and vents, type/batch or lot numbers/designation of duct and connectors tested
• Documentation that test specimens confirm to dimensional tolerances
• Documentation of two weeks immersion of specimens in water basin prior to testing
• Mass of duct specimens prior to testing
• Table containing test specimen temperature, duration of test, individual values and average values over last 3 readings for resistance, capacitance, and loss factor, for duct only, duct with connector and duct with connector and vent
• Pictures of testing
• Manufacture’s component drawings (confidential information provided to authorized parties only)
• Any hand written field notes used in preparing final report
• Certified calibration reports of measuring and testing equipment.
Annex B: System assessment procedures

B.3 EIT performance of anchorage-duct assembly

B.3.1 Objective/purpose

B.3.1.1 To confirm the electrical resistance properties of the anchorage-duct assembly, i.e duct, trumpet, connector(s) and anchorage cap intended to be used for tendons PL3

B.3.1.2 To establish a basis that the anchorage-duct assembly may achieve sufficient electrical resistance to meet the assembled duct system EIT test requirement on site for tendons PL3.

B.3.1.3 To confirm the stability of eventual coatings on metallic anchorage surfaces in alkaline environment.

B.3.2 Performance requirements

B.3.2.1 What is essential:
  • Performance

B.3.2.2 What is tested:
  • Anchorage-duct assembly

B.3.2.3 How often are tests required or updated:
  • Initially
  • If a change of design and/or manufacturing process of polymer ducts, trumpet or anchorage components
  • For each type of duct material used
  • When a new anchorage or trumpet is proposed for use

B.3.2.4 Type of testing, number of tests, size of test specimens:
  • Approval testing: 1 test per size, performed on 1 medium representative duct size (see Section 8.5) for PL3 only
  • FPC testing: Not required (see Section 9.2)
  • Audit testing: Not required (see Section 9.3).

B.3.3 Testing methods

B.3.3.1 Test specimens, see Fig. B.3-1:
  • Polymer duct length of at least 300 mm
  • Trumpet / transition to anchorage
  • PT anchorage (bearing plate, anchor head and cap)
  • Connector between duct and trumpet with vent as applicable
  • Particular components to provide electrical isolation of tendon as per the PT system documentation
  • Any other component that forms part of the anchorage-duct assembly as per the PT system documentation.

B.3.3.2 Measuring and testing equipment:
  • Thermometer (accuracy ± 0.5 °C)
  • Scale for weighing duct or components
  • LCR meter
    
    Note: A suitable LCR meter is the product ELC-131 D or CMT-437 or equivalent
  • Container/tank large enough to place anchorage-duct assembly inside
  • Test frame which serves to apply a nominal pre-compression between anchor head and bearing plate or a higher value as applicable for the actual system

B.3.3.3 Test specimen temperature:
• 23 °C ± 5 °C

B.3.3.4 Test procedure:
• Prepare anchorage-duct test specimen assembly
• Install electrically isolating plates in test frame to avoid short circuit between inside and outside of anchorage-duct assembly
• Install steel rod and apply the nominal pre-compression between anchor head and bearing plate of 1 kN total force or a higher value as applicable for the actual system to seal the assembly
• Confirm test specimen temperature
• Install anchorage-duct assembly up-side down into container/tank
• Fill inside of anchorage-duct assembly test specimen with saturated Ca(OH)$_2$ solution as electrolyte
  ▪ Verify that electrolyte fills inside of anchorage cap and that no electrolyte leaks from assembly
  ▪ Measure electrical resistance between steel rod and steel test frame with LCR meter as indicated in Fig. B.3-1 to confirm electrical isolation between frame and tendon
  ▪ Maintain test specimen immersed and measure electrical resistance between steel rod and steel test frame with LCR meter again after 24 hours as indicated in Fig. B.3-1
• Now fill tank on the outside of the anchorage-duct assembly test specimen with saturated Ca(OH)$_2$ solution as electrolyte. Note that the level of electrolyte should be above the connector between trumpet and polymer duct. However, the end of the vent pipe should be above the level of electrolyte. Note that there should be an excess quantity of Ca(OH)$_2$ provided on the bottom of the tank such that any loss due to reaction with the carbon-dioxide in the air may be compensated. Loss of electrolyte should be compensated to maintain the initial level
  ▪ Test duration is 28 days
  ▪ Measure electrical resistance between steel rod and steel test frame with LCR meter as indicated in Fig. B.3-1 every 2 days
• Measure and record:
  1. Test specimen temperature
  2. Applied pre-compression between anchor head and bearing plate
  3. Level of electrolyte and sufficient quantity of Ca(OH)$_2$
  4. Test duration
  5. Mass of polymer duct system components
Annex B: System assessment procedures

B.3.4 Acceptance criteria

B.3.4.1 Required for PL3:
- Electrical resistance of at least 15 kOhm over entire duration of test
- Eventual coatings on metallic anchorage surfaces remain visually intact.

B.3.5 Reporting

B.3.5.1 Test report should contain at a minimum:
- Date and location of testing
- Name of laboratory and individuals who performed and/or witnessed the testing
- Tested polymer material properties and type/batch or lot numbers/designation of duct, trumpet and connectors tested
- Documentation that all components of test specimens confirm to dimensional tolerances
- Mass of duct specimens prior to testing
- Table containing test specimen temperature, applied pre-compression load between anchor head and bearing plate, values of measured electrical resistance, duration of test and pass/fail designation for each sample tested
- Pictures of testing
- Manufacture’s PT system and polymer duct system components drawings and material specification of electrical isolating plate (confidential information provided to authorized parties only)
- Any hand written field notes used in preparing final report
- Certified calibration reports of measuring and testing equipment.
B.4 Full scale duct system assembly

B.4.1 Objective/purpose

B.4.1.1 To confirm the compatibility of duct system components and other post-tensioning system components for installation of tendons PL2 and PL3 on site to a specified typical tendon profile

B.4.1.2 To confirm that the duct system of tendons PL2 and PL3 can be installed to the specified typical profile and to the specified tendon length without kinks or other discontinuities in the duct system in accordance with the relevant PT system method statement

B.4.1.3 To confirm that the above objectives apply to each of the installation methods intended to be used for tendons PL2 and PL3 with the particular polymer duct system.

B.4.2 Performance requirements

B.4.2.1 What is essential:
• Compatibility of system components

B.4.2.2 What is tested:
• Duct, duct connectors, other polymer duct system accessories as may apply, trumpets and post-tensioning system anchorages and/or couplers

B.4.2.3 How often are tests required or updated:
• Initially
• When a new duct or connector or a new installation method is proposed for use

B.4.2.4 Type of testing, number of tests, size of test specimens:
• Approval testing: 1 test per size, performed on 1 medium representative tendon size (see Section 8.5)
• FPC testing: Not required (see Section 9.2)
• Audit testing: Not required (see Section 9.3).

B.4.3 Testing methods

B.4.3.1 Test specimens, see Fig. B.4-1:
• Duct as required for the test specimen supplied in typical supply conditions
• Connectors, vents and other duct system accessories as required for the test specimen
• Anchorage and coupler (if part of PT system) components of the post-tensioning system as required for the test specimen
• Duct / tendon supports as required for the test specimen
• Tendon axis defined by two second order parabolas through the end anchorage (1), the low point (2), the transition points (3) and (5) of parabolas, the high point (4), and the end anchorage (6) or coupler (if part of PT system). The tendon radius of curvature at the high point should be the declared minimum radius of curvature for field installation

B.4.3.2 Measuring and testing equipment:
• Thermometer (accuracy ± 0.5 °C)
• Measuring tape or scale (accuracy ± 1 mm)
• Scale for weighing duct or components
B.4.3.3 Test specimen temperature:

- **Ambient**
  
  *Note: Typically, a temperature of 23 °C +/- 5 °C would be considered suitable. Other temperatures are acceptable if considered typical for the location of intended use.*

B.4.3.4 Test procedure:

- Prepare all components required for assembly of the specimen
- Prepare clean and flat surface for installation of test specimen
- Prepare method statement for the installation of the tendon as applicable for the particular PT system. Specify maximum permissible tendon support spacing for actual polymer duct system along test specimen (see Section 6.2). Specify acceptable duct profile installation tolerance by reference to any of the specifications given in fib MC (2010), Section 8.4.3, or national specifications.
- If several installation methods are anticipated (e.g. use of prefabricated tendons and assembly in formwork on site), one method statement should be prepared for each intended installation method
- Determine tendon profile in accordance with B.4.3.1 above considering declared minimum radius of curvature for polymer duct system and any other system related aspects such as half shells at supports or similar
- Install rebar cage and duct supports at the maximum permissible support spacing (SS) as determined according to Section 6.2 and in accordance with above determined tendon profile and the PT system method statement
  
  *Note: Rebar cage / stirrups may be open on top to facilitate duct or tendon installation.*
- Install anchorage(s) and coupler (if part of the PT system) in accordance with the PT system method statement
- Install duct system or tendon in accordance with the PT system method statement. If several installation methods are intended to be used, the complete test procedure should be performed for each of the intended installation methods
- Perform initial measurement campaign of geometry of assembled system
- Install prestressing steel if not already installed for prefabricated tendons
- Leave test specimen exposed to environment and weather for 14 days minimum, and record ambient and duct temperatures continuously over test period
- Perform final measurement campaign of geometry of assembled system
- Measure and record:
  
  1. **Initial:**
     - Confirm ambient and polymer duct temperature at end anchorages or coupler (1) and (6), low point (2) and high point (4)
     - Measure actual tendon profile along test specimen at each tendon support and in middle between tendon supports
     - Check for any kinks, discontinuities in the tendon profile or at connectors, and any loose connections between ducts and connectors or anchorage trumpets
  2. **Continuously over entire test period:**
     - Ambient and duct temperature at end anchorages or coupler (1) and (6), low point (2) and high point (4)
  3. **Final:**
     - Confirm ambient and polymer duct temperature at end anchorages or coupler (1) and (6), low point (2) and high point (4)
- Measure actual tendon profile along test specimen at each tendon support and in middle between tendon supports
- Check for any kinks, discontinuities in the tendon profile or at connectors, and any loose connections between ducts and connectors or anchorage trumpets

5. Mass of duct specimens prior to installation (typical 1-metre piece)
6. Any unusual observations.

**Fig. B.4-1: Test specimen for full-scale duct system assembly**

### B.4.4 Acceptance criteria

**B.4.4.1** The assembly test should be deemed acceptable if both at initial and final measurement:
- All components can be installed as specified in the method statement, and
- Duct profile complies with the specified profile within specified tolerances as per method statement, and
- No apparent tendon profile kinks or discontinuities or loose connections, and
- No excessive duct deformations on the duct support or duct deflections between the supports.

### B.4.5 Reporting

**B.4.5.1** Test report should contain at a minimum:
- Date and location of testing
- Name of laboratory and individuals who performed and/or witnessed the testing
- Tested material properties including type/batch or lot numbers/designation of duct and connectors
- Documentation that duct, connectors and anchorage components confirm to dimensional tolerances
• Documentation / method statement of tested installation method
• Mass of duct specimens prior to installation (typical 1-metre piece)
• Graph(s) showing ambient temperature and duct temperature at four locations over entire test period for each tested installation method
• Table(s) showing measured actual tendon profile along test specimen at each tendon support and in middle between tendon supports, at initial and final measurement for each tested installation method
• Pictures of test specimen and details for each testing phase for each tested installation method
• Manufacture’s duct and PT component drawings (confidential information provided to authorized parties only)
• Any hand written field notes used in preparing final report
• Certified calibration reports of measuring and testing equipment
B.5 Leak tightness of assembled duct system

B.5.1 Objective/purpose

B.5.1.1 To confirm that the fully assembled duct system with PT anchorages maintains leak tightness when exposed to project conditions for tendons PL2 and PL3

B.5.2 Performance requirements

B.5.2.1 What is essential:

• Performance

B.5.2.2 What is tested:

• Test specimen after completion of assessment procedure B.4 with duct, duct connectors, other polymer duct system accessories as may apply, trumpets and post-tensioning system anchorages and/or couplers, and installed prestressing steel

B.5.2.3 How often are tests required or updated:

• Initially
• When a new duct or connector or a new installation method is proposed for use

B.5.2.4 Type of testing, number of tests, size of test specimens:

• Approval testing: 1 test per size, performed on 1 medium representative tendon size (see Section 8.5)
• FPC testing: Not required (see Section 9.2)
• Audit testing: Not required (see Section 9.3)

B.5.3 Testing methods

B.5.3.1 Test specimens, see Fig. B.4-1:

• Test specimen of assessment procedure B.4 after completion of testing and with installed prestressing steel

B.5.3.2 Measuring and testing equipment:

• Thermometer (accuracy ± 0.5 °C)
• Pressure gauge [accuracy ± 0.01 bar (1 0.001 N/mm²)]
• Scale for weighing duct or components

B.5.3.3 Test specimen temperature:

• Ambient

  Note: Typically, a temperature of 23 °C +/- 5 °C would be considered suitable. Other temperatures are acceptable if considered typical for the location of intended use

B.5.3.4 Test procedure:

• Use test specimen of assessment procedure B.4
• Cut prestressing steel at anchorage(s) and coupler as applicable and install anchorage cap(s) for tendons PL2 and PL3 in accordance with method statement
• Confirm ambient and duct temperature at end anchorages or coupler (1) and (6), low point (2) and high point (4)

  Note: Preferably perform test at a time of little temperature change/heat input from sun so that effects of temperature movements of duct system are minimised

• Positive pressure test for PL2 and PL3:
  • Apply positive air pressure of 0.5 bar (0.050 N/mm²)
  • Maintain air pressure for duration of 1 hour
Adjust positive air pressure to 0.5 bar (0.050 N/mm²) as required and close valve to pump

Monitor air pressure inside duct system for a period of 5 minutes

Confirm ambient and duct temperatures at end anchorages or coupler (1) and (6), low point (2) and high point (4)

- Measure and record:
  1. Ambient and polymer duct temperature at end anchorages or coupler (1) and (6), low point (2) and high point (4) at the start and at the end of test
  2. Applied pressure and duration over which it was held constant
  3. Test pressure at start of 5 minutes after closing valve to pump
  4. Test pressure at end of 5 minutes after closing valve to pump
  5. Mass of duct specimens prior to installation (typical 1-metre piece)
  6. Any unusual observations.

**B.5.4 Acceptance criteria**

**B.5.4.1** Required for PL2 and PL3:
- Pressure loss after test duration of 5 minutes should not exceed 10% of initial pressure, i.e. 0.05 bar (0.005 N/mm²).

**B.5.5 Reporting**

**B.5.5.1** Test report should contain at a minimum:
- Date and location of testing
- Name of laboratory and individuals who performed and/or witnessed the testing
- Tested material properties including type/ batch or lot numbers /designation of duct and connectors
- Documentation that duct, connectors and anchorage components confirm to dimensional tolerances
- Documentation / method statement of tested installation method
- Mass of duct specimens prior to installation (typical 1-metre piece)
- Table showing ambient temperature and duct temperature at four locations at the start and at the end of the test for each tested installation method
- Table(s) showing measured applied test pressure, duration over which it was held constant, pressure at start of 5 minutes after closing valve to pump, pressure at end of 5 minutes after closing valve to pump, pressure loss during 5 minutes for each tested installation method
- Pictures of test specimen for each tested installation method
- Manufacture’s duct and PT component drawings (confidential information provided to authorized parties only)
- Any hand written field notes used in preparing final report
- Certified calibration reports of measuring and testing equipment.
## Annex C

### Summary of requirements, methods of verification and acceptance criteria for polymer-duct systems – Recommended specification

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Sika Schweiz, Switzerland
VSL International, Switzerland
CECI - China Engineering Consultants, Taiwan (China)
PBL Group, Thailand
CCL Stressing Systems, United Kingdom
### fib Bulletins published since 1998

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