Durability of post-tensioning tendons
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Recommendation prepared by
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Durability specifics for prestressed concrete structures

December 2005
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Foreword

The aim of fib Commission 5, *Structural service life aspects*, is to provide rational procedures to obtain an optimal technical-economic performance of concrete structures in service. A series of Task Groups have been established dealing with design, construction, assessment, maintenance and rehabilitation of concrete structures.

However, it appeared necessary to develop a recommendation dealing exclusively with prestressed concrete structures. Of course, this recommendation does not repeat what is already considered by other Task Groups and which is common for both reinforced concrete and prestressed concrete structures. Its focus is only on the specifics for prestressed concrete structures: the durability of post-tensioning tendons.

Pre-tensioning, which is used extensively in the precast industry, is not considered here, although conclusions and recommendations herein may, in many cases, also be applicable.

This recommendation has been prepared by the below-mentioned members of Working Party 5.4.2, *Durability specifics for prestressed concrete structures*, in cooperation with fib Commission 9, *Reinforcing and prestressing materials and systems*.

A preliminary version of this recommendation served as the basic document for the second workshop on “Durability of post-tensioning tendons”, held on 11-12 October 2004 in Zurich. This workshop was a follow-up to the first workshop held in Ghent in 2001 [1]. The present document includes revisions corresponding to the agreed results of the Zurich workshop.

Jean-Philippe Fuzier  Hans Rudolf Ganz  Peter Matt
1 Design concepts for durable post-tensioning tendons

1.0 Introduction

The durability of post-tensioning tendons depends undoubtedly on the durability of the materials used such as prestressing steels, anchorages, ducts and filling materials (e.g. cement grout) and the installation of these materials, but there are design concept specifics which are also of major importance: the post-tensioning layout and layers of protection such as concrete cover and selected materials in view of the aggressivity of the environment for instance.

In fact, it is well known that sustainability principles guide the Engineer from the very beginning, at the project conception, during construction and the service life of a structure. Several choices and decisions are taken by the Engineer when answering the following questions:

- what is the intended use?
- what are the required performance criteria?
- what are the environmental conditions, today and tomorrow?

Other choices have to be made during the project development:

- the structural configuration and the materials;
- the geometry and the main construction principles;
- any specific corrosion protection;
- the inspection and maintenance requirements.

Decisions made during conceptual and design stage have the largest influence on the durability and sustainability of post-tensioning tendons.

1.1 Post-tensioning tendon definitions and principles

1.1.1 Post-tensioning and pre-tensioning

In practice, the prestressing of the concrete is realized either by using pre-tensioned or post-tensioned high strength steel. High strength steel may consist of wires, strands or bars as defined in chapter 2 [2].

Post-tensioning

Post-tensioning has opened the way to creating structures such as large span concrete bridges, special containment vessels, domes, nuclear and marine structures. At present, most of the railway and highway bridges or flyovers consist of post-tensioned cast-in-place or segmental concrete structures. Post-tensioning has been developed into a variety of forms, namely internal and external as well as bonded and unbonded tendons. These different types can be used for cast-in-place and for precast segmental construction.

Post-tensioning systems (pt-systems) shall generally meet standardised requirements, in terms of:

- resistance to static load;
- resistance to fatigue;
- load transfer to the structure;
- deviation limits (e.g. minimum radii);
- practicability and reliability of installation;
- durability concerns.

Details are presented in chapter 2.
**Pre-tensioning**

In the precast concrete industry, pre-tensioning is well established and has created many possibilities for the manufacturing of structural elements such as medium span bridge girders, roof beams and floor systems. In pre-tensioned concrete members, individual strands or wires are stressed to a predetermined tension and anchored to fixed bulkheads or moulds. The concrete is then cast and cured. Upon hardening, the stressed steel is released from the anchorages, thereby placing the hardened concrete into a state of compression due to the bond between the prestressing steel and the concrete.

1.1.2 **Internal and external tendons**

In the case of post-tensioning, permanent compressive stresses are generated in concrete elements using tendons which are placed either within the body of a concrete section: this is internal post-tensioning; or with a tendon path situated outside the cross-section of a structure or member but inside its envelope: this is external post-tensioning [2].

After hardening of the concrete, the tendons are tensioned and anchored. From a structural point of view, a distinction is to be made between designs having the tendons bonded along their full length to the concrete element and designs with unbonded tendons (see section 1.1.3).

Both systems, internal and external, are equivalent when properly used and executed. They have specific characteristics. The selection of the system should be made in close relationship with the type of structure and the construction method to be used. This guide does not endorse developments of some Highway Authorities which have practically banned internal, bonded tendons.

External tendons, with the tendon path outside the envelope of the structure or member, and stay cables are not considered by this guide.

1.1.3 **Bonded and unbonded tendons**

The establishment of bond between the tendons and the concrete member requires that, after stressing the tendons, the ducts be cement grouted throughout their length. In order for the bond to be effective, the grout used to fill the ducts and the duct itself should have appropriate strength and shape characteristics. Cement grouts in combination with ducts made from corrugated bare or galvanized metal strips or plastic materials are widely used in this respect and have proven to behave satisfactorily from a structural point of view. Adequately grouted tendons allow a local stress transfer from the concrete to the tendon and from the tendon to the concrete to occur throughout the section. As a result, structures with bonded tendons typically exhibit a more uniform crack distribution at ultimate load.

Unbonded tendons solely rely on the transfer of the prestressing forces to a structure at the anchorages and at deviators. Unbonded tendons can be used for internal and external application. As described in chapter 2, different possibilities exist to protect the prestressing steel of unbonded tendons against corrosion.

Full bond between the post-tensioning tendons and the concrete element can only be obtained with internal ducts.

1.1.4 **Specific tendon categories and innovative post-tensioning systems**

**Restressable tendon**

Post-tensioning systems which allow safe and reliable re-stressing of tendons at any time during the service life of the structure without compromising the corrosion protection system of the tendon.

**Exchangeable tendon**

Post-tensioning systems which allow safe and reliable replacement in the works during the service life while assuring a reliable permanent corrosion protection.

**Internal bonded tendon with plastic duct**

Post-tensioning systems which use plastic ducts in place of corrugated metal ducts.
Encapsulated tendon
Post-tensioning systems which are sufficiently leak tight to assure full encapsulation.

Electrically isolated tendon
Post-tensioning systems which demonstrate a sufficient electrical resistance between the prestressing steel and the structure to be considered electrically isolated.

1.1.5 Durability considerations

At present, high strength steel is the only cost effective material that can be used for post-tensioning tendons. The high strength steel is prone to corrosion. However in prestressed concrete in particular, corrosion potentially has much more serious consequences than in normal reinforced concrete. Tendons are subjected to high mechanical stresses, often between 60 to 75 percent of their tensile strength. Consequently, corrosive attack (general corrosion and in particular pitting corrosion) that results in significant weakening of the steel may rapidly lead to fracture of the tendons.

Consequently it is of primary importance to protect the highly stressed steel from external corrosive agents such as water, oxygen and, especially in the case of bridges and parking structures, the infiltration of chlorides from de-icing salts. This requires that the tendons be completely surrounded with protective layers:

a) Bonded tendons

Quality and thickness of the concrete cover:
A first line of defence (and for pre-tensioned elements in fact the only defence) is the concrete surrounding the tendons. For bridges and other structures additional lines of defence may be waterproofing membranes etc. The concrete quality and the cover thickness are key elements in providing efficient corrosion protection for the prestressing steel.

Ducts:
Traditionally, corrugated metal ducts made of sheet metal strips are used for internal bonded post-tensioning. These ducts provide only a limited protection against corrosion attack. Recent developments with respect to duct designs for bonded tendons show that the duct itself can completely seal the prestressing steel against the ingress of aggressive agents. Thus, the duct becomes another line of defence. Such developments have been made in corrugated robust plastic ducts applicable to bonded systems.

Cement grout:
For bonded tendons, the cement grout also has a protective function. In addition to providing additional lines of defence between the tendon and aggressive agents potentially penetrating through the concrete, cement grouts are strongly alkaline (pH up to 13). This alkalinity will inhibit the corrosion of the steel provided that it is not neutralized (pH falling below 9) by reaction with atmospheric carbon dioxide. Infiltration of chlorides will de-passivate the surface of the steel and will allow corrosion to develop. The ducts should be completely filled. Ducts that are not fully grouted can collect water which is detrimental for the durability of the tendons.

b) Unbonded tendons

For unbonded, internal tendons typically individually greased and plastic sheathed strands are used. For unbonded, external tendons, the use of smooth plastic ducts in conjunction with cement grouting is common practice. Other protection systems for unbonded tendons include different systems such as galvanizing the prestressing steel inside grease or wax injected ducts, or individually greased and sheathed strands with cement grout injected ducts.
1.2 Deterioration mechanisms

1.2.1 Experiences and observations

The major factors causing deterioration of post-tensioned structures are chloride attack, alkali-aggregate reaction, freezing and thawing action, carbonation of concrete and fatigue due to live loads. Chloride attack has been found to be the leading factor in the deterioration of post-tensioned bridges and other structures such as parking garages. The presence of chloride in concrete is due to various reasons such as the improper use of sea sand in concrete construction, spindrift with salt in coastal area, use of de-icing salt on bridge decks, and de-icing salts brought by cars into parking structures.

Corrosion is promoted by the ingress of chlorides and other deleterious agents through vulnerable areas such as anchorages, joints, cracks and porous concrete cover.

Corrosion of prestressing steel can be divided into three main types according to the manner it affects the steel:

- electrolytic corrosion (uniform or pitting);
- stress corrosion cracking;
- hydrogen embrittlement corrosion.

The third form of corrosion is very rare with only a few cases reported throughout the world where quenched and tempered steels were used [3]. Brittle fractures attributed to stress corrosion cracking have been found in some cases.

Recent surveys and investigations conducted in Switzerland did not show any damage due to stress corrosion cracking on bridges post-tensioned with cement grouted strand or wire tendons [4].

Conventional electrolytic corrosion is by far the most widespread form. Most corrosion defects are caused by water, maybe contaminated by aggressive agents, which seeps through cracks, leaking seals or zones of porous concrete and flows through the network of ducts which have been incompletely grouted.

1.2.2 Fundamentals

A general discussion of fundamentals of corrosion of prestressing steel is given in [5]. The process by which corrosion occurs is generally recognized to be electrochemical in nature, i.e. a galvanic cell is developed. In this cell, the metal releases electrons that are absorbed by the corroding agent, which is usually oxygen. Galvanic corrosion, in a classical sense, is caused by a difference in electric potential when two dissimilar metals are coupled (a battery effect). However, the term galvanic corrosion is used, in a broad sense, to denote corrosion occurring from dissimilar surface conditions of a metal, differences in oxygen concentrations or differences in environmental conditions (moisture content of concrete). The steel may be affected in different manners:

a) Uniform corrosion

In this type of corrosion, an approximately uniform surface attack of the steel occurs which implies that no discrete anodic and cathodic sites exist. Consequently, the anodic and cathodic areas are equal, polarization of both areas is equal and both processes equally control the corrosion rate. This type of corrosion can develop when unprotected steel is exposed to the environment as during shipping, storage or prior to grouting.

In uniform corrosion, the corrosion products form a continuous film and thus may retard further corrosion.

b) Localized corrosion / pitting corrosion

Due to lack of homogeneity of the metal surface and/or the corrosive environment, discrete electrochemical cells may develop and localized corrosion can occur. As the ratio of anodic area to
cathodic area is very small, a locally high corrosion rate (metal dissolution) occurs at the anodic sites. Localized corrosion occurs at locations where the metal surface passivation has been destroyed or damaged. In the presence of aggressive ions, such as chlorides, a pitting mechanism may develop.

For a pitting mechanism to be initiated on an otherwise passivated steel surface, it is necessary to have an initial threshold potential above which pitting corrosion can occur. As the corrosion current begins to flow through the localized pit (or anode), the potential will generally decrease which will cause a repassivation of the remaining non-pitted steel surface. Due to the hydrolysis within the pit, the pH of the electrolyte decreases which maintains the reaction within the pit. Because of the very small ratio of anode to cathode, there will be a high current density which will strengthen the corrosion cell activity as well.

c) Stress corrosion cracking

Stress corrosion cracking is a type of locally concentrated corrosion defined as cracking that may result from the combined action of corrosion and static tensile stress which may be either residual or externally applied. Stress corrosion cracking occurs mainly in alloys where a passivated oxide film on the surface has developed. The attack of the corrosion agent (mostly chloride ions) concentrates on certain sensitive regions of the steel such as cracks or spalls.

Although many mechanisms of stress corrosion have been proposed, no theory completely explains the mechanism. However, localized corrosion produces pits whereby the bottom of the pit is anodic and is undergoing active metal dissolution while the sides of the pit are passivated. Thus, any tensile stress present is highly concentrated at the bottom of the pit causing a crack formation that produces further fresh metal surface available for corrosion; therefore, crack propagation is a function of the joint action of stress and corrosion. Cracks propagate either along grain boundaries (intergranular) or on slip planes within the crystal lattice (transgranular). Eventually, these cracks cause sufficient reduction in cross-section for a brittle failure to occur without any warning.

d) Hydrogen embrittlement

Cracking due to hydrogen embrittlement of steel under stress occurs when atomic hydrogen diffuses through the metal lattice, where it recombines to hydrogen molecules producing an internal pressure in the metal. This form of corrosion is very rare; a few cases have been reported in Germany where quenched and tempered steels were used.

e) Stray current corrosion

Structures which may be affected by stray current corrosion are those associated among others with electrified rail or tramway systems driven by direct current. Stray direct current is present in the ground as a result of electrical leaks or failure to provide permanent electrical insulation. Stray currents cause corrosion at locations where current leaves the conductor (tendon) and enters the structure, ground or water electrolyte.

High strength steel tendons are more sensitive to stray current corrosion than ordinary reinforcing steel. Precautions must be taken in structures where this type of corrosion may occur. The development of stray current can be suppressed with proper isolation of the structure, with good metallic contact of the steel components of a structure with the source of the stray current or by using electrically isolated tendons.

1.2.3 Scenario of deterioration

a) Example of a box girder

Various countries reported deterioration processes of prestressed concrete structures. A typical scenario of deterioration of a prestressed box girder is described hereafter (Fig. 1.1).

For each type of structure with its particular protection concept, the water, possibly chloride-contaminated might reach the prestressing steel in different ways. When assessing a prestressed concrete bridge, the study of the structural drawings, the construction and maintenance reports and the
observations of the owner and his maintenance staff provide information about hazardous circumstances and situations where damage could develop or has been developing. The key-question is: where does aggressive water get in contact with the structure and how does it flow off?

Figure 1.1: Hazard scenarios for prestressing steel in a typical box girder bridge: Indication of potentially "weak points" where water (possibly contaminated with chlorides) can gain access to the tendons and cause corrosion, [6]

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<th>Failure of external barriers:</th>
<th>Failure of tendon corrosion protection system:</th>
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<tr>
<td>1. Defective wearing course (e.g. cracks)</td>
<td>9. Partly or fully open grouting in- and outlets (vents)</td>
</tr>
<tr>
<td>2. Missing or defective waterproofing membrane incl. edge areas</td>
<td>10. Leaking, damaged metallic ducts mechanically or by corrosion [not shown on figure]</td>
</tr>
<tr>
<td>3. Defective drainage intakes and pipes</td>
<td>11. Cracked and porous pocket concrete</td>
</tr>
<tr>
<td>4. Wrongly placed outlets for the drainage of wearing course and waterproofing</td>
<td>12. Grout voids at tendon high and low points</td>
</tr>
<tr>
<td>5. Leaking expansion joints</td>
<td></td>
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<tr>
<td>6. Cracked and leaking construction or element joints</td>
<td></td>
</tr>
<tr>
<td>7. Inserts (e.g. for electricity)</td>
<td></td>
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<tr>
<td>8. Defective concrete cover</td>
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In addition, a thorough visual inspection (preferably after rainfall) of the concrete surfaces provides information on damages and potential risk situations, along with their location with regard to the stressed steel such as:
- water flow, wet or moist areas;
- discoloration (e.g. rust stains);
- spalling, delamination;
- cracks;
- honey-combing;
- concrete deterioration by freezing and freezing-thawing;
- joint leakage.
The findings can then be substantiated by in–situ and laboratory investigations. Following these procedures, potential corrosion damage of prestressing steel can be recognized and counter-measures can be taken in good time.

Similar mechanisms could be observed in other types of prestressed concrete structures.

b) Buildings and parking structures

Observations have been reported in several countries about deterioration of post-tensioned concrete slabs built using unbonded tendons, e.g. [1]. It is apparent that deterioration can occur not only in a corrosive environment (parking structures with de-icing salts) but also in a non-corrosive environment where moisture entered the tendons during construction (plastic or paper sheathing was damaged or temporarily removed).

The following categories of moisture penetration risk are considered:

- High Risk: underground levels where tendon anchorages are exposed to ground water infiltration and parking decks that are without waterproofing;
- Medium Risk: exposed balcony slabs or plaza levels where rainfall or snow melt may access anchorages at slab edges or penetrate slab cracks;
- Low Risk: above ground interior areas where the slab edges are protected by exterior walls and slabs are in a dry service environment.

1.3 Design strategies

1.3.1 Durability design principles

General

In developing a design strategy, the nature and intensity of the aggressive actions – and how they might penetrate to the steel – is of fundamental importance. This applies both to the conceptual design and to the evolution of design details. The transport mechanisms for chlorides are much influenced by the combined effects of wind, water and temperature. The provision of resistance to those requires an integrated approach involving design concept, detailing, material selection and construction quality. The importance of this cannot be over-emphasised. According to [7], it includes:

- materials and components;
- constructibility;
- construction and expansion joints;
- cracking;
- duct and anchorage layout;
- precast segmental construction and joint details;
- proximity to seawater;
- de-icing salts, waterproofing and drainage;
- access for inspection and maintenance.

Principle of multi-layer protection

In recognition of the difficulty of achieving perfect protection by any individual means, a multi-layer protection approach to the design for durability of post-tensioned construction is recommended. Each layer is able to provide by itself a total protection. This has been used for ground anchors and requires the provision of a number of protective measures on the basis that the total integrity of one layer will maintain the integrity of the whole even if another one of the layers of protection becomes partially ineffective.

There are a large number of layers of protection available. A layer of protection is anything whose purpose is to ensure the overall long-term integrity of the tendons. Hence methods of inspection (and subsequent maintenance) could ultimately also be considered as layers of protection.
A prime concern is to minimise the contact of water with the concrete members. This involves a combination of conceptual design, structural detailing and attention to finishes to the structure including items such as drainage, waterproofing and surfacing.

**Bridge durability parameters**

In preparing the durability strategy for a bridge (as an example), the following factors should be considered:

a) The bridge location and exposure conditions. Chloride-induced corrosion is one of the major concerns in concrete bridges wherever the structure is subject to road de-icing salts or wind-borne chlorides (in the case of marine environment).

b) Structural articulation with a view to minimising movement joints and provision of structural continuity, possibly in the form of integral bridges.

c) Type of cross-section and its shape, particularly at its boundaries, to minimise the risk of contaminants penetrating the structure.

d) Access for inspection, testing, maintenance and possible replacement of elements with a short design life.

e) The overall layout of the tendons to suit the methods of construction and maintenance. A main decision here is whether the tendons are external, internal or a mixture of the two systems.

f) Location, detailing and protection of the anchorages.

g) Filling the ducts with cement grout or wax as appropriate.

h) Quality assurance and testing during construction.

i) Provision for additional prestressing.

j) Specifications for the duct system – e.g. corrosion-resistant duct material designed to exclude contaminants.

k) Detailing the deck waterproofing system and drainage design to avoid ingress of water - the normal transport mechanism for contaminants. This needs to consider the expected life for the system components and the risks associated with component failure.

l) Specifications for the quality of the concrete and the cover.

m) The method of construction with its associated buildability and workmanship factors.

### 1.3.2 Specifications

First of all, the quality of materials and components are of great importance and therefore good specifications are crucial. They should be prepared with a clear idea of the performance requirements and of a methodology to ensure that the chosen items do in fact comply.

Of particular interest is the quality of the post-tensioning system, its installation, stressing and grouting which can now be certified according to the "Guideline for European technical approval of post-tensioning kits for prestressing of structures" ETAG 013 [2].

### 1.3.3 Concrete quality and cover

Internationally recognised Codes and Specifications give recommendations for minimum concrete performance and cover requirements for prestressed concrete structures and concrete specifications which will give a reasonably dense, low permeability concrete protection to the ducts. Feedback from service has demonstrated that the specified cover is not always achieved in practice. Good quality control is therefore essential.
It is possible to improve the concrete protection by increasing the cover or reducing the permeability of the concrete. However, increasing cover would often require increased section thickness and increased prestress adding overall weight and cost to the structure. Reducing the permeability of the concrete is possible by reducing the water/cement ratio or by cement replacement using e.g. pulverised fly ash. High performance concretes can provide excellent low permeability characteristics. In some cases, surface protection systems could be used (see section 1.3.4).

1.3.4 Waterproofing systems and other surface protection systems

Where installed, the waterproofing system is the first line of defence against ingress of road salts applied to the bridge deck surface. Unfortunately there are no systems available which can be guaranteed to remain waterproof throughout the life of the bridge.

The use of surface treatments (surface protection systems) on concrete will provide a protective barrier against aggressive agents. In selecting a surface treatment, the whole life cycle performance should be taken into account since the cost of application, maintenance, expected life and possible re-application can be significant.

1.3.5 Drainage system

It is essential that the drainage system should work efficiently to drain water from the road surface as well as the water which passes through the surfacing down to the bridge deck waterproofing system. The details of the drainage paths should be such that if items of the equipment fail, leak or become blocked then the water does not find access to the tendons.

1.3.6 Expansion joints

Expansion joints usually leak and their effectiveness and life span are very dependent on the quality of installation and maintenance.

Where expansion joints are used, provision should be made for inspection of the joint and the structure underneath the joint. The details should be based on the assumption that the joint will leak and will not provide protection against ingress of water and road salts. Appropriate drainage paths for the leakage should be provided ensuring that it cannot get access to the tendon anchorages or the bearings.

1.3.7 Cracking

Cracking in concrete can occur for a number of reasons; its relevance to durability is largely related to corrosion and depends on the type and magnitude of the cracks. Care is required, when considering the layout and sequencing of concrete pours and prestressing to minimise the risks of cracking particularly in the vicinity of anchorages. The application of a low initial prestress at an early age can help to counteract early-age cracking. The reinforcement provided in the direction of the prestress is usually much less than that used in reinforced concrete bridges and should be checked for adequate distribution of early-age cracking.

1.3.8 Construction joints

Well-made construction joints should not leak, particularly when protected by waterproofing membranes. However, waterproofing membranes often do not provide a complete seal and do not last indefinitely, and joints leak. It is therefore advisable to keep construction joints in deck slabs away from anchorages and prevent, by means of drips, any access for the leakage to the anchorages.

1.3.9 Segment joints

Construction methods using match cast prefabricated segments have been successfully used during the last decades. Usually match cast joints are properly sealed with epoxy resin which is satisfactory in durability terms. However particular care is required when considering the continuity of ducts across the joints. The requirements for tightness or encapsulation can only be met if a proper system provides this
function. Today duct couplers have been proposed allowing a correct positioning and alignment of the ducts in each segment but also providing a seal against ingress of segment glue, aggressive agents, or against leakage of cement grout, see Fig. 2.6.

1.3.10 Tendon layout

In addition to structural considerations, the construction method may often influence the tendon layout and location of anchorages. Therefore, it should be considered at the preliminary design stage. For example, the layout of tendons for span-by-span construction will be different to that for structures built using the balanced cantilever method. The profile also affects the ease of grouting.

The positioning of anchorages and couplers requires careful consideration in a number of respects. They should be installed in zones where they are protected from direct water run-off. Where this is not possible, additional protection measures should be introduced, see Figs. 1.2 and 1.3. Anchorages in top recesses of bridge decks are not recommended unless specific protective countermeasures are provided.

The location of anchorages affects the ease of subsequent inspection.

![Fig.1.2 Buried anchorage for internal tendons at end of deck with abutment gallery, or beneath expansion joints, [7]](image1)

![Fig.1.3 Exposed anchorage for internal tendons in blister near construction or segment joint, [7]](image2)

1.3.11 Access for inspection and maintenance

Access for inspection and maintenance should be regarded as an essential element in the multi-layer protection strategy and should always be provided. In particular, inspection galleries should be provided, so that anchorages can be inspected; this is also required at or near to key locations such as deviators and joints. These key elements should feature strongly in any inspection checklist, together with checks on changes in moisture conditions caused by failed expansion joints or blocked drains. Maintaining the exposure condition assumed in design is an important element in management and maintenance.

One of the main concerns about post-tensioning systems is the inability to inspect the tendons visually. For both internal (grouted) tendons and external grouted tendons, the difficulties are similar. However a visual inspection can be carried out in the straight sections between anchorages and deviators if transparent ducts are used. This subject is developed in chapter 2.
1.4 Tendon protection strategies

1.4.1 General principles

The scenarios of deterioration described in section 1.2.3 have identified the weak points which can be found either in the external protection layers provided by various structural components or in the corrosion protection of the tendons themselves. The objective of the following strategy is to select the protection level of post-tensioning tendons based on:

- the aggressivity of the environment;
- the exposure of the structure or element;
- the number of protection layers provided by the structure.

It is the combination of the Protection Level (PL) provided to the post-tensioning tendons and the Protection Layers provided to the structure which together provide the resistance against the aggressivity of the environment and the particular exposure condition of the structural element.

1.4.2 Protection levels of tendons

Definitions

With regard to the degree of corrosion protection, the following tendon categories are recommended, providing an increasing degree of protection, whether it concerns internal or external, bonded or unbonded tendons.

Three tendon categories are defined as follows (PL = Protection Level):

<table>
<thead>
<tr>
<th>PL1: A duct with a filling material providing durable corrosion protection</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Performance requirements (generic):</td>
</tr>
<tr>
<td>- Duct sufficiently strong and durable for fabrication, transport, installation, concrete placement and tendon stressing, sufficiently leak tight for concrete placing and injection</td>
</tr>
<tr>
<td>- Duct material non-reactive with concrete, prestressing steel, reinforcing steel, and tendon filling material</td>
</tr>
<tr>
<td>- Filling material to be chemically stable, non-reactive with prestressing steel, and tendon duct</td>
</tr>
<tr>
<td>- Filling procedure to leave no voids in duct.</td>
</tr>
<tr>
<td>- Examples, test procedures, acceptance criteria:</td>
</tr>
<tr>
<td>- Corrugated metal duct (EN 523, 524)</td>
</tr>
<tr>
<td>- Cement grout (fib Bulletin 20, draft revision EN 447, 445)</td>
</tr>
<tr>
<td>- Filling procedures (fib Bulletin 20, draft revision EN 446, TR 47)</td>
</tr>
<tr>
<td>- Greased and sheathed strand (ETAG 013, PTI and ACI recommendations).</td>
</tr>
</tbody>
</table>

Note: Other examples to satisfy the same generic performance requirements exist or may become available – Corresponding material and test requirements to be developed.

<table>
<thead>
<tr>
<th>PL2: PL1 plus an envelope, enclosing the tensile element bundle over its full length, and providing a permanent leak tight barrier</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Performance requirements (generic):</td>
</tr>
<tr>
<td>- Envelope to be watertight and impermeable to water vapour over entire length</td>
</tr>
<tr>
<td>- Envelope material chemically stable, without embrittlement or softening during anticipated exposure temperature range and service life, no free chloride ions extractable from material.</td>
</tr>
</tbody>
</table>
- Examples, test procedures, acceptance criteria:
  - Envelope of corrugated plastic duct (*fib* Bulletin 7, FL DOT Specifications)
  - System testing (*fib* Bulletin 7, TR 47, FL DOT Specifications)
  - Specific tests demonstrating leak tightness of overall system (e.g. air pressure testing of duct in accordance with TR47 or *fib* Bulletin 7).

Note: Other examples to satisfy the same generic performance requirements exist or may become available – Corresponding material and test requirements to be developed.

<table>
<thead>
<tr>
<th>PL3: PL2 plus integrity of tendon or encapsulation to be monitorable or inspectable at any time</th>
</tr>
</thead>
</table>

- Performance requirements (generic):
  - Integrity of envelope of prestressing steel and/or of prestressing steel to be demonstrated. Measurements to be reproducible
  - Initial approval testing of method and performance necessary.

- Examples, test procedures, acceptance criteria:
  - Electrically Isolated Tendons (EIT) allowing monitoring and also protection against stray currents in accordance with Swiss Guideline „Measures to ensure the durability of post-tensioned tendons in bridges“, Swiss Federal Road Authority and Swiss Federal Railways, 2001 [28].

Note: Other examples to satisfy the same generic performance requirements exist or may become available – Corresponding material and test requirements to be developed.

This strategy is summarized in Table 1.2. The entry points in the diagram are the Aggressivity/Exposure and the Structural protection layers which permit to choose an appropriate Protection Level for the post-tensioning tendon.

<table>
<thead>
<tr>
<th>Aggressivity / Exposure</th>
<th>Structural protection layers</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Medium</td>
<td></td>
</tr>
<tr>
<td>Low</td>
<td></td>
</tr>
</tbody>
</table>

Table 1.2: Protection Levels for post-tensioning tendons based on aggressivity/exposure versus structural protection layers
1.4.3 Aggressivity of the environment and exposure

In order to provide information on appropriate entry points for aggressivity and exposure, reference is made to EN 206-1 [44]. It defines in chapter 4 the classification of the principal environments to which concrete structures are exposed and the corrosivity of these environments.

Six classes 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
   Special care shall be taken when considering structures partly immersed in water or partly buried in soil.
   Three different zones are usually defined:
   - the underwater zone is the area which is permanently exposed to water;
   - the intermediate (fluctuating level) zone is the area in which the water level changes due to natural or artificial effects, thus giving rise to increased corrosion due to the combined impact of water and the atmosphere;
   - the splash zone is the area wetted by wave and spray action which can give rise to exceptionally high corrosion action.
5. Freeze / thaw attack with or without de-icing agents: XF
6. Chemical attack: XA.

Table 1.3 consists of the original table of EN 206-1 [44] to which the column "Aggressivity levels" was added. The levels low/medium/high can be used in Table 1.2 of this Recommendation.

<table>
<thead>
<tr>
<th>Aggressivity levels</th>
<th>Class designation</th>
<th>Description of the environment</th>
<th>Informative 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></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1.3 contains the original table of EN 206-1 [44] to which the column "Aggressivity levels" was added. The levels low/medium/high can be used in Table 1.2 of this Recommendation.
<table>
<thead>
<tr>
<th>Aggressivity levels</th>
<th>Class designation</th>
<th>Description of the environment</th>
<th>Informative examples where exposure classes may occur</th>
</tr>
</thead>
<tbody>
<tr>
<td>Medium</td>
<td>XD1</td>
<td>Moderate humidity</td>
<td>Concrete surfaces exposed to airborne chlorides</td>
</tr>
<tr>
<td></td>
<td>XD2</td>
<td>Wet, rarely dry</td>
<td>Swimming pools Concrete exposed to industrial waters containing chlorides</td>
</tr>
<tr>
<td>High</td>
<td>XD3</td>
<td>Cyclic wet and dry</td>
<td>Parts of bridges exposed to spray containing chlorides Pavements Car park slabs</td>
</tr>
<tr>
<td>Medium</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></td>
<td>XS2</td>
<td>Permanently submerged</td>
<td>Parts of marine structures</td>
</tr>
<tr>
<td></td>
<td>XS3</td>
<td>Tidal, splash and spray zones</td>
<td>Parts of marine structures</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>
<tr>
<td>High</td>
<td>XF4</td>
<td>High water saturation with de-icing agent or sea water</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 according to table 2 (of EN 206-1)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>XA2</td>
<td>Moderately aggressive chemical environment according to table 2 (of EN 206-1)</td>
<td></td>
</tr>
<tr>
<td>High</td>
<td>XA3</td>
<td>Highly aggressive chemical environment according to table 2 (of EN 206-1)</td>
<td></td>
</tr>
</tbody>
</table>

Table 1.3: Aggressivity level and exposure examples as entry points in Table 1.2 (after EN 206-1)

### 1.4.4 Considerations for selecting the protection layers provided by the structure

For applying the principle of multi-layer protection (see section 1.3.1), reference should be made to the following sections:

- section 1.3.3 Concrete quality and cover;
- section 1.3.4 Waterproofing systems and other surface protection systems;
- section 1.3.5 Drainage system;
- section 1.3.6 Expansion joints;
- section 1.3.7 Cracking;
- section 1.3.8 Construction joints;
- section 1.3.9 Segment joints;
- section 1.3.10 Tendon layout;
- section 1.3.11 Access for inspection and maintenance.

Further considerations are:
- the quality of construction: contractor qualification, specific competence, workmanship certification;
- products availability, quality of materials;
- inspection and maintenance programme;
- possibility of tendon replacement.

1.4.5 Protection level examples

The following examples illustrate what protection level can be achieved with certain tendon details. However the actual PL achieved should be confirmed by testing and compliance with acceptance criteria as listed in section 1.4.2:

- Internal tendons (bonded or unbonded)
  1. Bare strand + corrugated metal duct + cement grout PL 1
  2. Bare strand + plastic duct + cement grout or other filling materials (anchorage zone non-encapsulated) PL 1
  3. Idem 2 + encapsulation of anchorage zone PL 2
  4. Idem 3 + monitoring (e.g. electrically isolated tendons: see Fig. 1.4) PL 3
  5. Greased and sheathed strand (anchorage zone non-encapsulated) PL 1
  6. Greased and sheathed strand + encapsulation of anchorage zone PL 2

- External tendons
  1. Bare strand + cement grout or other filling materials + plastic pipe (anchorage zone non-encapsulated and plastic pipe not continuous at deviators) PL 1
  2. Idem 7 + encapsulation of anchorage zone and pipe continuous at deviators PL 2
  3. Idem 8 + monitoring PL 3

The list only contains typical examples. An illustration of internal tendon systems for PL 1, PL 2 and PL 3 successfully used in practice is given in Fig. 1.4. Other system solutions are described in chapter 2.
Fig. 1.4: Examples of post-tensioning systems for different Protection Levels

Note: For unbonded tendons, the cement grout is replaced by grease in the above systems, and there should be a permanent cap for all systems

1.4.6 Guidance for further developments

Further developments of the Recommendation should be done according to the following principles:

1. The focus of the Recommendation is on post-tensioning design, supply and installation. However, the Recommendation must provide sufficient guidance to the designer for the overall design of the structure so that they can be properly applied. The multi-level protection concept will, of necessity, include design detailing beyond the scope of post-tensioning. It is an important point to recognize within the document but other references must be relied upon for protection features not included in
the post-tensioning scope of supply. In future, the Recommendation should be extended also to pre-tensioning.

2. The Recommendations should emphasize the quality of the constructed works through consistent reference to international quality control standards. However good design practice must be matched with good construction practice if durability of the finished works is to be realized. Expertise and craftsmanship must be recognised and required in project specifications in order to assure that best practices are followed in the field for post-tensioning installation and the application of structural protection layers.

3. There is a broad array of international practices for protection levels; only a general performance standard can encompass this range of international practice, allowing national bodies to extend the Recommendation to suit their local needs. The Recommendation should retain their basic approach to performance levels based on the current state of the art for corrosion protection systems.

4. The Protection Levels (PL) should be established by performance testing rather than prescriptive solutions with specific standards to be met for certifying a product to a given PL. These tests could include pressure tests, leak tests and physical durability tests, many of which exist in various forms within current national standards. The reference to specific systems, such as metal duct, plastic duct, full encapsulation and electrically isolated systems can serve as examples of approaches that typically meet a particular PL.

5. It is important to address the importance of post-tensioning system details in achieving durability: there should be standards for corrosion protection and barrier performance for integrated systems which will encompass all couplers, trumpets, anchorages, duct splices, precast segmental joint connections etc.

6. The technical requirements for durability of post-tensioning systems and the technical performance standards should remain the basis for criteria and definitions within the Recommendation. Cost factors can be included in a joint owner/designer decision that can reflect each owner’s financial conditions, much the same as for other design decisions. Whereas the initial costs for post-tensioning increases from PL 1 to PL 3, the increase in the overall costs of a structure is comparatively small and generally beneficial, taking life cycle costs into account.
2 Materials and construction

2.1 Requirements for materials

This section presents the materials that are considered as best value for the durability of post-tensioning tendons and prestressed concrete structures. Recommendations are given regarding the suitability of these materials for each Protection Level (PL). Traditional materials and systems are considered suitable for PL1. However, the focus of this chapter is on improved materials and systems which are considered suitable for durable construction with PL2 and PL3.

Complementary information can be found in the following recent publications:

fib Bulletin n°7: “Corrugated plastic ducts for internal bonded post-tensioning”, [9]


2.1.1 Prestressing steel and FRP materials

Today three main forms of prestressing steels are used for post-tensioning, see Table 2.1:

<table>
<thead>
<tr>
<th>Type</th>
<th>Size</th>
<th>Tensile strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cold drawn plain wire</td>
<td>5-7 mm nominal diameter</td>
<td>1670 – 1860 MPa.</td>
</tr>
<tr>
<td>Cold drawn plain 7-wire</td>
<td>13-16 mm nominal diameter</td>
<td>1770 – 1860 MPa</td>
</tr>
<tr>
<td>prestressing strand</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hot rolled plain or ribbed</td>
<td>15-40 mm nominal diameter</td>
<td>1050 MPa</td>
</tr>
<tr>
<td>prestressing bar</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2.1: Prestressing steels

The most important steel for use in post-tensioning is the 7-wire prestressing strand. The three types of prestressing steel are available as uncoated / bare steel or with metallic and non-metallic coatings applied in the factory. However, coated prestressing steels are rarely used for post-tensioning. The 7-wire strand is also available with plastic sheathing. Fig. 2.1 shows uncoated and sheathed 7-wire strand. Other forms of factory applied corrosion protection systems of prestressing steels are epoxy coating, double sheathed strand, sheathing and resin with delayed curing (“After-Bond”). Their use is still limited and therefore, they are not further described here. The interested reader is referred to [10].

a) Uncoated / bare prestressing steel

These steels have been standardised for many years and reference is often made to ASTM, British, and draft Euronorm standards, see Table 2.2. These standards assure high quality prestressing steels.

<table>
<thead>
<tr>
<th>Type of steel</th>
<th>ASTM Standards</th>
<th>British Standards</th>
<th>Draft Euronorm Standards</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cold drawn wire</td>
<td>A 421</td>
<td>BS 5896</td>
<td>Draft EN 10138-2</td>
</tr>
<tr>
<td>7-wire strand</td>
<td>A 416</td>
<td>BS 5896</td>
<td>Draft EN 10138-3</td>
</tr>
<tr>
<td>Hot rolled bar</td>
<td>A 722</td>
<td>BS 4486</td>
<td>Draft EN 10138-4</td>
</tr>
</tbody>
</table>

Table 2.2: Frequently referenced standards for prestressing steel
The following comments apply to selected prestressing steel characteristics specified in the above referenced standards:

(1) Ductility of prestressing steel: This is usually defined with a minimum elongation of the steel of 3.5% at maximum load over a given specimen length. In addition to the minimum elongation, the steel should break in a ductile manner with corresponding reduction of area, visible to the unaided eye. For wire, the reverse bend test has proven to be practical and reliable. A minimum number of bends is specified around a given bend radius. A corresponding test has been developed for 7-wire strand by FIP, [12], and PTI, [13]. These are the deflected tensile test and one-pin test, respectively. These tests limit the reduction of the tensile strength of a strand deviated around a specified mandrel to 28% for post-tensioning applications.

(2) Relaxation of prestressing steel: While in the past several relaxation classes existed, the trend for wires and strand is to one class with a very low relaxation of only 2.5% at room temperature in 1000 hours when initially stressed to 70% of the characteristic strength. Bars have higher relaxation values which are in the range of 4-6% depending on the bar diameter.

(3) Fatigue strength of prestressing steel: This is usually defined as a stress range which can be sustained by the steel without failure over 2x10⁶ cycles at an upper load corresponding to 70% of the characteristic breaking load. Specified fatigue stress ranges are in the order of 180-200 MPa. This test is considered a good control of the actual quality of manufacturing of the prestressing steel (e.g. surface defects). This test is done with the prestressing steel in air. It should be noted that the behaviour and fatigue performance of prestressing steel in grouted ducts may be affected by fretting fatigue and therefore, may be significantly lower. However, for most building and road bridge applications the fatigue performance of tendons will usually not be critical. This may however, not be true for railway bridge applications.

(4) Stress corrosion test for prestressing steel: This test should confirm that a particular type of prestressing steel is sufficiently resistant to stress corrosion. Different test methods have been proposed and used. The test method most commonly referred to is the one developed by FIP, [14], in which the prestressing steel is immersed under tension into an ammonium thiocyanate solution. A minimum time of exposure before failure is specified for each type of prestressing steel. Since the test results may show significant scatter, a minimum and average value are specified. These values are in the order of 1.5 - 5 hours for wire and strand but are significantly larger for bars with large diameter.

The FIP test has been developed and is well suited for cold drawn wire and strand. There is some doubt of its suitability for other types of steel such as quenched and tempered prestressing wire. Cold drawn wire and strand in accordance with the above referenced standards are highly resistant to stress corrosion. Bars with a tensile strength of 1050 MPa are also considered insensitive to stress corrosion. Bars of higher tensile strength however, are more sensitive and therefore, have not been included in Table 2.1.

(5) Quenched and tempered steel: This type of steel, which is not covered by the above referenced standards, is not recommended for use in post-tensioning, see FIP Notes, [15].

Cold drawn wire, 7-wire strand, and hot rolled bar which comply with standards including the above characteristics (1) to (4) demonstrate properties suitable for post-tensioning, and good durability. Other types of prestressing steel not covered by the above should be considered with caution before using them for post-tensioning.
a) Uncoated / bare prestressing steel

b) Sheathed prestressing steel

Fig. 2.1: 7-wire prestressing steel strand

b) Sheathed prestressing steel

Prestressing strand protected with a layer of grease and an extruded HDPE sheathing, see Fig. 2.1b, has been used for several decades primarily as monostrand for post-tensioning of building slabs. The Post-Tensioning Institute (PTI) in the USA has introduced specifications for this type of tendon. These specifications have been amended recently by PTI and ACI, [16], and are considered to provide a reliable level of long term protection. Key aspects for the durability of these tendons are the material specifications for grease and HDPE. France and Belgium have developed a standard for monostrands which has been considered in the guideline for European technical approval of post-tensioning systems, [2]. The novelty of these provisions is that performance characteristics are specified for the raw materials, grease and HDPE, before and after manufacturing of the sheathing. Maximum changes which are considered acceptable during manufacturing are specified for selected properties. This permits control of the quality achieved by the manufacturing process and of the manufactured product.

The grease should satisfy requirements as listed in section 2.1.5c) below. The sheathing thickness for PL2 and PL3 should be a minimum of 1.5mm. For PL1 a thickness of 1.0mm is considered sufficient.

The typical monostrand discussed above is encased inside concrete. The sheathing and grease provide a low friction interface to facilitate stressing of the monostrand tendons. Therefore, a maximum friction force for moving the strand inside the sheathing is specified by the standards with a typical value of 60N/m, [17].

On the other hand, there is strand with tightly extruded sheathing which provides sufficient friction to prevent relative movements between strand and sheathing. This type of monostrand is suitable only for ungrouted applications since it would produce excessive friction in grouted conditions. For these applications, the grease is often replaced by wax. For such ungrouted applications e.g. in stay cables, the wax and HDPE sheathing has also been combined with zinc coating. However, these types of sheathed monostrands are not used for post-tensioning.

c) FRP materials

FRP materials have been successfully used for a number of pilot applications in construction. A considerable amount of research and testing has been carried out on the use of FRP for post-tensioning tendons. Various groups are working on the development of guidelines for the design of structures with FRP tendons, e.g. fib Task Group 9.3, ACI Committee 440, and Japanese Society for Civil Engineers. A small number of projects have been carried out with FRP post-tensioning tendons, and experience is being collected on their performance in practice.

However, there is insufficient experience available to consider FRP tendons generally suitable for post-tensioning in today's practice. In any case, FRP tendons used for post-tensioning should satisfy the same performance criteria as tendons made from prestressing steel including all aspects of durability.
Attention should be given to the protection of these materials from UV radiation and mechanical damage.

### 2.1.2 Anchorages

Anchorages are the heart of any post-tensioning system and are usually based on proprietary designs by the system owner. It is important to recognise that the basic concepts of anchoring prestressing steels mostly are quite simple, however, that the actual behaviour is significantly more complex and often is beyond mathematical or even numerical analysis. Hence, much of the design and confirmation of the anchorage concepts still relies on experience and detailed testing. It is recommended that testing includes fatigue testing because, apart from the fatigue performance, it is able to detect unsuitable detailing of anchorages.

Post-tensioning anchorages can be grouped into active or stressing anchorages, i.e. allowing stressing of the tendon, passive or dead end anchorages, i.e. not permitting stressing, and coupling anchorages to connect tendons.

#### a) Anchorage of the prestressing steel

The main methods of anchoring prestressing steels in post-tensioning anchorages are by wedge, button head, nut, and bond, see Table 2.3.

<table>
<thead>
<tr>
<th>Type</th>
<th>Connection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anchorage by wedge</td>
<td>Wedge / Anchor head</td>
</tr>
<tr>
<td></td>
<td>Wedge / Strand</td>
</tr>
<tr>
<td>Anchorage by button head</td>
<td>Button head on anchor block</td>
</tr>
<tr>
<td>Anchorage by nut and thread</td>
<td>Nut / Threaded bar</td>
</tr>
<tr>
<td></td>
<td>Nut / Bearing plate</td>
</tr>
<tr>
<td>Anchorage by bond</td>
<td>Prestressing steel / Concrete bond interface</td>
</tr>
</tbody>
</table>

*Table 2.3: Common types of anchorages for strand, wire and bar*

The behaviour and performance of all the anchorage concepts depend significantly on the manufacturing tolerances and the consistent quality of these tolerances. They also depend on the preparation of the contact surfaces e.g. lubrication, oxidation/corrosion and cleanliness. It is therefore important to have specialists for installation and assembly of the anchorages on site who are knowledgeable of these aspects and in the behaviour of the anchorages and who can take appropriate measures, if needed.
Anchorage of prestressing steel by bond, such as used in pretensioning, has been used for post-tensioning also. However, improved protection concepts such as full encapsulation are difficult to apply to this type of anchorage, and therefore, this type of anchorage is considered suitable only for PL1.

b) Post-tensioning anchorages

The design of post-tensioning anchorages is important for durability of tendons in terms of fatigue behaviour. The possibility for encapsulating the tendon in the anchorage is relevant for the corrosion protection.

Basic bearing plate and trumpet:
This is a simple steel plate that transfers the tendon load applied by the anchor head by direct bearing into the concrete or onto other materials such as steel, masonry and timber. This concept has been used since the start of post-tensioning and is used for tendons of all types of prestressing steel. Fig. 2.2 illustrates such an anchorage with basic bearing plate.

For anchorages placed in areas where potentially aggressive media can find access to the tendon e.g. through cracks or joints, i.e. where PL2 or PL3 is needed, trumpets of these anchorages should be fabricated in corrosion resistant materials such as plastic, or metallic trumpets should receive a permanent corrosion protection, to form a full encapsulation for the tendon. The bearing plate itself needs a suitable corrosion protection on any surface which is left exposed, i.e. not encased in concrete.

![Basic bearing plate for multistrand tendon](image)

Fig. 2.2: Basic bearing plate for multistrand tendon

Special bearing plate:
These are either machined or typically cast iron anchorage bodies that transfer the load from the anchor head to the surrounding concrete at several levels via flanges etc. For small tendon sizes there are also special bearing plates into which the anchor head is integrated, i.e. one component for both functions. Fig. 2.3 presents such special bearing plates for multistrand and monostrand tendons. Surfaces left exposed, i.e. not encased in concrete, need to be suitably protected against corrosion.

For both basic and special bearing plates, the contact stresses between bearing plate and concrete should be limited to avoid excessive cracking. This is only possible by adequate confinement of the concrete in the immediate vicinity of the bearing plate. This area that needs confinement is often the called local anchorage zone. Confinement is typically provided by spiral reinforcement or stirrups. This confinement reinforcement is considered part of the post-tensioning system. The behaviour of the local zone and the concrete beneath it is complex. Therefore, verification of the load transfer is primarily based on testing, see [2, 18].
c) **Coupling of tendons**

Coupling of tendons is common in certain parts of the world but typically avoided in others such as the USA and France. A common type of coupling tendons is by having two anchor heads, one for each tendon segment, back to back and connected by a threaded sleeve. Another common type is by overlapping the tendon ends in a common coupling anchorage, usually one tendon segment anchored in the centre, the other along the perimeter. Fig. 2.4 illustrates such coupling anchorages.

![Coupling tendons](image)

**Fig. 2.4: Tendon couplers**

Couplers form a discontinuity in the tendon for the flow of the tendon force and particularly for grouting. Special procedures and care are needed to assure reliable filling of couplings. Couplers also introduce discontinuities in the flow of forces in the structure, and require careful detailing with supplementary reinforcement at the joints. It is therefore, common practice to not couple more than 50% of the tendons at one particular section, and to add sufficient non-prestressed reinforcement across the joints and in the neighbourhood of the couplers.

Couplers are typically placed at construction joints which form a preferred path for access of aggressive media such as water and de-icing salts. For tendons which need PL2 or PL3 couplers should therefore, be suitably protected with encapsulation in plastic, or the joints be sealed at the surface of the structure with membranes. Since encapsulation is difficult particularly for large tendons, it may be preferable to avoid couplers for PL2 and PL3 and replace them with two end anchorages which provide suitable overlap of the two tendon ends.

**d) Performance of post-tensioning anchorages**

While many post-tensioning anchorages still look similar to those at the early stages of prestressed concrete, they have gone through a continuous evolution. Their quality has steadily improved, and has reached an exceptionally high level of performance and reliability.
Acceptance of the post-tensioning anchorages is today widely based on detailed testing with stringent performance criteria. Such test procedures were developed in particular by FIP, [18], and have been implemented in many countries in Europe. They form the basis of the European technical approval of post-tensioning systems, ETAG 013, [2]. They have also been widely accepted throughout Asia including Japan. Also the acceptance tests in the USA by PTI are converging gradually towards the FIP procedures. The guideline for European technical approvals of post-tensioning systems, ETAG 013, is the most up-to-date testing specification for post-tensioning systems, and is suggested as a general reference.

These system acceptance tests include three basic test procedures:

- the static tensile test which primarily confirms the reliable anchorage of the prestressing steel;
- the load transfer test which verifies the transfer of the tendon load from the anchorage into the surrounding concrete;
- the fatigue test that assesses the performance of the anchorage under stress variations in the tendon.

Acceptance criteria as per FIP and ETAG 013 are stringent since the anchorage is required to achieve an ultimate load of 95\% of the actual tensile strength of the prestressing steel with a minimum of 2\% tendon elongation. This corresponds approximately to the specified ultimate tendon capacity. While these tests mainly focus on mechanical performance, they ensure a minimum performance which is also relevant for proper performance under stress variations in the tendon and good durability of the post-tensioning systems. Compliance with the fatigue test requirements assures good detailing and robustness of the anchorage in general for durable prestressed concrete construction.

In addition to the above mentioned testing for strength, anchorages for PL2 and PL3 need to have a sufficiently leak tight encapsulation. This leak tightness may be tested by subjecting the anchorage encapsulation with the connection to the duct to hydrostatic pressure. [16] specifies such testing to a hydrostatic pressure of 8.6 kPa (0.9m water head). [9] requires such testing for ducts and duct couplers bent to the specified minimum radius of curvature and subjected to a hydrostatic pressure of 50 kPa (5m water head). Test specifications for the anchorage encapsulation could be based on these documents.

Apart from the above-discussed performance, post-tensioning anchorages need to have a reliable quality. This is achieved by designing the components with a sufficient safety margin, consistent quality of manufacturing, and installation by experienced and trained personnel. It also requires selection of suitable materials for each of the anchorage components. The selected materials need, apart from strength, to offer sufficient ductility. They also need to be tough and insensitive to small defects.

2.1.3 Ducts

While not structural, ducts are an essential component of any post-tensioning system for reliable installation, stressing, and grouting, and for long term durability of the tendon.

Ducts serve different objectives in post-tensioning. For internal tendons, they first create the void in a concrete structure, in a defined alignment, that allows installation and the free movement of the prestressing steel during stressing. They also form the contact surface that determines the friction losses during stressing. Finally, they form the interface between prestressing steel, grout and structure to transfer bond forces. For external tendons, the ducts serve as a guide for installation of the prestressing steel. They again form the contact surface that determines the friction losses at deviation points during stressing. The duct must resist the injection pressure of the filling material. Last but not least, the duct needs to provide a robust encapsulation of the external tendon for long-term protection to compensate for the absence of concrete cover.

Usually, ducts have a round cross section. However, particularly for thin slabs in buildings and bridge decks, flat or oval ducts are often used.

Unlined ducts and bio-degradable ducts such as cardboard tubes are not used anymore as they have poor behaviour regarding friction, waterproofing and durability. Another material that is not recommended is
PVC due to the risk of the formation of chloric acid which may start at moderate temperatures in the order of 70-80°C and which could attack the prestressing steel.

Lined ducts have normally been formed using either corrugated metal duct or steel tube. The advantage of spirally wound tube is that it is flexible and can be bent on site to match the required tendon profile. More recently, non-metallic ducts have been used. These have been made out of Polypropylene (PP) or High Density Polyethylene (HDPE), now known as PE80. fib has published a Technical Report [9] on plastic duct properties, performance requirements for bonded tendons and on suggested test methods to ensure that these ducts are suitable for post-tensioning.

The following is a brief review of different types of ducts considered suitable for post-tensioning.

a) Corrugated metal ducts

This is the most widely used type of duct for internal bonded post-tensioning. It is made from sheet metal strips, spirally wound into a continuous duct. The thickness of the sheet metal strips is usually between 0.2 and 0.7 mm depending on the duct size, whether tendons are prefabricated or installed on site after concreting, and depending on the expected concrete pressure or other loads during construction. Individual segments of duct are typically joined with a sleeve made of an oversized duct that can be threaded onto the corrugation, and sealed with tape or equivalent products. Fig. 2.5a shows such a typical corrugated duct with sleeve.

In Europe, this type of duct has been standardised in EN 523 [19], and EN 524, [20]. These standards can be considered to assure use of state-of-the-art corrugated duct. Performance specifications cover the essential requirements, and detailed test procedures permit the verification of the actual behaviour. The main characteristics specified in the standard include:

- duct geometry including the degree of corrugation to ensure bond development;
- stiffness of the duct to avoid excessive deflection of ducts between supports during concreting;
- flexibility of the duct to allow defined smooth curvatures;
- resistance to transverse loads to avoid collapse of the duct during concreting;
- resistance to longitudinal loads during construction;
- leak tightness of the duct to laitance.

Ducts must be free of rust to assure reliable friction losses during the stressing of the tendon. The use of galvanised duct is common in many parts of the world to avoid the corrosion of the duct surface during construction. The galvanising also serves as lubrication and thus, reduces the friction losses compared with a dry and clean black steel surface. Cold-drawn wire and strand tendons, in accordance with section 2.1.1, have been demonstrated to be insensitive to the potential development of hydrogen due to the contact of the galvanised duct with fresh cementitious grout. The use of galvanised ducts however, is not recommended when the prestressing steel is sensitive to hydrogen embrittlement or if the environment of the duct could lead to a galvanic cell.

Corrugated metal ducts, whether made in black steel or galvanised will quickly corrode once they are exposed to water and de-icing salts. Particularly vulnerable are zones which are not in direct contact with concrete or grout, e.g. zones underneath duct tape. Therefore, these ducts cannot be considered to represent an independent barrier for the corrosion protection of the prestressing steel. They are therefore, suitable only for tendons with PL1.
a) Corrugated metal duct and sleeve (one end before and one after application of tape): For PL1 only

b) Corrugated plastic duct and coupler: For PL2 and PL3

Fig. 2.5 Internal tendon ducts

b) Corrugated plastic ducts

At the beginning of the 1990's a new generation of thick-walled corrugated plastic ducts for bonded, internal tendons was developed and gradually introduced in the market. These ducts were specifically designed for use with bonded tendons. Fig. 2.5b shows this type of plastic duct with coupler.

These plastic ducts can provide complete encapsulation to protect the tendon against ingress of aggressive media from the outside, if properly designed, manufactured, and installed. fib has published a technical report on these plastic ducts for bonded tendons which specifies the requirements for the plastic materials, the individual components, and for the fully assembled system [9]. Plastic ducts in accordance with [9] are suitable for PL2 and PL3.

Unlike steel, the characteristics of plastics strongly depend on the temperature to which they are exposed. Therefore, the temperature is an important parameter in the verification of the performance of plastic duct systems. In-situ measurements have shown that black plastic ducts exposed to direct sunshine will reach temperatures up to 50-60 °C. High temperatures will make the plastics softer, i.e. the ducts become less stiff. The main risk involved with this softening is the reduced resistance of ducts to transverse loads applied at duct supports, and during concrete placing. This may lead to local deformations/indentations of the duct at supports at which the prestressing steel may cut through the duct wall during stressing of the tendon. In severe cases, crushing of the duct may occur during pouring of the concrete. Test procedures to avoid these problems are specified in the fib report, [9].

The heat of hydration of concrete has been mentioned as a potential cause of softening and crushing of the ducts inside young concrete. This is not a relevant concern, in general, because the concrete is sufficiently stiff to support its weight once the heat of hydration achieves values above say 40°C and therefore, crushing of the duct is not possible. However, stressing of tendons at the peak heat of hydration may cause problems with the prestressing steel cutting more easily into or through the duct.

Temperatures below the freezing point also need particular attention because the plastic materials become stiffer and less ductile. This may cause problems when the ducts are placed with small radii of curvature. Particular attention and procedures are necessary with tendons prefabricated and placed on coils in a workshop, and later un-coiled on site at temperatures near or below 0°C. This may lead in severe cases to cracking of the plastic ducts. Therefore, un-coiling should be done at similar temperatures as the coiling, preferably around 20°C.

Another concern which has arisen because of the high coefficient of thermal expansion of plastics is that installation of a plastic duct at elevated temperatures may form a gap in the concrete around the duct once the structure and duct cool down. Theoretical as well as experimental investigations have confirmed that this concern is not justified, such gaps do not develop, [21]. Any eventual risk may further be reduced with appropriate grouting procedures in which the final grouting pressure is maintained while all the vents are closed.
Corrugated plastic ducts designed and tested in accordance with the fib report, [9], have demonstrated satisfactory performance in practice. The new generation of such ducts has been successfully applied since the early 1990’s and several millions of metres of these ducts have been installed. However, experience with plastic ducts in prestressed concrete is significantly older. A first generation of plastic ducts had already been used in the 1970’s in Switzerland with more than 300,000m installed at the time. Observations from structures with these plastic ducts demolished recently have confirmed their good performance, [22].

With suitable connection details, these duct systems have been confirmed by testing to provide a durable and completely leak tight encapsulation of the prestressing steel even across relatively wide and active cracks, [23].

The plastic duct system has also been confirmed to reduce the risk of fretting fatigue of the prestressing steel, [24].

Plastic ducts in accordance with [9] combined with suitable details in the anchorage zones may provide electrical isolation of the tendons from the structure. Such electrically isolated tendons (EIT) are protected from the harmful effects of stray currents as discussed in section 1.2.2.e). Electrically isolated tendons also permit monitoring of the quality of the encapsulation of the tendons. A high electrical resistance is positive confirmation of the high quality of the encapsulation. In general, the measured electrical resistance of a tendon will gradually increase with age because of the hydration of grout and concrete. Any significant drop of the measured electrical resistance (say by 30% or more) during the life of the structure positively indicates the ingress of moisture or water into the tendon. The defect can then be located either visually or with electrical measurement (leakage of electrical current, see chapter 3), and the defect either repaired or the location protected with supplementary methods, e.g. with membranes.

A particular point of concern is the encapsulation of tendons across the joints between precast segments. Dry joints (without epoxy resin) and internal tendons with discontinuous plastic ducts are not acceptable for any tendon PL. Joints adequately filled with a suitable epoxy resin are acceptable for PL1. However, for PL2 and PL3 either sealing of the exposed segment joints with a suitable membrane or full encapsulation of the tendon with plastic across the joints is considered necessary in addition to the epoxy resin. This can be achieved e.g. by special duct couplers across the segment joints. Fig. 2.6 shows one of the available duct couplers for continuity of the tendon encapsulation across joints in precast segmental construction. This type of coupler has been installed in a segmental bridge project in Florida, and feed back from the site has been positive (oral report at American Segmental Bridge Board meeting held at ASBI Convention 2002).

![Coupler for ducts to seal joints in precast segmental construction.](image)

Continuity of the tendon encapsulation across joints in precast segmental construction can also be achieved with the use of double tubing. A first duct is installed before concrete pouring to form the void for the tendon. This duct is discontinuous at the joints. A second, fully continuous plastic duct is pulled into the void formed by the first duct after erection of the structure. The tendon can then be installed into the second duct and the space between the two ducts is grouted together with the inside of the continuous plastic duct. Alternatively, a block-out can be provided and the duct can be coupled with a duct sleeve and encapsulated with heat-shrink sleeve.
Any such joint detail should be subjected to leak tightness testing similar to the one specified for duct and couplers in [9].

c) PE pipe

Thick walled PE pipe is the commonly used type of duct for external post-tensioning. The pipe serves partly similar purposes to the internal ducts. However, since external tendons are not protected by a thick layer of concrete, there are some differences that warrant attention. PE pipe for external tendons may be subjected to significant internal pressure during grouting, and must be designed to safely carry this pressure. The European technical approval for post-tensioning systems, [2], e.g. specifies 1 MPa (10 bar) design pressure for the pipe. PE pipe for external tendons may be subjected to significant temperature variations. In particular, low temperatures may introduce significant restraint stresses into grouted PE pipes. Unlike for internal tendons, the PE pipe is the only element providing encapsulation to an external tendon. Hence, it must be sufficiently leak tight to assure proper grouting and to assure long term protection and durability of the tendon. Vacuum assisted grouting is advisable when there are some difficulties with standard grouting procedures (position of grout vent away from the high point, difficulties of access). At the same time, application of a vacuum will serve as confirmation of the leak tightness of the encapsulation.

Careful selection of the PE material is a key element for successful use and durability of the pipes. Only new PE material (granulate) should be used. Recycled material should not be used. PE pipes in accordance with the guidelines for European technical approval for post-tensioning systems, [2], and ASTM D3035, [25], or ASTM F714, [26], can be considered suitable for use in external tendons for all PLs.

Thick-walled PE pipe has been demonstrated to be sufficiently robust to support the high transverse pressure applied by the tendons to the pipe at deviation points, [27]. Hence, if no bond is assumed in the design at the deviation points, the PE pipe is preferably made continuous through the deviation points to provide full encapsulation, see Fig. 2.7a. However, a smooth steel pipe is required if bond is specified in the deviation points. Suitable details with sleeves are required for the transition from the steel pipe to the PE pipe, see Fig. 2.7b.

Image: a) PE pipe continuous through deviation saddle b) PE pipe connected with neoprene sleeve to steel pipe in deviation saddle

Fig. 2.7: PE pipe details at deviation saddles

Since about 2000, transparent pipe made from fibre reinforced plastic has become available in Japan, see Fig. 2.8. The authors are not aware of any particular specification for this type of duct. However, the duct should satisfy similar requirements as specified in [2, 9, 25, 26] as far as applicable. This type of duct facilitates the inspection of the quality of grouting in the accessible areas of the tendon. Between 2000 – 2002 about 150 km of this type of duct has been installed in projects of the Japan Highway Public Corporation. Other Japanese owners have not followed this development and continue to use more traditional types of duct.
d) Steel pipe

For certain special applications, smooth steel pipe is used as duct for tendons. These steel pipes can be considered durable and suitable for PL1, PL2 and PL3 due to their wall thickness which is significantly larger than for corrugated ducts. Fig. 2.9a shows an application in an offshore structure. Other applications include e.g. long vertical tendons, which are intended to be grouted completely at one time. The use of steel pipe confines the grouting pressure and thus, protects the surrounding concrete. Smooth steel pipe is also used in locations of tight tendon curvature such as loop anchorages, Fig. 2.9b, and external tendon deviations. The smooth pipe must be bent in the workshop to the specified geometry. It is sufficiently rigid to maintain the specified geometry even under relatively rough conditions. The smooth surface also reduces the secondary transverse stresses applied to the prestressing steel in tight tendon curvatures. These pipes need permanent corrosion protection on all exposed surfaces, and temporary corrosion protection on the inside. Temporary protection on the inside is important to assure low and reliable friction parameters during tendon stressing. This protection is often achieved by galvanising. The same comments for galvanising apply as made for corrugated metal ducts, see 2.1.3a).

The wall thickness of such pipe is often specified as 2% of the pipe diameter but should not be less than 3 mm to permit welding, if needed.

As for any duct, sealing to provide a leak-tight system is also important for steel pipe. Since the steel pipe is rigid compared to other types of duct, it can only accommodate placing tolerances at the pipe segment joints by creating a gap between adjacent pipe ends. Therefore, careful detailing, execution and control of the quality of pipe joints are essential to avoid problems with leaking joints, and pipe blockages.

a) Steel pipe used in offshore structures

b) Steel pipe used as duct for loop anchorages

Fig. 2.8: Transparent duct used by Japan Highway Public Corporation (Courtesy Japan Highway Public Corporation)

Fig. 2.9: Steel pipe used as tendon duct
2.1.4 Accessories

Accessories of post-tensioning systems include such non-structural components as temporary and permanent anchorage caps, grout inlets and outlets (called vents in this report), coupling connections between duct segments or between duct and anchorage, etc.

Many of these components serve a temporary purpose during installation, and in particular during grouting and have often not received the attention they actually deserve. A leak tight duct system including all connections and anchorages is necessary to assure complete filling of tendons with grout, and consequently good durability. Many of these components are now required to provide permanently full encapsulation to tendons. In any case, whether temporary or permanent, these accessories need to be properly detailed and therefore, they should all be shown on shop drawings for the specific project.

For use in post-tensioning systems for PL2 and PL3 these accessories should be included in the leak tightness testing as discussed for anchorages and ducts.

a) Vents

Grout vents have traditionally consisted of a plastic hose, closed with tie wire, and cut flush with the concrete surface after setting of the grout, Fig. 2.10a. Except for PL1, these types of vents are no longer considered acceptable because they form a preferred path for ingress of aggressive media into the tendon. Carefully detailed systems are available with threaded connections including valves and caps. Such systems provide positive connections that resist site conditions, and which allow proper sealing of the vent after grout setting. Figs. 10 b, c illustrate recommended types of vents with caps and valves which permit encapsulation of the tendon and therefore, are suitable for PL2 and PL3.

![Smooth hose closed with tie wire](image1.png) ![Corrugated hose with cap](image2.png) ![Corrugated hose with valve](image3.png)

a) Smooth hose closed with tie wire (for PL1 only) b) Corrugated hose with cap (for PL2 and PL3) c) Corrugated hose with valve (for PL2 and PL3)

Fig. 2.10: Different types of grout vents

Vents with permanent caps need to be suitably set back into the concrete because they must not be cut off. A suitably detailed recess to accommodate vent and cap is shown in Fig. 2.11.
Fig. 2.11  Recess former for grout vent

Commonly used accessories and connections for the vents on corrugated metal duct are shown in Fig. 2.12a. These details often employ the use of tie wire and duct tape. As mentioned previously for the metal duct, these solutions are only suitable for PL1. For plastic duct systems that offer complete encapsulation, special coupling and connection devices are available which are fully compatible with the duct. Such details as shown in Fig. 2.12b avoid risk of improvisation on site and assure consistent quality and leak tightness of all connections for PL2 and PL3.

Fig. 2.12:  Duct accessories and connections

b)  Duct couplers and transitions to anchorages

Corrugated metal duct segments are joined on site with corrugated steel sleeves. These are slightly larger in diameter and thread onto the duct. These sleeves should be sufficiently long to force the adjacent duct segments into a smooth tendon profile. Typically, a sleeve length of 2-3 duct diameters is recommended. The sleeve is sealed with duct tape. Fig. 2.5a shows such details. These details are only suitable for PL1.

Corrugated plastic duct segments can either be joined by special coupling devices or by mirror welding, if duct details and dimensions are suitable. Fig. 2.5b shows a special duct coupling device which can also provide a connection for a vent, where needed, and which is suitable for PL2 and PL3.

Smooth PE pipe can be joined by mirror welding or by using electro-fusion couplers, see Fig. 2.13a. Such couplers can also be equipped with vents. Oversized PE pipe sleeves to join PE pipe segments have been used but are not recommended for PL2 and PL3, Fig. 2.13b.

Steel pipe joined with steel sleeves and sealed with tape is, for the reasons mentioned above, not considered suitable for PL2 and PL3. Replacement of the tape by robust heat-shrink sleeves may make the connection suitable for PL2 and PL3.

For the transition of the duct to the anchorages, similar details and comments apply as discussed above for the connection between duct segments.
a) Fusion coupler to join PE pipe and for vents (for PL2 and PL3)

b) PE sleeve to join PE pipe (for PL1 only)

Fig. 2.13: PE pipe duct connections and vents

c) Caps

It is still common practice in many countries to seal anchorages for grouting either with quick-setting mortar (dry packing) or by concreting the anchorage recess before grouting. These procedures are not recommended for any PL because they do not permit control of the quality of grouting. Most modern post-tensioning systems offer solutions with temporary and/or permanent caps to seal the anchorage, see Fig. 2.14. The use of temporary grout caps, Fig. 2.14a, permits the verification of the quality of grouting at the time of construction. These caps are removed after grouting and the recess in the concrete is then typically filled with a low-shrinkage concrete (pour back). There is some concern that the bond between pour back and concrete may fail over time, and that the joint may provide a path for ingress of aggressive media to the anchorage. Therefore, temporary grout caps and pour back are considered only suitable for PL1.

For PL2 and PL3, a permanent grout cap either made of permanently protected metal, Fig. 2.14b, or plastic, Fig. 2.14c, should be provided. These caps should provide leak tight encapsulation to the anchorage zone. Leak tightness may be verified with a test in which the anchorage and cap are subjected to hydrostatic pressure, [9, 16]. More severe leak tightness tests have been proposed recently for stay cable anchorages, [13, 28]. The permanent cap significantly contributes to the durability of tendons which need PL2 or PL3. Depending on the intended type and extent of inspection, the recess around these permanent caps may be filled with mortar or concrete or the caps may be left exposed.

a) Temporary steel cap for grouting (PL1)

b) Permanent metal cap (PL2)

c) Permanent plastic cap (PL2 and PL3)

Fig. 2.14: Caps for sealing of anchorages
d) **Monostrand encapsulation**

Monostrand tendons with extruded sheathing provide excellent corrosion protection along the tendon length. However, the sheathing needs to be stripped at the tendon end for the anchorage of the prestressing steel. For all PLs, full encapsulation of the monostrand anchorage zone is recommended. No part of the prestressing steel should be left exposed. This can be achieved with a sleeve as transition from the monostrand to the anchorage, and a permanent cap on the anchorage. Voids inside the anchorage, sleeve and cap should be filled with grease. With such details the grease is fully contained and is assured to remain a permanent protection of the prestressing steel. Fig. 2.15 shows such a completely encapsulated monostrand anchorage. For PL2 and PL3 it is particularly important that the connection between sleeve and anchorage is leak-tight and can resist axial forces to avoid being pulled off the anchorage due to temperature movements of the sheathing.

![Fully encapsulated monostrand tendon (for all PLs)](image)

**Fig. 2.15:** Fully encapsulated monostrand tendon (for all PLs)

It is absolutely essential to protect the monostrands during construction to avoid penetration of water into the grease. Water in the grease and inside the encapsulation may cause degradation of the grease and initiate corrosion of the prestressing steel.

**2.1.5 Corrosion protection materials**

Prestressing steel must be effectively protected against corrosion to achieve durable post-tensioning tendons. The objective is to achieve a design life of the tendon which is comparable to that of the structure in which it is placed. The design of the corrosion protection systems should take into account that most parts of the tendon are not accessible during the design life and that individual components or the entire tendon are not replaceable, in general. Even if special details are provided to allow replaceability of the tendon during the design life, this should be considered an exceptional case that is not normally expected to really happen. Generally, the corrosion protection should be designed for the entire design life of the structure.

Mild steel components of anchorages, deviators, and accessories which are easily accessible may obtain a corrosion protection that needs regular maintenance, say every 15-25 years, during the design life of the structure, see e.g. [8].

A detailed discussion of all aspects of corrosion mechanisms and protection of prestressing steels is provided in FIP recommendations, [5]. Corrosion protection of post-tensioning systems includes temporary protection of the components. To be effective, corrosion protection measures must be applied already at the manufacturing place of the components.

a) **Temporary corrosion protection materials**

Materials and components for post-tensioning should be protected and stored such as to avoid their corrosion and staining. Typically, light superficial corrosion that can be removed by wiping with a soft cloth is acceptable. More severe corrosion should generally be considered reason to clean/repair, or in severe cases, reject the materials. This is particularly important on surfaces where corrosion may impair the proper functioning of the component. This applies especially to the anchor head wedge cavities, the
wedges and also to the inside of the ducts. Temporary protection by oils or grease is often sufficient since these surfaces will receive permanent protection at a later time, e.g. by grouting. Light to moderate corrosion on surfaces which do not need cleanliness for proper functioning, e.g. the outside of bearing plates cast into concrete, is not harmful and therefore, not considered reason to reject these materials.

Due to its high strength, prestressing steel is more susceptible to corrosion (in particular pitting) than other components and therefore, must be stored and protected carefully. Bare prestressing steel can be packed and wrapped by the manufacturer to provide specified temporary protection. The prestressing steel should be stored on site in a dry and clean location, off the ground, and with sufficient ventilation to prevent condensation. In special cases, it may be stored in an air-conditioned area.

For extended periods of storage on site, the temporary protection can be improved by application of oils onto the prestressing steel. These oils should not contain substances potentially harmful to the prestressing steel. They should preferably be applied at the manufacturing place. Only products should be specified which do not excessively reduce the bond properties of the steel and which do not need to be removed before application of the permanent protection. Temporary corrosion protection oils used for prestressing steel are effective for a limited period of time in the order of a few months. In any case, the actual product, expected period of protection and the environments to which prestressing materials will be exposed should be verified with the supplier.

Once the prestressing steel is installed in the structure, it should be stressed and permanently protected, e.g. by grouting, as quickly as possible. Guidance on the maximum period of time between installation of the prestressing steel, stressing of the tendon, and final protection of the tendon made of bare prestressing steel is given in fib Bulletin 20 “Grouting of tendons in prestressed concrete”, [11]. In aggressive environments, unprotected stressed prestressing steel should not be left ungrouted for more than about 2 weeks. In benign and moderately aggressive environments, somewhat longer periods up to 4-6 weeks may be accepted.

Leaving prestressing steel inside the duct without temporary or permanent corrosion protection for extended time, has been reported as a contributing factor or even as cause for durability problems and subsequent failures of post-tensioning tendons. Pitting corrosion on the prestressing steel must be avoided since it may affect the durability of the tendon. Pitting corrosion can also lead to a reduced fatigue life of the prestressing steel.

If these above mentioned limits of leaving the tendon ungrouted cannot be safely assured, the prestressing steel has to be provided with temporary corrosion protection before installation. Based on recent investigations in Switzerland [29], the preferred protection is by application of suitable water soluble oils as discussed above. These oils should preferably be applied in the factory to assure uniform distribution on the steel surface, and sufficient drying before installation. Once the tendon is installed and stressed, all tendon ends and vents should be sealed to avoid ingress of water into the duct system. In the above referenced investigation in Switzerland, the product Rust-Ban 310 was used. Tendons were protected with Rust-Ban 310, stressed, and left for six months during winter in the ducts without grouting. They were then removed and inspected for corrosion. Only insignificant traces of rust were found and limited to areas near the tendon ends, see Fig. 2.16. Hence, a very effective protection had been provided by Rust-Ban 310 for a period of six months.

In the same study, see [29], it had been demonstrated that the bond of prestressing steel protected with Rust-Ban 310 was not significantly affected if the product had sufficiently dried on the steel surface. Hence, tendons protected with Rust-Ban 310 can be grouted without removing the water-soluble oil by flushing with water.
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<th>Rust Ban 310</th>
<th>Blowing of Dry Air</th>
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<td><strong>RUST DOTS</strong></td>
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Notes: Results are shown in groups of two per protection method:
- Left bar is plastic duct
- Right bar is metal duct

**Fig. 2.16:** Total rust point counts for different types of temporary corrosion protection (from [29])

In the same study, two other temporary corrosion protection methods were investigated. Filling of tendons with nitrogen gas did for some reason not provide the expected level of protection, and the tendons showed a significant amount of corrosion comparable to the reference tendons without any specific temporary protection. Continuous blowing with dry air provided some protection. However, signs of corrosion were more frequent than with Rust-Ban 310, and extended over a larger portion of the tendon length. Overall, the protection of the pre-stressing steel with Rust-Ban 310 provided the best, and in absolute terms, a fully satisfactory protection for the investigated duration of six months. Blowing of dry air may be considered where temporary protection was not applied to the pre-stressing steel prior to installation. The effectiveness of nitrogen for temporary protection was not conclusive in this test, and the method was difficult to implement in practice.

Testing of different water soluble oils in the US confirmed the good performance of the Rust-Ban 310 and also confirmed that there are several other suitable products for temporary protection of pre-stressing steels on the market, [30].

**b) Cementitious grout for permanent corrosion protection**

**Basics:**
The cementitious grout has two roles:
- protecting the steel tendon from corrosion. One important feature is that it is strongly alkaline (pH 13 or higher). This alkalinity will inhibit the corrosion of the steel provided that it is not neutralised (pH falling below 9) by reaction with atmospheric carbon dioxide or infiltration of chlorides;
- bonding the tendon to the surrounding concrete member throughout its length for internal tendons.

Improvements on the corrosion protection provided by cementitious grout cannot be achieved by any single action on its own but require parallel developments in the grouting materials, grouting techniques, grouting equipment and QA/QC systems. It is recognized that proper installation and use of a system is as important as the performance of the system components for the successful application of pre-stressing.

It has therefore been the objective of the various actions to develop:
- better grouts which have improved properties: Flowability, bleed resistance, reduced permeability, stability;
- more realistic tests to verify the grout performance;
- improved grouting techniques, equipments and specifications;
- QA systems which can be applied during and immediately after grouting;
- inspection and long term monitoring systems.
Extensive work has been recently done in various countries in order to characterise the properties of the grout components. The Post-Tensioning Institute (PTI) issued in February 2001 its “Specification for grouting of post-tensioned structures”, [31]. The fib has issued its Bulletin 20 “Grouting of tendons in prestressed concrete”, [11]. France has introduced an approval procedure for cementitious grouts, [32]. Europe is updating the grouting standards EN 445, 446 and 447. This chapter will summarise some of the important aspects. For details, the reader should refer to the above listed references. Only grouts in accordance with these recent specifications should be used for all types of post-tensioning. Cementitious grout in accordance with these recent specifications is considered a very reliable permanent protection for prestressing steel for all required PLs.

**Grout materials:**

**Cement:**

Cement used for grouting should be ordinary Portland cement. However, cements blended with some mineral additives may be considered for grout. Cement should not contain any substances harmful to the prestressing steel and should not have lumps. Cement should not show flash set.

**Additives:**

Mineral additives such as silica fume may be used to improve some properties of the grout such as strength, permeability and bleed. However, the effect of these additives on the alkalinity of the grout should be checked. Silica fume may develop hydrogen and should therefore, only be used with prestressing steels mentioned in section 2.1.1 which are not sensitive to hydrogen. Furnace slag and fly ash additives are not suggested to be used for grout because of the potential variability of their constituent materials.

**Admixtures:**

Admixtures are used to improve selected properties of grout such as viscosity, bleed, and stability. They should not contain any substances harmful to the prestressing steel especially thiocyanates, nitrates, nitrites, formiates and sulphurs and should only contain marginal traces of chloride ions.

Air entraining admixtures and corrosion inhibitors are commonly used in concrete, but historically have not been specified in grouts. Corrosion inhibitors applied in wrong dosage have been reported to accelerate corrosion, [33].

**Water:**

Water should not contain ingredients harmful to the prestressing steel or the cementitious grout. It should not contain more than 300mg of chloride ions per litre or 200mg per litre of SO₄²⁻ ions or any organic materials, [11]. Drinking water is generally acceptable for grout.

**Grout performance:**

The following performance characteristics should be achieved:

**Flowability:**

The grout has to be sufficiently fluid to permit pumping at relatively low pressures. The flowability is usually assessed by the time needed for a given quantity of grout to efflux from a cone of defined geometry. TheMarsh flow cone typically used in Europe is shown in Fig. 2.17a. The flow time with the Marsh cone (diameter: 10mm) has to be less than 25 seconds in the range of temperatures defined by the manufacturer to allow injection at acceptable pumping pressure and to be sufficiently fluid to fill the duct. Another flow cone typically used is the one specified by the US Army Corps of Engineers and FIP, Fig. 2.17b. Flow times between these two cones typically differ by several seconds. The cone actually used should therefore, always be referenced.

Grouts may have thixotropic behaviour. This is the property of a grout that enables it to stiffen in a short time while at rest but to acquire a lower viscosity when mechanically agitated. This process is reversible. The fluidity of thixotropic grout cannot be measured with the flow cone. In the laboratory, the shear stress can be measured with a 'scissometer' and expressed in g/cm². Viscosity should be in the
range of 120 g/cm$^2$ to 200 g/cm$^2$. On site, the spread of a given grout volume on a flat glass surface may be used as a measure for the flowability of thixotropic grouts, Fig. 2.17c, [34].

The flow time has to be remain reasonably stable (say within 20% of initial value) until at least 30 minutes after mixing, or until the time defined by the manufacturer in which the grout may be injected.

Bleed requirements:

The grout is a suspension which should remain stable, i.e. it should show only marginal sedimentation and bleed, if any. Sedimentation and bleed are the main cause of voids in tendon ducts. The stability of the grout should be verified in the presence of the prestressing steel. The quantity of bleed water and air from the grout should typically remain less than 0.3% in the reduced scale wick-induced bleed test and in the large scale inclined tube test, [11]. The grout must be designed to maintain these properties in the range of temperatures defined by the manufacturer. The presence of large pressure such as may occur in long vertical tendons may increase bleed. This effect may be verified with the Schupack pressure bleed test specified in the PTI guide specification [31].

Other performance characteristics to be determined are:

Mechanical strength, setting time, capillary absorption, volume change, sedimentation and density.

![Images of flow test methods](image)

**Fig. 2.17: Typical grout flow test methods**

**Testing regimes for grout:**

The purpose of testing is to ensure suitability of the grout to achieve the aim of full protection and bond of the prestressing steel. The testing regime may include initial tests (either in a laboratory or site conditions), suitability test (on site) and acceptance tests (on site). Additionally in some countries system type approvals are required by the authorities that may include the testing of groutability and of the grout itself, [32]. Special grouting trials may be required for certain projects in addition to, or as part of, the suitability testing.

**System type approvals / initial testing:**

Grout should be subjected to an approval procedure similar to those used for post-tensioning systems. These approval procedures should be applied in two stages: First, to the grout mix to demonstrate the adequacy of the particular mix design to satisfy the requirements. Second, to the grout prepared in a specific grout mixer intended to be used by the specialist contractor on the site. Approval testing includes testing of grout strength, bleed, volume change, fluidity, and density and demonstrating compliance with the specified limits. Bleed properties should be verified with the large scale inclined tube test and the reduced scale wick-induced test, see [11]. Once the approval procedure has been satisfied, and provided the details proposed for use on a project are considered to be typical, testing may be limited to suitability and acceptance as described below.
Suitability tests:
It is advisable to perform the testing of the suitability of the grout for the site conditions before using the grout on the project. Suitability testing includes the same tests as approval testing but without the large scale inclined tube test. Verification of bleed should be based on the wick-induced bleed test.

Grouting trials:
Experience has shown that full-scale trials of grout and grouting procedures are valuable to prove adequacy for exceptional or special conditions not found on typical projects. For such projects it may be advisable to carry out project specific trials of grouting which should be planned and carried out well in advance of site operations. However, recent test results of identical grout mixes for similar tendon configurations may be acceptable for many projects. Initial tests should include results of examining the completeness of filling of the duct, particularly at anchorages and at high points of the tendon profiles where bleed and air voids may form. This can be achieved by core drilling into the trial tendon or opening the tendon after the grout has set and by physical examination.

Acceptance tests:
Routine acceptance testing is carried out on all projects during grouting operations to demonstrate compliance and consistency of the grout performance with the project requirements and confirm that the required durability should be achieved. The testing includes tests for grout strength, bleed with the reduced scale wick-induced test, volume change, and fluidity. The test frequency should suit the complexity of the project.

Relevant test procedures for each of the testing regimes and recommended test frequencies for acceptance testing are presented in the fib Guide to Good Practice, [11].

c) Soft filling materials for permanent corrosion protection

Basics:
For unbonded tendons a flexible corrosion protection material is required. The most commonly used materials are grease and wax.

Waxes are made of saturated hydrocarbon with a high percentage of ramified chains and a micro crystallisation. This explains its flexibility and its adhesive properties to various supports. Some specific additives provide excellent behaviour under external pressure (fretting corrosion).

Greases are a mix of oil and soap with anti-corrosion additives.

For applications where low friction is required, grease is the preferred material. For applications where there is no need for low friction (e.g. with injection after stressing, sheathed strand not embedded in grout or concrete) wax may be preferred over grease because its crystalline structure provides greater long term stability.

Wax and grease specifications:
Wax products have a high viscosity at ambient temperature and need to be heated to about 80-100 °C to permit injection. Grease is injected at ambient temperature under pressure. Both products shrink while cooling. They expand under temperature increase. These movements have to be considered in the design and detailing of ducts, vents, and caps.

The main performance characteristics of these products are:
- For wax: Congealing point, cone penetration, bleeding, resistance to oxidation, corrosion protection, and contents of aggressive elements.
- For grease: Dropping point, cone penetration, oil separation, resistance to oxidation, corrosion protection, and contents of aggressive elements. For grease also the values of the flash point, water content, and soak test results should be declared.
Further information and detailed requirements for the above listed characteristics may be found in the ETAG 013, [2], FIP Recommendations on corrosion protection of prestressing steels, [5], and PTI/ACI recommendations, [16]. The origin and the composition of the wax and grease should be declared by the supplier. Grease and wax in accordance with the above specifications are considered suitable for all PLs. However, ingress of water must be positively prevented during fabrication, storage and installation on site.

### 2.2 Requirements for construction

Valuable information on the requirements for installation of post-tensioning systems has been provided recently in the CEN Workshop Agreement, CWA 14646, [36]. This document is recommended for implementation into the specifications of all projects.

Post-tensioning systems should be installed by a specialist company in accordance with a quality plan and general procedures defined by the system supplier. However, some components such as duct and bursting reinforcement may be installed by other companies in accordance with the instructions of the specialist company. Stressing the prestressing steel and filling operations of ducts, if applicable, must be carried out in accordance with the quality plan, and must comply with the general procedures defined by the system supplier. In all cases, installation, stressing and grouting operations should be supervised on a continuous basis by a qualified supervisor. Execution of the work should be carried out by suitably trained and experienced site operators.

The specialist company should have a quality plan for each contract, adapted to the size and importance of the project, with relevant procedures adapted to the specific site, prepared in collaboration with the main contractor, as required by the project. The quality plan should include method statements for relevant key tendon installation processes such as duct placing, tendon installation, stressing and application of the permanent protection, with the indication of inspection and/or verification by the specialist company, customer, client or the relevant authorities necessary at hold points. Furthermore the quality plan should identify the human resources, responsibilities, names of the supervisor, materials, equipment and its maintenance, controls, inspection, measuring and test equipment, hold points, reference standards and acceptance criteria to meet the project requirements.

The specialist company should also have a safety plan covering all installation, stressing and filling operations of the post-tensioning systems.

#### 2.2.1 Packaging – transportation – storage – handling

Materials prone to corrosion or damage such as prestressing steel, ducts, anchorage devices, couplers, prefabricated tendons and tendons fabricated on site, should be protected from harmful influences during transport and storage and also while placed in the structure prior to permanent protection. Materials that have corroded significantly, and cannot be adequately cleaned, should not be used and should be replaced by suitable materials. Depending on the environment and the duration of storage, temporary protection may need to be applied to the materials, see section 2.1.5a).

Prestressing steel should be segregated from zones where welding operations are performed.

Cement and admixtures for grout should be used before their expiry date and be protected from water and moisture during transport and storage on site.

#### 2.2.2 Installation equipment

Reliable installation of post-tensioning systems on site requires the use of suitable specialised equipment adapted to the particular post-tensioning system and operated by experienced and well-trained personnel. There are three main types of equipment used in post-tensioning work, i.e. for installation of the prestressing steel, for stressing of the tendon and for filling of the duct. This equipment is described mainly for tendons installed on site. Tendons prefabricated at a workshop and
installed as a complete unit on site may require additional equipment and modified installation procedures to avoid damage to the tendons during handling.

Equipment for installation of the prestressing steel by threading must provide firm gripping of the steel without damaging it. This aspect is particularly important for coated and sheathed prestressing steel. Typically, the prestressing steel is gripped by wheels and pushed by the machine into the duct. A typical pusher for strand is shown in Fig. 2.18. Alternatively, the prestressing steel may be pre-assembled into a bundle and pulled into the duct with a rope. Connection of the rope to the bundle can either be provided with mechanical connectors or by welding. Any length of prestressing steel likely affected by welding should be cut-off after installation.

![Image](image1.jpg) **Fig. 2.18** Strand coil with pusher for threading of strand  
![Image](image2.jpg) **Fig. 2.19**: Multistrand stressing jack

Stressing equipment for post-tensioning tendons consists of stressing jacks and accessories to temporarily hold and then release the prestressing steel during stressing. Stressing equipment must ensure reliable stressing of the prestressing steel to the specified load, and reliable transfer of the load from the jack to the permanent tendon anchorage. Stressing jack and accessories must be fully compatible with the specific post-tensioning anchorage to ensure such things as complete release of the wedges during stressing to avoid excessive friction in the anchorage or scratching of the prestressing steel, and reliable seating of the wedges at transfer of the tendon load to the anchorage to assure the expected anchorage performance. Stressing equipment must also permit multiple stressing stages to accommodate the elongation of long tendons. In addition, it must allow detensioning of a tendon, if a problem occurs during stressing. Stressing jack and accessories such as the gripping devices must permit simultaneous stressing of the entire tendon, and assure equal forces and elongations in all tendon elements even for multiple stage stressing. Stressing equipment should be regularly calibrated by a qualified body. Many specifications require that the calibration of the stressing equipment is not older than 6 months. Above all, stressing equipment must allow safe operation on site, every time a tendon is stressed. An unintended sudden release of the energy stored in a post-tensioning tendon stressed to 70-80% of its strength could be disastrous. A typical stressing jack for multistrand tendons is shown in Fig. 2.19.

For all the above reasons, post-tensioning systems typically are installed with specific proprietary equipment. It is important that the equipment is included in the independent assessment by a qualified body during the post-tensioning system approval. For its potential effect on the performance of the tendon anchorage, the FIP recommendation, [18], and the guideline for the European technical approval of post-tensioning systems ETAG 013, [2], require that the tendon in the static tensile test discussed in section 2.1.2d) be loaded to 80% of the specified tendon strength with the stressing equipment. Only at this 80% level, the load is transferred to the testing rig for further loading up to ultimate.

### 2.2.3 Installation of tendons

The post-tensioning tendons should be assembled in accordance with the general instructions by the system supplier, the specific method statements prepared for the site by the specialist company, the relevant shop drawings, and the provisions valid at the construction site.
The type, class and traceability references of the prestressing steel should be recorded for each tendon. Other post-tensioning system components should be traceable as specified for the project. Any damaged post-tensioning component which cannot be adequately repaired should be replaced. Welding of prestressing steel and anchor heads is not permitted. Oxygen cutting or welding in the vicinity of prestressing steel is not permitted unless special provisions have been implemented to protect the steel.

Ducts and their joints should be sealed against the ingress of water during installation and against ingress of laitance during pouring of concrete.

Post-tensioning tendons and components should be placed and secured in a manner that maintains their location within permissible tolerances. Installation tolerances may be found in PTI, ACI, EN and ISO documents, [16, 37]. The fixing should also avoid floating of the duct during pouring of concrete. Duct supports should be designed and spaced such as to avoid damage to the ducts and to limit the wobble effect. Spacing of duct supports should be designed for the type of duct used. Round steel bars are suitable for corrugated steel and plastic ducts. However, additional measures to avoid deformations such as indentations of the duct are necessary for plastic ducts at tight tendon curvatures such as at tendon high points. At such locations, placing of half-shells between plastic duct and tendon support is necessary to protect the duct, see Fig. 2.20. The tendon axis should be coincident and parallel with the axis of the anchorage and couplers, in their vicinity. The tendon profile should be checked to avoid any kinks. Such kinks in metal ducts may cause breakage of the prestressing steel wire during stressing. Kinks in plastic ducts may cause leakage at duct couplers and wear-through of the duct.

The specialist company should have a documented procedure for the installation and checking of the duct system which comprises: Ducts, duct connectors, grouting connections, vents, vent connections, drains if any (e.g. in climates with risk of water freezing), transitions to anchorages and anchorage caps. If the duct installation is not done by the specialist company itself it should apply an acceptance procedure of the ducts before the concrete is poured.

Vents on the ducts should be provided at both tendon ends and at the points of the tendon where air or water may accumulate. Vents should be properly marked to identify the cable, and their location along the cable. During the construction, tendons should be adequately sealed against penetration of moisture.

After installation of the anchorages and ducts and before concreting, the tendons may be subjected to an air pressure testing to confirm the leak tightness for tendons with PL2 and PL3, [7, 9].

![Image](image-url)

**Fig. 2.20:** Plastic duct support with metal half-shells at tight tendon curvature to protect the duct from local deformations by the support bar

### 2.2.4 Stressing of tendons

Written instructions for the stressing should be available on site. Stressing should comply with a prearranged and approved stressing programme including at least:

- the identification of the construction stages when tendon stressing is needed;
- inside each stage, the order in which successive tendons have to be stressed and, if necessary, the requirements for friction tests and partial stressing of a tendon;
- for every tendon, the initial stressing force and the corresponding elongation;
- the tolerances on initial stressing forces and corresponding elongations according to the national regulations or the project specifications.

Stressing jacks should be compatible with the post-tensioning system. Valid calibration records for the force measuring devices should be available on site before the stressing starts.

Application and/or transfer of prestressing to a structure should be done progressively and is only allowed when the concrete strength is equal to or greater than the minimum compressive strength specified for the post-tensioning system.

The stressing results should be recorded for every tendon, including at least the force and elongation at each stage of stressing and their conformity or non-conformity with the requirements.

In the case of deviation from the specified performance during stressing, the cutting of the tendon ends or grouting should not proceed. Works which can impair the re-stressing should not be carried out. All these works should be postponed until corrective actions have been taken and the revised stressing report has been approved by the Engineer.

2.2.5 Injection / Filling of tendons

A proper filling material mix, well-functioning injection equipment and suitable injection procedures are a prerequisite for durable corrosion protection of the prestressing steel and sufficient bond between the tendon and the structure. The filling operation should only be carried out by qualified and well trained personnel, directed by an experienced specialist. Injection work should be under the responsibility of the prestressing system supplier or grouting personnel with certified experience and training.

a) Grouting equipment

The mixer and related components should have sufficient power to sufficiently shear the entire mass of grout, without depositing cement in the bottom of the tank and to obtain a colloidal mixture. Some mixers are fitted with recycling systems. The grout is pumped across the turbine and discharged under pressure in the top part of the tank. Water and cement need to be dosed within tight tolerances to ensure the correct grout mix. The mixing time used in the grout approval needs to be adhered to and assured on site.

An agitator and related components should be provided for the storage of quantities of grout which permit continuous filling of the tendon to be injected. Slow movement of the grout in the agitator is advised without creating air bubbles. The grout should be conveyed from the mixer to the agitator through a sieve to hold back any lumps.

The pump should be designed to inject grout with continuous flow. The equipment should be designed for injection at variable rates, so as to be able to satisfy working conditions in the best possible manner (injection rate modulated according to the type of duct and tendon, slow final pressure increase, etc.). The pump rate selected depends on the selected injection speed.

Grouting hoses should be designed to resist the service pressure with adequate safety margin. When the grouting pump is located away from the tendon inlet, it may be necessary to install a pressure measurement instrument at the line end.

Fig. 2.21 shows a group mixer/pump for typical post-tensioning work, and a grout plant for large scale projects requiring large grout volumes, respectively.
b) Injecting grout

Before grouting can start, the installation and position of vents and drains, if any, should be checked. The temporary or permanent grout caps can be installed, and the duct system can be checked for free passage of grout by blowing compressed air through the duct. Alternatively to, or in addition to, the air pressure test mentioned in section 2.2.3, the duct system can be tested for leak tightness at this time with air pressure. However, due to the presence of the concrete around the duct system, the test done at this time is less severe than the one performed in section 2.2.3.

Grouting of a tendon should always follow the method statement set up for the specific tendon. Typical procedures imply grouting from one tendon end until grout is flowing out of the first vent with a consistency similar to the one previously measured at the pump. The vent is then closed and grouting continued, progressively repeating this for all subsequent vents to the end of the tendon. When grout of correct consistency is flowing out of the last vent, the vent is closed and the pressure maintained for about one minute, and then the inlet is closed. When vents are used slightly downstream from crest vents, the downstream vents should be closed before their associated crest vent.

Special considerations and method statements should be prepared for couplers, vertical tendons, horizontal and external tendons when special precautions have to be observed.

The tests which are to be carried out prior to the grouting operation (suitability tests) and during grouting operation (acceptance tests) have been described above.

Vacuum assisted grouting may be used for specific cases such as external tendons without vents at the high points, long horizontal tendons, or repair grouting. The partial vacuum is applied first. After checking that the vacuum can be maintained the grout is injected into the duct until it is completely filled. Fig. 2.22 shows a typical vacuum grouting equipment set-up.

Vertical ducts can be required in bridges, for example as tie-down tendons of unbalanced cantilevers and for deep webs in box girders and piers. They may also be used in reservoirs, off-shore structures and nuclear containments. Vertical grouting presents somewhat different problems and special measures are required. Water is separated from the grout by capillary action and is filtered through the voids between the wires of the strands. This effect is amplified because of the differential pressure between bottom and top of the duct. This may induce water and air pockets in the ducts beneath the top tendon anchorage and therefore, special procedures should be employed to avoid these pockets.

It has been documented that slight vibrations of structures during the early setting of high quality grout do not have a detrimental effect on the grout properties, in general, [38].
Grouting should not be carried out at temperatures below 3 °C because of the risk of freezing of the water. It should only be commenced when the temperature is confirmed to stay above 3 °C for at least 48 hours.

c) Injecting soft filling materials

Injection of soft filling materials follows similar procedures as for grout. However, special care has to be taken to assure leak tight connections in the duct system particularly for wax which is injected at temperatures of 80-100 °C. Particular safety procedures may have to be implemented in view of the high temperatures. Fig. 2.23 shows tendons pre-injected with soft filling material.

2.2.6 Inspection of tendons

a) Prior to concreting

Before casting operations start, inspections should include:
- the position of the tendons, ducts, vents, drains if any, anchorages and couplers in respect of the project specification, including the concrete cover and the spacing of the tendons;
- checking the tendon alignment for any local kinks in the ducts;
- the fixture of the tendons and ducts, including the provision of adequate resistance against buoyancy and the stability of their supports;
- the ducts, vents, anchorages, couplers and their sealing to ensure that they are undamaged;
- the tendons, anchorages and/or couplers to ensure that they are not corroded;
- the cleanliness of the ducts, anchorages and couplers;
- the leak tightness between anchorages and ducts, couplers and ducts.
For tendons encapsulated in plastic ducts the following additional procedures should be applied:
- verification that duct supports have not caused indentations into the plastic ducts which will cause a hard spot in the tendon during stressing;
- leak tightness testing with air pressure test or verification for defects by light during the night or by smoke aerosol (dry ice);
- visual inspection of the sheathing of greased and sheathed strands and repair of any damage.

b) Prior to stressing

Before stressing operations start, the following should be confirmed:
- the availability on site of the documents and equipment to suit the tensioning programme;
- that the actual concrete strength meets/exceeds the strength required;
- the certificate of the calibration of the jacks is available and current;
- the prestressing force and the expected elongation for each tendon is known;
- safety precautions have been implemented;
- the condition of the tendons with exposed strands at the anchorages is acceptable (no unacceptable rust, etc).

c) Prior to grouting

Grouting is the most important operation to assure the durability of the tendons. The following should be checked before the grouting operation starts:
- necessary equipment, such as air compressor, grouting mixer and pump, is adequately positioned;
- the temperature. If it is lower than 3°C, grouting should not commence;
- that the ducts have been blown through with air to confirm that the tendon and vents are not blocked (do not flush with water);
- grout hoses at vents, and repaired if damaged;
- injection hoses to ensure that they are fixed firmly;
- the quality of grout. This must be tested to confirm the suitability of the mix and the intended grouting equipment.

d) After grouting

Any grouting should conclude with a careful checking of the duct filling at critical locations such as high points and anchorages. This should be done shortly after grouting to ensure that the grout is still sufficiently fluid for pumping. All accessible areas of tendons, connections such as vents and drains, caps, exposed duct, etc. should be checked for complete filling by light tapping against them shortly after grouting (a hollow sound indicates a void). Accessible parts such as caps and external tendon pipe may be provided in transparent plastics to permit visual inspection.

If voids are detected at this stage, grout can be pumped again as needed.

All vents should be opened the day after grouting to check the level of grout, and any voids should be filled with fresh grout. Special ports have been introduced recently into the anchorage designs which permit inspection of the filling of the anchorage just behind the anchor head, see Fig. 2.24.

If these procedures are systematically applied, voids in ducts can be completely avoided at these critical locations. Results of this check, including a list of locations checked, should be recorded.
2.3 Certification of suppliers and installers

Durable post-tensioning tendons are only achieved if the post-tensioning systems are installed on site in accordance with proven procedures for assembly of the components, installation and stressing of the prestressing steel, and grouting. Installation must be carried out by experienced and well qualified personnel intimately familiar with the particular post-tensioning system and the corresponding equipment. The personnel must be knowledgeable of the potential consequences of poor installation on safety and durability, and must be able to react correctly if problems are detected. Only suitable equipment adapted to the particular post-tensioning system, and operated by experienced and qualified personnel should be used.

The above basic principles are best assured if the installation of the post-tensioning system is done by a specialist contractor who has either developed the system, or has been adequately trained by the system developer. The personnel on site in charge of post-tensioning works should be specifically trained as “post-tensioning craftsman” for the specific system. This concept was recognised many years ago in France, and has led to the creation of a new profession, the “Chargé de Mise en Précontrainte (CMP)”.

In addition, national approvals for post-tensioning systems in France include the notion of qualification of the specialist contractor and its personnel (CMFs), and includes the verification of this aspect in the regular audits performed by the certification body.

These principles were applied in the early days of post-tensioned concrete because the company that developed a post-tensioning system normally installed it also. However, over time this has changed for a number of reasons. Post-tensioning was probably considered by some to be a commodity which can be done by everybody. In the authors’ opinion today’s durability problems are at least partly a consequence of this “commodity / do-it-yourself approach”.

The UK has recognised the importance of qualification of companies and personnel during the period of the temporary ban of post-tensioning, and has subsequently introduced a certification procedure for post-tensioning companies, see TR47 report, [7]. The Post-Tensioning Institute (PTI) has introduced a certification procedure for field personnel for unbonded monostrand post-tensioning. Also FIP published a recommendation on the qualification and approval of prestressing contractors and system suppliers, [39]. The American Segmental Bridge Institute (ASBI) has introduced a special certification program for grouting which applies to all grouting supervisors and inspection personnel.

In 2003, a European guideline was published through a CEN workshop agreement on the “Requirements for the installation of post-tensioning systems for prestressing of structures and qualification of the specialist company and its personnel”, [36]. This document provides recommendations for the qualification of post-tensioning specialist companies, and for the experience, knowledge, training and qualification of the personnel. This document also recommends that post-tensioning specialist companies be certified by an independent qualified body.
3 Maintenance, assessment and rehabilitation

3.1 Introduction

This chapter deals with maintenance, assessment and rehabilitation of prestressed concrete structures focusing primarily on the post-tensioning tendons as important structural elements. It is furthermore assumed that both structures and post-tensioning tendons have been designed and executed according to the recommendations provided in the previous chapters. With regard to the general framework of activities required for the service life of a concrete structure it is referred to the fib Technical Report / Bulletin 17 "Management, maintenance and strengthening of concrete structures" (April 2002), [40]. In particular, the following definitions given in [40] are used:

Assessment: A process of gathering and evaluating information about the form and current condition of a structure or its components, its service environment and general circumstances, whereby its adequacy for future service may be established against specified performance requirements, loadings, durability or other criteria.

Damage: Physical disruption or change in the condition of a structure or its components, brought about by external actions and influences, such that some aspect of either the current or future functionality of the structure or its components will be impaired.

Deficiency: Lack of something, possibly arising as a result of an error in design, specification or construction, which affects the ability of the structure to perform some aspect of its intended function, either now or in the future. Often concerned with specific issues, such as strength or ductility, but may be more general in nature and concern matters such as durability.

Degradation: A worsening of condition with time.

Deterioration: A worsening of condition with time, or a progressive reduction in the ability of a structure or its components to perform some aspect of their intended function.

Ingress: The entry of substances into structural and/or non-structural components of the fabric of a building or structure. Often the term 'ingress' is associated with the entry of substances which cause deterioration (e.g. chlorides into reinforced or prestressed concrete, sulphates and carbon-dioxide (CO₂) into concretes, etc.).

Inspection: A primarily visual examination, often at close range, of a structure or its components with the objective of gathering information about their form, current condition, service environment and general circumstances.

Investigation: The process of inquiry into the cause or mechanism associated with some form of deterioration or degradation of the structure and the evaluation of its significance in terms of their current and future functionality. The term may also be employed during the assessment of defects and deficiencies. The process of inquiry might employ sampling, testing and various other means of gathering information about the structure, as well as theoretical studies to evaluate the importance of the findings in terms of the functional integrity of the structure.

Maintenance: A (usually) periodic activity intended to either prevent or correct the effects of minor deterioration, degradation or mechanical wear of the structure or its components in order to keep their future functionality at the level anticipated by the designer.
Monitoring: To keep watch over, recording progress and changes with time; possibly also controlling the functioning or working of an entity or process. Structural monitoring typically involves gathering information by a range of possible techniques and procedures to aid the management of an individual structure or class of structures. It is often taken to involve the automatic recording of performance data for the structure and possibly also some degree of associated data processing. Strictly this does need to be so, there being a variety of means of gathering appropriate data.

Reconstruction: To reinstate all or part of the functionality of a structure or component which is in a changed, defective or deteriorated state to its original or higher level of functionality without restriction upon the methods or materials employed. Generally concerned with meeting specific objectives such as strength or future durability requirements.

Rehabilitation: Similar to reconstruction, but possibly with greater emphasis upon the serviceability requirements associated with the existing or proposed revised usage of the structure.

Repair: Generally action taken to reinstate to an acceptable level the current functionality of a structure or its components which are either defective, deteriorated, degraded or damaged in some way and without restriction upon the materials or methods employed. The action may not be intended to bring the structure or its components so treated back to its original level of functionality or durability. The work may sometimes be intended simply to reduce the rate of deterioration or degradation, without significantly enhancing the current level of functionality.

Experience with the assessment of an existing structure has shown that it would be extremely valuable to know the condition of the structure as–built. It has been recommended to establish at commissioning a birth certificate (in [40] called “reference condition”) providing also the structural key data with regard to durability [41]. Such data would include the verified thickness of the concrete cover and its quality (e.g. permeability measured by adequate testing method such as Torrent [42]). Also important would be specific information on other protection measures such as waterproofing membranes and surface protection systems.

It is also recommended that the following are established during the design and construction phase: a maintenance plan and a surveillance plan.

These plans shall contain the required measures for maintenance and surveillance during the life of a prestressed concrete structure and, in the context of this report, of its post-tensioning tendons.

3.2 Maintenance

As mentioned in section 3.1 it is assumed that both structure and tendons have been designed and executed as specified. For those cases where this objective was not achieved, reference should be made to the Appendix.

For internal tendons of categories PL1 and PL2 (either bonded or unbonded) the maintenance plan would not contain any specific measures. Exceptionally tendon anchorages of internal tendons are exposed. The corrosion protection of these anchorages (caps, anchor plates) would periodically need maintenance measures (e.g. renewal of the corrosion protection) as given in the maintenance plan and substantiated by inspection.

For tendons of category PL3 the measures additionally include the maintenance of the monitoring system consisting of the measuring cables, measuring box (Fig. 3.1) and measuring instruments (Fig. 3.2).
For external tendons the accessible areas can be visually inspected and, if required, maintenance measures can be performed such as correcting the effects of minor deterioration of the protective plastic or steel pipes.

Besides the maintenance measures for the post-tensioning tendons themselves, it is also necessary to maintain the effectiveness of the other protection layers such as the concrete cover, any surface protection systems (e.g. waterproofing membranes), and filling of the anchorage recesses.

### 3.3 Assessment

#### 3.3.1 General

In [40] the methodology and procedures for assessing concrete structures is explained. Assessment activities need good planning and include routine inspections (standard, initial, regular), detailed investigations, deterioration assessment and if necessary structural assessment. Whereas these principles are generally respected in public areas such as in the management of bridges, this is often not the case in the private sector for the management of buildings and industrial structures.

Regular routine inspections of structures form the main basis – technically and economically – for planning the necessary maintenance and repair activities for a specific structure in order to meet the functional and safety requirements in the most cost-optimal way. Besides that, regular routine inspections give the owner a tool to record the condition of the structure.

The basis of the routine inspections is a systematic – mainly visual – evaluation of the condition of each element of the structure. The first principal inspection is carried out just after the completion of the construction works, and may be defined as the Reference Condition of the structure. The next inspections are carried out in intervals of 3-6 years dependent on the condition of the structure. For elements placed in very severe environment or exposed to high load levels or in increasingly poor condition, inspections may be carried out more frequently.

The routine inspection includes:
- condition evaluation of all elements of the structure and of the structure as a whole;
- assessment of type and extent of the main damage seen;
- evaluation of the quality of the maintenance;
- evaluation of the need for remedial or repair works: type of repair, price estimate, optimal time of execution;
- necessity for detailed investigations. If costly remedial works are expected to be carried out, a
detailed investigation is normally recommended;
- time for next inspection.

In general, detailed investigations are only warranted when costly remedial work is necessary such as
the replacement of a bridge pavement, the waterproofing membrane and other structural elements with a
service life shorter than the load-bearing structure, e.g. every 20 to 25 years. With regard to
deterioration problems, reference is made to section 1.2.3 and in particular to Fig. 1.1.

3.3.2 Tendons of category PL1 and PL2

For internal tendons of category PL1 and PL2, either bonded or unbonded, constructed according to up-
to-date specifications only minor assessment activities are necessary. Those are generally limited to the
rare cases where anchorages are exposed.

For external tendons the protection pipes in accessible areas can be assessed by visual inspection.

3.3.3 Tendons of category PL3

a) General

In the following a solution is presented in detail complying with the requirements of PL3 and having
shown a good track record in practical application for over 10 years. Other solutions may exist, but are
not known to the authors, or may be developed in the future.

The electrical isolation of tendons allows checking of the quality of the tendon installation, the
monitoring of the leak-tightness of the encapsulation and finally assures the protection of the
prestressing steel against actions of stray currents should this be required [35]. The prestressing steel is
protected by a chemically stable, sufficiently diffusion, respectively leak-tight and electrically isolated
envelope. Its leak-tightness can be measured by means of the impedance measurement (electrical
resistance measurement with alternating current; for simplification, this test will be referred to in the
following as electrical resistance measurement).

The monitoring of the leak-tightness of the protective envelope in category PL3 should be performed
during the execution and periodically during the entire service life of the structure.

The extent and sequence over time of the electrical resistance measurements should be specified:
- in the control plan for the execution phase
- in the surveillance plan for the service life.

The electrical resistance measurement of the tendon category PL3 requires careful preparation during the
planning phase. Each tendon to be tested needs an electrical connection. Also the reinforcing steel
has to be electrically connected.

The electrical connections and measuring cables need to be electrically and mechanically safe and
durable. The measuring cables should be brought together in one or several measuring boxes.

The requirement for comprehensive corrosion protection, i.e. electrical isolation of the prestressing steel
from the reinforcement and leak-tightness of the protective envelope, is satisfied if the stressed and
grouted tendon complies with the specified limit of the specific resistance $\rho$ according to Table 3.2.

Since the requirements on the leak-tightness of the protective envelope with the electrical resistance test
are severe, it is recommended to include in the tender documents a specified acceptable failure rate. This
failure rate should not exceed 10% of the tendons. In cases of less than 10 tendons only one tendon may
not satisfy the requirements. The cause of failures should be investigated if these rates are exceeded, the
location of defects detected, the consequences evaluated and if necessary, corrective measures be
implemented (e.g. more intensive surveillance or, if considered critical, repair).
b) Measuring instruments and readings

The measuring instruments should satisfy the following requirements:

- **Measuring frequency:** 1 kHz alternating voltage
- **Measuring amplitude:** minimum 0.5 V alternating voltage
- **Measuring range:** digital display for
  - ohmic resistance R: \( 0.1 \, \Omega \) - \( 10 \, M\Omega \)
  - (resolution in the lower range: \( 0.1 \, \Omega \))
  - capacitance C: \( 0.1 \, nF \) - \( 100 \, \mu F \)
  - loss factor D: \( 0.001 \) - \( 10 \).
- **Measuring instrument:** The measuring instruments should measure the ohmic and capacitive part of the electrical impedance (AC resistance); commercially available LCR instruments are e.g. ESCORT ELC-131.

During the measurements the following results are obtained and displayed:

- **Resistance R:**
  This is the ohmic resistance against the flow of current. The ohmic resistance decreases with the length of the tendon.

- **Capacitance C:**
  The capacitance C is proportional to the length of the tendon and is characteristic for the specific type of duct used.

- **Loss factor D:**
  The loss factor D is the ratio of R and C; it is independent of the tendon length.

For a given tendon length \( L \), the following specific values can be calculated from these results:

- specific resistance \( \rho \, (R \cdot L) \), unit in \( \Omega m \);
- specific capacitance \( C_s \, (C/L) \), unit \( F/m \);
- loss factor D (dimension-less, as above).

c) Time of measurements

The designer specifies the necessary measurements in the control plan (execution phase) and in the surveillance plan (utilisation phase). Table 3.1 summarises the time of measurements, the interpretation of the results and possible measures to be taken.
<table>
<thead>
<tr>
<th>Execution and utilisation phase</th>
<th>Requirements and interpretation of the results</th>
<th>Measures</th>
</tr>
</thead>
<tbody>
<tr>
<td>After stressing</td>
<td>Short circuits (i.e. values of the ohmic resistance $R &lt; 10\Omega$) at an anchorage or due to defect in the duct at tendon supports can be detected. Capacitance $C$ and loss factor $D$ are not relevant as the grout is not yet present.</td>
<td>Locate and repair the defect(s). In consideration of the acceptable failure rate of 10%, the post-tensioning company proposes measures and submits them for approval of the site engineer.</td>
</tr>
<tr>
<td>Measurement recommended</td>
<td></td>
<td></td>
</tr>
<tr>
<td>After grouting</td>
<td>Mandatory measurement approximately 28 days after grouting in presence of site engineer. The limiting values that shall be respected are summarised in Table 3.2.</td>
<td>If the acceptable failure rate of 10% is exceeded, the causes have to be determined and the consequences assessed. If necessary, measures have to be taken (e.g. more intense surveillance).</td>
</tr>
<tr>
<td>Measurement mandatory</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Further measurements at the time of acceptance and afterwards during the service life of the structure according to the surveillance plan.</td>
<td>In general, the values of the ohmic resistance $R$ increase, the capacitance $C$ remains constant and loss factor $D$ decreases (hydration and drying of concrete and grout). A reduction of more than 30% of the resistance $R$ of a tendon indicates the ingress of humidity at a defect in the duct.</td>
<td>Significant changes have to be assessed by an expert. Leaks and water ingress have to be located and repaired. Shorter measurement intervals may be required.</td>
</tr>
<tr>
<td>Measurement mandatory</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3.1: Time of measurements, requirements and interpretation of the results and possible measures

**d) Limiting values**

Reproducible and meaningful values that can be interpreted with respect to the electrical isolation and the leak-tightness of the plastic duct can only be obtained if the measuring circuit between the prestressing steel and the ordinary reinforcement is closed electrically by the measuring cables and electrolytically by the grout and concrete.

**Before grouting:**
Before grouting, e.g. after the stressing of the tendons, very high values of the ohmic resistance $R$ are measured for intact ducts; low values $R < 10 \Omega$ indicate an electrical short circuit at a defect of the duct. In this case, the values of the capacitance $C$ and the loss factor $D$ are meaningless.

**After grouting:**
After grouting of the ducts, when performing the mandatory measurement, meaningful results can be obtained. The values of the ohmic resistance $R$ and the capacitance $C$ however, depend on the length of the tendon and on the type of duct. Therefore, specific limiting values are defined. From laboratory and field measurements for a particular duct type with properly executed vents and duct connections, the following limiting and control values have been obtained [43]:

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<table>
<thead>
<tr>
<th>Type of duct</th>
<th>Limiting values</th>
<th>Control values</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>specific resistance $\rho^*$</td>
<td>specific capacitance $C_s^{**}$</td>
</tr>
<tr>
<td>$\varnothing$ 59 mm</td>
<td>$&gt; 500 , \text{k}\Omega$</td>
<td>$&lt; 2.35 , \text{nF/m}$</td>
</tr>
<tr>
<td>$\varnothing$ 76 mm</td>
<td>$&gt; 400 , \text{k}\Omega$</td>
<td>$&lt; 3.05 , \text{nF/m}$</td>
</tr>
<tr>
<td>$\varnothing$ 100 mm</td>
<td>$&gt; 300 , \text{k}\Omega$</td>
<td>$&lt; 3.35 , \text{nF/m}$</td>
</tr>
<tr>
<td>$\varnothing$ 130 mm</td>
<td>$&gt; 250 , \text{k}\Omega$</td>
<td>$&lt; 4.30 , \text{nF/m}$</td>
</tr>
</tbody>
</table>

**Table 3.2:** Specific limiting and control values for electrically isolated tendons with a particular duct type \(^1\) in concrete measured approximately 28 days after grouting \(^2\) (measurements at a frequency of 1 kHz).

* The experimentally measured values of the ohmic resistance $R$ have to be multiplied by the length of the tendon, $L$, before comparing with the limiting values in Table 3.2. E.g. for tendons with a duct of $\varnothing$ 59 mm and 100 m length a value of $R > 5k\Omega$ has to be measured in order to satisfy the limiting value.

** The experimentally measured values of the capacitance $C$ have to be divided by the length of the tendon, $L$, before comparing with the control values in Table 3.2. For tendons with a duct of $\varnothing$ 59 mm and 100 m length experimental values of $C = 235 \pm 4 \, \text{nF}$ should be measured. Lower capacitance values are obtained for higher wall thickness of the ducts and are thus no problem. The capacitance values are not sensitive to the presence of small defects in the duct.

*** The loss factor $D$ is the only measured value being independent of the tendon length. This value allows a quick control and assessment of the overall condition of the tendon. It is, however, not to be considered as limiting value.

\(^1\) The particular duct type for which the given values are valid is known as duct PT-PLUS. To the knowledge of the author it is the only type for which these values have been experimentally determined. At the same time, this duct fulfils the requirements of the fib Technical Report – Bulletin 7 “Corrugated plastic ducts for internal bonded post-tensioning”, January 2000.

\(^2\) The Guideline [35] is currently under revision. The revised document should be available in late 2006. Based on recent field experience and laboratory tests, the values in Table 3.2 are verified and may be changed.

e) Interpretation of the measurements

The following factors influence the measured values of $R$, $C$ and $D$ systematically:

- **Tendon length and duct diameter:**
  The resistance $R$ decreases proportionally to the tendon length; the capacitance $C$ increases proportionally to the length and depends on the diameter and the wall thickness of the duct. The loss factor $D$ is independent of the tendon length however, it changes with the diameter of the duct.

- **Type of duct system:**
  Mechanical duct couplers or welded duct connections lead to a slightly higher capacitance $C$ compared to ducts of the same length but without couplers and connections. The loss factor $D$ is also slightly higher.

- **Specific electrical resistance of concrete and grout:**
  The specific electrical resistance of the concrete and grout depends on temperature, humidity and degree of cement hydration. The specific resistance increases with increasing degree of hydration (increasing age), with decreasing humidity and temperature.
The experimentally measured electrical resistance $R$ corresponds to the resistance in a parallel circuit with all the individual components which represent "defects" (couplers, grout vents, etc.) and actual defects in the duct. The detection of actual defects in the duct is more easily possible in tendons containing less components with reduced resistance (couplers, grout vents etc.).

- Number and detailing of grout inlets and air vents:
  After injection, the grout inlets and air vents are filled with grout, i.e. they can create an electrolytical connection to the surrounding concrete and thus to the ordinary reinforcement. It is essential to seal all the grout inlets and air vents with a leak-tight plastic cap (Fig. 3.3). Without the caps every grout vent acts like a defect in the duct and as a result lower values of the ohmic resistance $R$ and higher loss factors $D$ are measured.

- Number and size of duct defects:
  This is the objective of the surveillance measurements.

If a short circuit (electrical contact) between prestressing steel and the ordinary reinforcement exists ($R < 10 \, \Omega$), the measured values of $C$ and $D$ are meaningless and no further information can be deduced.

---

**Fig. 3.3:** *Durable sealing of all grout inlets and vent pipes (valid for all tendon categories)*

The interpretation of the resistance values and the assessment with respect to the presence of defects is significantly more difficult in the case of electrically isolated tendons as compared to electrically isolated soil and rock anchors. This fact is due to the variation of the tendon geometry and the changes in humidity and temperature of the concrete. The aim is to achieve specific resistance values $\rho$ as high as possible and loss factors $D$ as low as possible.

The measured values can be interpreted as follows:

- Measured values $R < 10 \, \Omega$:
  Such results correspond – irrespective of the length of the tendon – to short circuits between prestressing steel and ordinary reinforcement. Possible causes for a short circuit are:
  - worn and damaged plastic duct after the stressing of the tendon and direct contact between prestressing steel and ordinary reinforcement;
  - isolation of the anchorage defective.
  It is not possible to obtain further information as the values for $C$ and $D$ are meaningless. The location of the short circuit can be determined with special procedures even after concreting, and if needed the short circuit can be eliminated.
- Measured values $\rho < 100 \, \text{k}\Omega$:
  Such values of the specific electrical resistance correspond to an insufficient electrical isolation of the tendon and insufficient leak-tightness of the duct. Major defects or damages are present in the duct.

- Measured values $\rho > 100 \, \text{k}\Omega$ up to the limiting value of the corresponding duct type in Table 3.2:
  Such values correspond to a barely sufficient electrical isolation and leak-tightness of the duct. Possibly, small defects are present in the duct or concrete and the grout is still very humid.

- Measured values $\rho >$ than the limiting value of the corresponding duct type according to Table 3.2:
  Such values of the specific electrical resistance exceeding the limiting value correspond to a high electrical isolation of the grouted tendons with only system-related, small defects which are insignificant for the corrosion protection of the tendon.

- Measured values $\rho > 1000 \, \text{k}\Omega$:
  These values correspond to a complete electrical isolation of the tendons and extremely leak-tight grouting vents and duct connections. There are no defects present.

At least as important as the absolute measured values is a comparison with other tendons of the same type and length present in the structure and comparison with previously obtained results:

- such comparisons allow identifying whether only a particular tendon exhibits insufficient electrical isolation or whether a systematic problem has occurred;
- a comparison with earlier measurements on the same tendon allows the detection of the ingress of water at defects of the duct (the resistance is significantly decreasing).

f) Assessment

As long as the required minimum value of the specific resistance $\rho$ given in Table 3.2 is satisfied, the tendon is comprehensively protected against corrosion. Even at values of $\rho$ around 100 k$\Omega$, indicating that small defects are present in the duct, the corrosion protection of the prestressing steel in the plastic duct is significantly better than of a tendon in a metallic duct of category PL1.

The possible risk for tendons with very low specific resistance ($\rho << 100 \, \text{k}\Omega$) or with a short circuit ($R < 10 \, \Omega$) can be assessed as follows for the two hazard scenarios mentioned below (considering the acceptable failure rate, this concerns only a small number of tendons):

- Chloride penetration:
  Even at a defect in the plastic duct, the prestressing steel is protected by the alkaline environment of the grout and the surrounding concrete. Hence, it remains passive and protected against corrosion. A macro corrosion cell cannot be formed.

  When chlorides are penetrating through the concrete and reach the area of the duct defect, this can be detected early by a decrease in the electrical resistance (before corrosion starts). The defect can be located with additional measurements and actions against the further ingress of chlorides can be taken (e.g. by repairing the waterproofing membrane).

- Stray currents:
  When stray currents are acting on a structure, a defect in the duct can act both as point of stray current ingress or exit (depending on the direction of the flow of current). At the stray current exit, anodic corrosion attack (metal dissolution) will occur. At the ingress, cathodic reaction can lead to the formation of hydrogen. If only small defects are present, the risk of metal dissolution and of hydrogen formation is very low because locally only small current densities occur due to the high ohmic resistance to the stray current flow. With large defects, it may become necessary to electrically connect the post-tensioning tendon to the rectifier.
3.4 Rehabilitation

Despite the improvements achieved with the multilayer protection concept including the new generation of tendons, rehabilitation and repair measures may still become necessary. The appropriate methodology and other relevant information are provided in the Appendix of this report.

References

[17] XP A 35-037-2 “Steel products – Protected sheathed high strength steel strands – Requirements for sliding protected and sheathed strands (type P)”, Association Francaise de la Normalisation (AFNOR)
[36] “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 Standardisation (CEN), Brussels, 2003


Appendix  Maintenance, assessment and rehabilitation of post-tensioning tendons in existing structures

A1  Introduction

In chapter 3 of the report the maintenance, assessment and rehabilitation of new prestressed concrete structures with post-tensioning tendons according to the requirements of Protection levels PL1, PL2 and PL3 is discussed. In the Appendix the same topics are presented for existing structures with traditional post-tensioning tendons.

At the IABSE / fib Workshop on "Durability of post-tensioning tendons" at Ghent (Belgium) in November 2001 the relevant corrosion problems of post-tensioning tendons in various structural applications were openly presented and discussed [A1].

A2  Maintenance

The maintenance of internal, either bonded or unbonded tendons in existing prestressed concrete structures is generally limited to ensure that the structural protection layers such as the concrete cover (including recess concrete) and surface protection systems can fulfill their function. In cases where tendon anchorages for internal tendons are exposed, planned maintenance measures, substantiated by inspection, have to be carried out. An example is the renewing of the corrosion protection to anchorage caps.

The latter also applies to external tendons with exposed anchorages. Additionally, the accessible areas of such tendons can be inspected and, if needed, maintenance measures can be performed such as correcting the effects of minor deterioration of the protective plastic or steel pipes.

A3  Assessment

A3.1  General

Post-tensioning tendons are structural elements essential for the safety, serviceability and durability of prestressed structures. Consequently it would be desirable to assess their behaviour in existing structures. Such checks to detect possible defects or damages, such as grout voids or tendon corrosion, should preferably be done by non-destructive or at least low-destructive inspection methods and with minimum disturbance to the user.

A3.2  Inspection methods

In a report published in 1988, the then available inspection methods were discussed and their usefulness and potential assessed [A2]. The conclusion was that these methods provide meaningful results limited only to localized areas, if at all. In the meantime, some of these methods have been developed further and new ones have appeared.

The inspection and monitoring methods listed below have either the aim of detecting existing grout voids, active corrosion of the prestressing steel or even ruptured wires, strands or bars in tendons.

A3.2.1  Georadar and covermeter

Experience with practical applications has shown that georadar is only suitable for the confirmation of the location of tendons. This is however, often a prerequisite for a detailed tendon inspection. Whereas under favourable condition (no congestion of reinforcement) georadar allows the location of tendons to a depth of up to 500 mm, even a powerful covermeter is generally not capable to detect ducts at concrete covers of more than 40 to 50 mm and again only if light reinforcement is present [A3].
A3.2.2 Potential mapping

Whereas potential mapping (measuring the electrical potential field) is a powerful tool for finding corroded normal reinforcement, in case of tendons it is only successful under very favourable conditions (e.g. small concrete cover to the ducts and light normal reinforcement as they may exist in thin webs of precast beams).

A3.2.3 Impact-Echo Method

Since 1983, the Impact-Echo Method has been under development primarily in the United States. It is stated that it can be used for detecting grout voids in tendons [A4].

In [A5], the method was verified in this respect and the findings can be summarized as follows:

"It is possible to use the Impact-Echo Method for checking a tendon for grout voids. It is however a delicate operation requiring experienced personnel. The presence of cracks and other concrete defects as often found in real structures significantly influence the test results and can make the evaluation impossible."

Applications in the United States have shown that under favourable conditions and in accessible areas, the Impact-Echo Method is able to identify grout voids. However, the method does not work with tendons in plastic ducts.

A3.2.4 Remanent Magnetism Method

The Remanent Magnetism Method was developed in Germany for detecting fractures in prestressing steel [A6]. The magnetizing and recording equipment has to be moved along the tendon path on auxiliary guidance rails and scaffolding fixed to the concrete surface. Thus it allows detection of localized fractures in the accessible areas. The difficulty is to cope with the disturbing magnetic signals originating from other embedded steel elements such as normal reinforcement, anchorage elements, duct couplers, steel plates, nails etc.

A3.2.5 Radiography

The application of radiography is today limited to special cases. Even in France, where the method had formerly been widely used, it has practically disappeared. Apart from the high cost, another important reason is that most countries have national regulations for the protection of people, animals and the environment when applying radiography. Whereas some of these regulations impose total evacuation of human beings in the neighbourhood (minimum distances depend on the intensity of the source; this generally means that all traffic has to be stopped in the area concerned), others ask for traffic suspension only when traffic jams are expected.

A3.2.6 Reflectometrical Impulse Measurement

Since about 1985, attempts were made to use the Time Domain Reflectometry, known from applications to coaxial telecommunication cables, for grouted tendons under the acronym RIMT (Reflectometrical Impulse Measurement). The method consists of sending high frequency impulses from an exposed anchorage through the tendon. By evaluating the recorded reflections it was hoped to detect anomalies along the tendon path. In [A7], the results of research work done at the Institute of Technology in Zurich is reported. The aim of the project was to understand the fundamentals when applying RIMT to a prestressed concrete structure. The conclusion was that "the recorded signals do not contain information regarding the condition of the tendon but are artefacts of the measurement procedure. Thus RIMT can definitely not be used as a diagnostic technique for grouted tendons."

A3.2.7 Ultrasonic Methods

Tests have shown that ultrasonic methods (transmission, reflection) for grouted tendons have very limited possibilities. Ultrasonic waves sent from a transmitter sitting on the end of the prestressing steel can detect anomalies only in special cases (e.g. only for smooth bars or wires) and only within a few meters from the tendon anchorage [A8].

Appendix: Maintenance, assessment and rehabilitation of post-tensioning tendons in existing structures
A3.2.8 Acoustic Monitoring

The detection of failures of prestressing steel by acoustic monitoring has been used for many years during in fatigue testing of tendons and stay cables. Therefore, acoustic monitoring can also be successfully applied in practice in equivalent situations such as for unbonded tendons and stay cables. Recently trials have been carried out in Great Britain to assess whether the method can also be used for internal bonded tendons. It is reported that these trials have been successful [A9]. It was shown that a single wire fracture can be detected above the ambient noise level, distinguished from other acoustic events and even located in position. It is too early to say to what extent and in which situations acoustic monitoring will find its place in practical application. It can however, be expected that for cost reasons the method will most likely be restricted to special cases.

A3.2.9 Other methods

It should finally be mentioned that in the technical literature further methods such as Thermography (infrared-scanner) and tomography are described, however not in relation to the assessment of post-tensioning tendons.

A3.2.10 Conclusions

A careful analysis of the suitability and limitations of these methods shows that none of them allows a full assessment of the condition of a tendon. Some of them however, permit a partial assessment in ideal structural situations.

A3.3 The Engineer's approach to tendon inspection

While the above listed methods may allow a partial assessment of a structure and its tendons, the interpretation of the results is not easy and often to some extent ambiguous. However, there is one method which is quite basic and practical, and overall rates best in terms of information and interpretation. This is the careful opening of tendon ducts by drilling into them, and subsequent visual inspection with an endoscope or similar devices. Sometimes, it may be advantageous to open a window around the tendon location to obtain easier access for inspection and taking samples for investigation. Such careful opening permits confirmation of the presence of voids in the duct at that particular location, and to allow the grout (powder) be collected during drilling and tested for the presence of chlorides or other aggressive chemicals. These methods have been used successfully since many years for local isolated inspections. More recently, these methods have also been applied for the inspection of entire series of structures, see [A10], and have allowed a reliable assessment of these structures. This method is particularly suitable if there is a reasonable doubt about the condition of a tendon at a particular location. Such doubt can be based on results of methods presented in section 3.2, or based on desk studies. Although this method is not non-destructive, the extent of intrusion is quite moderate, and is not considered harmful to the structure or tendon, if properly closed subsequently.

There are several publications to assist the engineer in such desk studies. In [A11, A12] the authors conclude that the inspection engineer when assessing an existing structure should be aware of the possible hazard scenarios for post-tensioning tendons. Fig. A1 shows potential "weak points" in the case of a typical box girder bridge.
**Non-structural elements:**
1. Defective wearing course (e.g. cracks)
2. Missing or defective waterproofing membrane incl. edge areas
3. Defective drainage intakes and pipes
4. Wrongly placed outlets for the drainage of wearing course and waterproofing
5. Leaking expansion joints
6. Cracked and leaking construction or element joints
7. Inserts (e.g. for electricity)

**Corrosion protection system:**
8. Defective concrete cover
9. Partly or fully open grouting in- and outlets (vents)
10. Leaking, damaged metallic ducts mechanically or by corrosion [not shown on figure]
11. Cracked and porous pocket concrete
12. Grout voids at tendon high and low points

**Fig. A1:** *Hazard scenarios for prestressing steel in a typical box girder bridge*

For each type of structure with its particular protection concept, water, possibly chloride-contaminated, can potentially reach the prestressing steel. Construction and maintenance reports and the observations of the owner and his maintenance staff provide information regarding damaging actions and hazard scenarios. The key-question is: Where does aggressive water get in contact with the structure and how does it flow off?

In addition, a thorough visual inspection (preferably after rainfall) of the concrete surfaces provides information on potential locations of damage to the unstressed and stressed reinforcement. The visual indicators include:
- water flow, wet or moist areas;
- discoloration (e.g. rust stains);
- spalling, delamination;
- cracks;
- honey-combing;
- concrete deterioration by freezing and freezing-thawing;
The findings can then be substantiated by in-situ and laboratory investigations. Following these procedures in inspection and maintenance, potential corrosion damage of prestressing steel can be recognized and counter-measures can be taken in good time.

### A4 Rehabilitation

#### A4.1 General

As mentioned in section 3.3, the careful opening of a tendon at questionable locations is currently the best method to verify its condition. Such a probing allows the determination of possible defects and deteriorations of a tendon including its anchorages and couplers. These include:

- defective grouting (e.g. grout voids, grout segregation) and water access to the prestressing steel;
- corrosion of the metallic duct, the prestressing steel, anchorages and couplers due to the ingress of water possibly contaminated by de-icing salts;
- fretting corrosion of the prestressing steel due to fatigue;
- corrosion of the prestressing steel due to stray currents.

The inspection of a tendon by opening it locally is a low-destructive method but has to be planned carefully. The planning should not only include the opening itself but also its closing after having carried out the inspection and the rehabilitation work possibly required to the tendon.

#### A4.2 Preparation

Based on non-destructive methods or desk studies, as described in chapter 3, the engineer selects the tendon locations which shall be investigated. The exact tendon locations need then be indicated on the surface of the structure. This can be done based on post-tensioning shop drawings ("as-built drawings") eventually supplemented with other methods described in chapter 3 to confirm the location. It is recommended to involve the post-tensioning specialist contractor to assist the engineer with system related questions.

The closing of the tendon opening which has been created by either drilling or by cutting a window needs to be well prepared such that the tendon can be closed immediately after inspection and eventual repair, if possible on the same day.

#### A4.3 Access to the tendon

The first step in the tendon inspection is to create access to the tendon duct or anchorage without damaging the duct or prestressing steel. The access needs to be kept as small as possible, at least initially. The following methods have been successfully used:

- drilling of a core of 50 to 80 mm diameter. The drilling machine can be equipped with an automatic switch-off when the core touches the metallic duct;
- removal of the concrete cover with an electric pick hammer. The concrete just adjacent to the tendon duct should be removed preferably by hand with light equipment.

The tendon duct can then be opened for tendon inspection in the following steps:

- cutting of the duct by hand with small, hand-held equipment such as disc cutter and flat chisel, and removal of the cut duct section. The duct opening is preferably kept smaller than the access in the concrete;
- small samples of grout can then be removed for analysis of the chloride content. Typically, a few grams of grout per sampling location are sufficient;
- if the duct is partially or completely without grout, visual inspection is possible and photos can be taken with an endoscope;
- if the prestressing steel is corroded, samples of corrosion products can be collected for analysis in a qualified laboratory to determine the type of corrosion.

The above methods to gain access to the tendon are illustrated in Fig. A2.

![Diagram of tendon access methods](image)

Fig. A2: Getting access to the tendon (Courtesy of Swiss Association of Post-Tensioning Contractors (VSV), adapted from [A13])

Appendix: Maintenance, assessment and rehabilitation of post-tensioning tendons in existing structures
A4.4 Grouting of voids

Before starting the grouting of existing voids, the exposed prestressing steel has to be carefully cleaned by a high pressure water jet, in particular where pitting corrosion or chloride contamination has been found inside the duct.

In order to select the appropriate grouting procedure, it is necessary to determine the geometrical characteristics of the detected void (length, cross-section, volume etc.). In case of a larger void vacuum assisted grouting is recommended. In special cases, the vacuum technique can also be used to measure the volume of the void and thus, determine its extent along the tendon. The vacuum pump reduces the air pressure inside the duct to a certain sub-atmospheric pressure (e.g. about 80% of the atmospheric pressure). The procedure is then automatically reversed and the air flowing back into the duct is measured and recorded. In order to determine the precision of the applied equipment preliminary tests are recommended for calibration. In principle, only cementitious, alkaline materials should be used for void filling. In case of very small voids, these can be patched by using a suitable mortar (thixotropic, if required). Tremie grouting can be applied with voids that are still comparatively small (maybe over a length of about one metre). For larger voids being several metres long, vacuum grouting is recommended using the same material as for new grouting. At the end of the grouting operation, the pressure should be increased typically by 1-3 bars and held for about 1 minute. The effectiveness of the chosen method should be tested beforehand. Fig. A3 shows a vacuum injection equipment which permits measurement of void and grout volume.

![Figure A3: Vacuum control and grouting equipment for tendons with defective grouting](image)

The advantage of the vacuum method is that only one access to a void is required. In general, this can be the borehole which has been made for the inspection of the tendon and for taking samples to determine the chloride contamination. A comparison of the previously measured void volume and the injected grout confirms the success of the procedure. In case of discrepancies, it may be necessary to make checks by additional boreholes.

A4.5 Closing of the tendon

In the following, four possibilities are given for the repair of tendon openings depending on access, see Fig. A4. In most cases, due to the presence of normal reinforcement, it is not possible to provide an additional protection by installing a half duct. Where the conditions are favourable replacement of the removed duct section should however be considered. The placing of repair concrete or mortar on to the tendon grout has generally to be made "wet-to-wet" to assure optimum bond.
(1) **Access to tendon from above, Fig. A4 a):**
   - Roughening and cleaning of concrete surface
   - Wetting of concrete surface
   - Filling of duct and covering the vicinity of the duct with a minimum of 40 mm of cementitious grout
   - Filling of the remaining space of the opening with a shrinkage compensated cementitious repair mortar in several layers in accordance with the instructions of the mortar supplier.

(2) **Access to tendon from below, Fig. A4 b):**
   - Roughening and cleaning of concrete surface
   - Filling of the opening in the concrete with a shrinkage compensated cementitious repair filler in several layers in accordance with the instructions of the filler supplier. In case of large voids inside the duct, the duct can subsequently be vacuum injected through a hose placed into the filler.

(3) **Access to tendon from the side, Fig. A4 c):**
   - Roughening, cleaning and wetting of the concrete surface
   - Placing and sealing of a formwork over the opening
   - Partial filling of the tendon opening and duct with a cementitious grout
   - Removal of the formwork
   - Filling of the remaining opening with a shrinkage compensated cementitious repair filler as in Item (2) above.

   **Note:** Alternatively, a thicker cover can be formed and filled with cementitious grout. A minimum of 40 mm on a roughened concrete surface is recommended.

(4) **Concrete pour back, Fig. A4 d):**

Alternatively to the above methods (1) to (3), the tendon opening can be poured back with concrete. This is particularly suitable, if the openings are large, e.g. in bridge box girders:

   - Roughening, cleaning, and wetting of concrete surface
   - Placing and sealing of formwork
   - Pouring back the opening with a repair concrete.

In all the above cases (1) to (4) it may be considered to provide an eventual protection of the concrete surface against ingress of humidity or chlorides with special surface protection systems.
a) Access to tendon from above

b) Access to tendon from below

c) Access to tendon from side:

d) Concrete pour back:

Fig. A4: Closing of tendon openings (Courtesy of Swiss Association of Post-Tensioning Association (VSP), adapted from [A13]).

A4.6 Rehabilitation of external tendons

The majority of the length of an external tendon is positioned outside of the concrete. Therefore, access to the tendon is much easier compared to the internal tendon discussed in section 4.3. In most cases, access to the tendon reduces to the careful opening of the duct. Typically, this is a plastic pipe which can be opened by cutting with a knife or similar tool. The actual investigation of the tendon and further rehabilitation is similar to that for internal tendons described above. For external tendons, the duct can be closed e.g. with a plastic sleeve with special grout connections, properly sealed, and then injected under vacuum. This method may even be applied for defects located inside diaphragms if access to the void is possible via the duct from outside the diaphragm.

If the damage to external tendons, e.g. by corrosion, is beyond repair, and if the tendon system permits, these tendons can be removed and replaced. For the majority of external tendons which used bare strand and cementitious grout inside a HDPE pipe, the tendon replacement must be carefully planned, and executed by experienced post-tensioning specialists. When a single strand is cut within the tendon
length, bond to the grout and adjacent strands will prevent it from freely shortening and releasing its force over the entire tendon length. Rather its force will be transferred over a relatively short distance on either side of the cut to the adjacent strands. Hence, the force in the remaining strands increases at the location of the cut. If cutting individual strands at the same location is continued, there is an inherent risk of a sudden failure of the remaining strands when the increasing stress approaches the ultimate strength. This sudden failure may be avoided if the following procedures for the cutting of a tendon are followed:

- slice and remove the plastic pipe in the free tendon length;
- carefully remove the grout in the free length and expose the tendon. This may be done by tapping or chiseling, with personnel placed behind protective shields;
- place the sliced plastic pipe around the exposed tendon, and secure the pipe with metal bands. Leave short sections of about 1 m open for access to the tendon on either side of tendon deviators and anchorages;
- install protective cages in front of access zones to tendon, fixed to the structure;
- start cutting the first strand by a disc cutter at the first opening, and repeat this at each opening. Make sure that at any tendon deviation point there is no more force unbalance than one strand. Make sure that the cut strand releases its force and elongation between tendon deviation points;
- cut the second strand similar to the first one, and repeat the procedure until all strands are cut;
- when all strands are cut, pull the tendon from the anchorage and from the deviators. If there is no double tubing at the deviator which allows removal, this section may be removed by chiseling and/or high pressure water jet.

The above described method has been successfully applied in a simplified manner on a number of single span tendons removed in Florida, [A14]. However, the method is also applicable to longer tendons running over several spans.

The above method is also applicable to external tendons with soft injection such as grease or wax, and monostrand tendons, if details for a controlled tendon detensioning have not been provided.

A4.7 Rehabilitation of internal, unbonded tendons (greased and sheathed monostrands)

Relevant information of the possibilities for rehabilitating internal, greased and sheathed tendons are given in [A1] and [A15].

If the damages consist of insufficient corrosion protection of the stressing anchorages and couplers or locally failed plastic sheathing these areas can be rehabilitated by adequate measures.

In cases where strands are heavily corroded or even broken, they can be replaced by pulling out the damaged strands, cleaning of the plastic sheath (including removal of moisture) and inserting the new strands with new grease.
Appendix references


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