

# Corrugated plastic ducts for internal bonded post-tensioning

# **Corrugated plastic ducts for internal bonded post-tensioning**

Technical report prepared by Task Group 9.6 *Plastic Ducts*  
of *fib* Commission 9

*Reinforcing and Prestressing Materials and Systems*

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Cover photo: Test specimen, definition of internal diameter  $d_1$

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# CONTENTS

<b>1</b>	<b>Introduction</b>	<b>1</b>
<b>2</b>	<b>Use of Plastic Ducts</b>	<b>2</b>
2.1	Types available	2
2.2	Sheathings for Monostrands (Common Fields of Use, General Features)	3
2.3	Smooth Plastic Tubes (Common Fields of Use, Material and Shape, General Features)	4
2.4	Corrugated Plastic Tubes (Common Fields of Use, Material and Shape, General Features)	5
<b>3</b>	<b>Material Properties and Requirements of HDPE and PP</b>	<b>7</b>
3.1	General	7
3.2	Specifications, Properties and Requirements	7
3.3	Test methods and Background	7
<b>4</b>	<b>Components and System Requirements</b>	<b>11</b>
4.1	Components Testing (Definition of Components, Flexural Behaviour of Duct, Flexibility of Duct, Lateral Load Resistance of Duct, Longitudinal Load Resistance of Duct System, Leak Tightness of Duct System, Wear Resistance of Duct, Bond Behaviour of Tendon, Friction Parameters, Durability / Corrosion Protection)	11
4.2	System Approval Testing (Stage 1 Test: Full Scale System Assembly; Stage 2 Test: Leak Tightness Test; Stage 3 Test: Stressing / Friction Test; Stage 4 Test: Grouting Test and Wear of Duct; Stage 5 Test: Electrical Resistance Test)	16
4.3	System Documentation	20
4.4	System Approval	20
4.5	Site Verification Test, Recommended Specification	20
<b>5</b>	<b>Recommend Use</b>	<b>21</b>
<b>6</b>	<b>References and Standards</b>	<b>23</b>
6.1	References	23
6.2	Standards	24
<b>Annexes</b>		
A1	Dimensional Tolerance of Duct	27
A2	Flexural Behaviour of Duct	28
A3	Flexibility of Duct	29
A4	Lateral Load Resistance of Duct	31
A5	Longitudinal Load Resistance	33
A6	Leak Tightness of Duct System	35
A7	Wear Resistance of Duct	36
A8	Bond Behaviour of Tendon	40
A9	System Approval Testing	45
A10	Summary of Requirements, Methods of Verification and Acceptance Criteria for Plastic Ducts - Recommended Specifications	47

# Preface

Optimum corrosion protection of post-tensioning tendons has been a priority since the beginning of this technology. The UK temporary ban of grouted post-tensioning tendons, from 1992-1996, has initiated a review of all aspect related to durability of post-tensioning tendons. One of the UK conclusions of this review was to require encapsulation of the post-tensioning tendons into wear-resistant and leaktight plastic ducts to serve as an additional corrosion protection barrier. Other countries have at least partially adopted similar approaches since.

Designs of these plastic ducts may vary significantly between different suppliers. In addition, experience with these systems is still relatively limited. Hence, these plastic ducts cannot be standardised at this time. Therefore, the former FIP Commission 2, and now fib Commission 9 “Reinforcing and Prestressing Materials and Systems” has set-up a task group to prepare a fib report on corrugated plastic ducts for internal, bonded post-tensioning. This report is written as a guide for an approval process for such plastic ducts. It shall serve readers such as authorities, and engineers as a guide on how to set-up a formal state approval process for these ducts, or at least allow them to properly assess systems offered for a specific project.

I wish to express my sincere thanks to all the members of the Task Group for preparing this report. I also extend my thanks to the many engineers who have contributed with written comments to the report from abroad.

H. R. GANZ  
Chairman  
fib Commission 9

The work done by the Task Group is greatly appreciated, and acknowledged. It has been a privilege to work with such active and knowledgeable colleagues.

H. R. GANZ  
Convenor  
fib Task Group for Plastic Ducts

# 1 Introduction

Ducts for bonded post-tensioning tendons have traditionally been made from steel strips with a special corrugation. A long experience with these ducts is available for many different applications. Their standardised use has allowed the creation of national and International Standards, [EN 523 (1997) ; EN 524 (1997)].

Plastic ducts have been used for many years in prestressing technology for such applications as monostrands, ground anchors, stay cables, and external tendons, mostly in the form of smooth pipes, i.e. not allowing any transfer of bond stresses from the tendon to the structure. An early example is the Schillersteg in Stuttgart completed in 1961. The stay cables are protected inside black polyethylene pipes. Material samples of the stay pipes were taken after 13 years of exposure to the environment and compared with virgin material. No particular changes of properties of the polyethylene have been observed over this period, [R. Saul, et. al. (1990)]. In July 1998 material samples were taken again but results were not available at the time of writing this report.

Corrugated plastic ducts have been used for ground anchors in the bond length. Between 1968 and 1974 about 300,000 m of corrugated black polyethylene ducts have been installed in highway overpasses, Chillon viaduct, and other bridges in Switzerland for bonded post-tensioning. After up to 30 years in use no deterioration of the polyethylene ducts has been observed in bridges eventually demolished or modified, [F. Hunkeler, et. al. (in preparation)].

But only recently thick-walled plastic ducts for post-tensioning tendons have become popular for use with curved tendons. They have been mainly introduced for such attractive features as for improved corrosion protection of the tendons, reduced friction losses during stressing of the tendon, increased fretting fatigue resistance of the tendon, and their feasibility for electrical monitoring of the tendon, [H. R. Ganz (1997)]. Substantial efforts have been made to document the knowledge and investigate the performance of thick walled plastic ducts for post-tensioning, [P. Matt (1990) ; J. Kollegger (1994) ; H. Cordes, et. al. (1996) ; P. Marti (1993)]. They have now found their way into some national specifications, [TR 47 (1996)]. In Switzerland and Germany these ducts have been subjected to a State Approval Process.

As any other product, plastic ducts have their particular properties which must be properly addressed. These properties include the flexibility of ducts which may cause excessive wobble of the tendons or even spalling of concrete during tendon stressing ; ordinary plastic ducts, not specifically designed for bonded post-tensioning applications, are relatively sensitive to local loads at tendon supports and may be crushed ; ducts not properly sealed at duct connections or thin-walled ducts cut through by the prestressing steel during stressing may leak during grouting. These effects are aggravated if the ducts are exposed to elevated temperature, and / or long term loading. However, negative effects can easily be avoided by proper design of the duct system, proper material specification, and correct, i.e. material specific, use and installation of the duct system on site.

The cost of corrugated plastic ducts for bonded post-tensioning is strongly influenced by the production method. These ducts are typically produced by extrusion process requiring significant investment. Since they are produced in relatively small quantities, corrugated plastic ducts for bonded post-tensioning are typically more expensive, with prices up to twice as high as for corrugated thin-walled steel ducts. Ducts represent about 5% of the installed

post-tensioning price which represents about 10% of the total construction cost of a bridge. Hence, doubling of the duct price represents about 0.5% increase of the construction cost for a significant improvement of durability and quality of the main reinforcement of a structure. However, long tendons with significant friction losses due to tendon deviation will benefit from the reduced friction coefficient of plastic ducts, and may even show an economy due to a more effective use, and therefore, a reduction of the required amount of prestressing steel.

Corrugated plastic ducts for bonded post-tensioning are a recent innovation. Products still differ widely in material properties, geometrical details, installation procedures and use on site. Therefore, they cannot be standardised yet as was done for corrugated steel ducts or smooth PE pipes. It is the opinion of the Task Group and Commission that these plastic ducts should be subjected to a "System Approval" process until sufficient experience is available to allow to standardise these products.

This report aims at providing guidance to owners and designers how to assess corrugated plastic duct systems for bonded post-tensioning and their use. After a brief review of the overall use of plastic ducts in prestressing technology, material specifications for polyethylene (PE) and polypropylene (PP) for ducts for bonded post-tensioning are proposed which have proven to perform satisfactorily. Essential requirements for corrugated plastic ducts for bonded post-tensioning are then listed, and test methods are proposed to verify these characteristics. A recommended specification for corrugated plastic ducts for bonded post-tensioning is attached for easy reference by potential users. These requirements apply to bonded post-tensioning only and should not necessarily be applied to plastic ducts for other usage.

## 2 Use of Plastic Ducts

Even though this report is addressing exclusively plastic ducts for bonded post-tensioning it was felt worthwhile to list other uses of plastic ducts in construction. Comparison of the requirements listed in this report for bonded post-tensioning with those of other perhaps better known applications for plastic ducts, may allow the reader a better appreciation of the performance level specified in this report for bonded post-tensioning. Experience with these other uses may also serve as a reference to the reader, and will hopefully generate an increased level of confidence in the use of plastics for post-tensioning ducts.

### 2.1 Types available

The types may be listed by their manufacturing process:

- Extruded ducts,
- Moulded ducts,
- Spirally or longitudinally welded ducts,

or using the order in which they appeared and are currently used for prestressing applications:

- Sheathings for monostrands,
- Smooth ducts,
- Corrugated ducts.

The latter classification is chosen for further discussion in this report.

## 2.2 Sheathings for Monostrands

### 2.2.1 Common Fields of Use

Prestressed slabs,  
Group of monostrands for ground anchors,  
Transverse prestressing of bridge decks,  
Vertical prestressing of webs,  
Group of monostrands for  
    internal prestressing,  
    external prestressing,  
Stay cables.

Monostrands have been designed to offer an unbonded prestressing tendon with a compact cross section eliminating grouting operations, thus more efficient and less labour intensive to install. In addition, they offer a factory applied and controlled corrosion protection system. Progressively their use was extended from prestressed slabs in buildings, to reservoirs and bridges over to stay cables, to cover the whole field of prestressing. They are applied for new construction as well as for repair and strengthening works.

### 2.2.2 General Features

Sheaths made of PE tube, of 1 to 2 mm wall thickness, either extruded around the strand during the strand manufacturing process or not, or in which the strand is threaded in (for ground anchors only). The space between strand and duct may be filled or not depending on the application. The filling material is grease, wax or tar-epoxy. The monostrand resulting from this assembly is a corrosion protected strand which does not generally require any further protection, e.g. by means of grouting.

Monostrand sheath and filling (grease, wax) are now generally extruded around the strand as part of the strand manufacturing process for improved quality of corrosion protection.

Special monostrands with regular interruption of greasing or PE extrusion can be produced as well, with an application mainly for ground anchors.

Threading strands into plastic tubes is still done for special purposes, e.g. ground anchors, for which a grease-free length is required for anchorage in the bond length. Threading strands in this application avoids the difficult operation of removing the grease from extruded strand. Threading of strand has to be done with special care to avoid entrapment of water inside the tubes.

Further developments of the monostrand product consist in extruding PE around several strands simultaneously to form a flat "ribbon" or inside a welded flat PE duct. The use of such products as internal prestressing should be limited to cases where concreting may be carried out without risk of air being kept trapped underneath. Moreover the rigidity of the ribbon does not allow for three dimensional tendon layout.

Bundles of monostrands have also been used inside a general sheath and grouted for internal unbonded and external tendons. This system offers improved corrosion protection and reduced friction losses compared with bare strand systems.



For uses where they remain free, e.g. for stay cables, monostrands are made out of a PE sheathing tightly extruded around the strand with a reduced filling of wax or grease, following the surface profile of the underlying steel strand. This improves the resistance of the sheath to impact.

To further improve corrosion protection, galvanised strands have been used inside the sheathing.

## **2.3 Smooth Plastic Tubes**

### **2.3.1 Common Fields of Use**

Ground anchors,  
Internal unbonded prestressing,  
External prestressing,  
Stay cables.

Basically these plastic tubes have been used wherever the prestressing had to be installed externally to concrete in conjunction or not with an aggressive environment, whether chemical or mechanical. A particular application includes the provision of plastic tubes to reduce wind drag on external or stay cables. Plastic tubes have been a good technical and cost effective alternative to steel pipes.

They have occasionally been used for internal prestressing also when no bonding of the prestressing steel to concrete is required.

### **2.3.2 Material and Shape**

The most commonly used material is high density polyethylene (HDPE). In certain conditions polypropylene (PP) is an alternative to HDPE. Polyvinyl Chloride (PVC) has been rarely used due to various unfavourable factors, such as the potential development of hydrochloric acid in a fire. According to experts, the formation of hydrochloric acid already occurs at temperatures of 70-80°C if exposed long term. It is not accepted for environmental reasons when possible recycling is required.

While the most common application has black colour with 2% carbon black added and a smooth surface, particular surface patterns such as straight or spiral ribs may be applied to favourably modify the behaviour for wind loading. Coloured layers of HDPE may also be applied to the surface of the pipe (co-extruded pipes).

Also, fully coloured external pipes have become available. Finally, two half shells joined with a clip or continuously welded to form a pipe have been used.

### **2.3.3 General Features**

A duct usually consists of a thick-walled HDPE tube. Specifications may differ according to the use:

- UV-resistance is important during storage and installation period in all cases, and in service for all exposed use of ducts such as external tendons and stay cables.
- External or full coloration is often required for stay cables, to reduce temperature effects in the stays, and for aesthetic reasons.

General specifications of the plastic duct cover:

- Water tightness,
- Climatic resistance,
- Resistance to oxidation and chemical aggression,
- Mechanical resistance, especially : during installation period,  
to grouting pressure and temperature,  
in stressed zones, e.g. at tendon deviations,
- Electrical isolation (optional).

## **2.4 Corrugated Plastic Tubes**

### **2.4.1 Common Fields of Use**

Ground anchors,  
Internal bonded prestressing.

Transfer of forces or mechanical bonding throughout the tendon length have required a corrugation in a similar manner as for standard steel sheaths in addition to the typical features of smooth plastic ducts. Therefore their use is generally limited to the above mentioned cases.

### **2.4.2 Material and Shape**

The most commonly used materials are HDPE and PP. Combination of different materials is possible to take advantage of selected characteristics.

Corrugations of the duct most typically are helical or circular. They can be continuous or intermittent. Cross sections of ducts often are round. However, oval cross sections are available to increase potential eccentricity of tendons in shallow structures such as slabs. A selection of typical corrugations of ducts is illustrated in Fig. 1. The ribs may be of different shapes such as sinusoidal or angular, etc. However, the effect of the shape on grouting should be checked.

### **2.4.3 General Features**

The corrugation is necessary to ensure bond with the external medium e.g. in the bond length of a ground anchor, or for bond transfer along a post-tensioning cable within the concrete.

General specifications of the plastic duct cover :

Water tightness,  
Resistance to oxidation and chemical aggression,

Mechanical resistance, especially

- during installation and pouring of concrete,
- to pressure and relative movement of prestressing steel during stressing,

Bond performance,

Electrical isolation (optional).

Generally, for the same basic wall thickness, less corrugation gives stiffer duct for flexural bending between duct supports but more corrugations give better resistance to local deformations.

Round plastic duct typically is supplied in straight lengths of about 4 to 12 m according to local demand and transportation methods, or may be produced on site to the total required length. Joining of duct sections on site to form a continuous duct may be achieved with different solutions such as threaded connectors, half shells clamped together, mirror welding, or heat-shrink sleeve.

Please note that large diameter duct should not be coiled for supply. Supply on coils for such ducts may cause excessive wobble of the tendons due to residual deformations in the plastic duct which remain even after uncoiling and installation.

Vents for drainage and grouting may be provided integral with half shell connectors, or may be drilled and welded to the duct.

Ducts are usually black, however, coloured ducts have been used and are available.

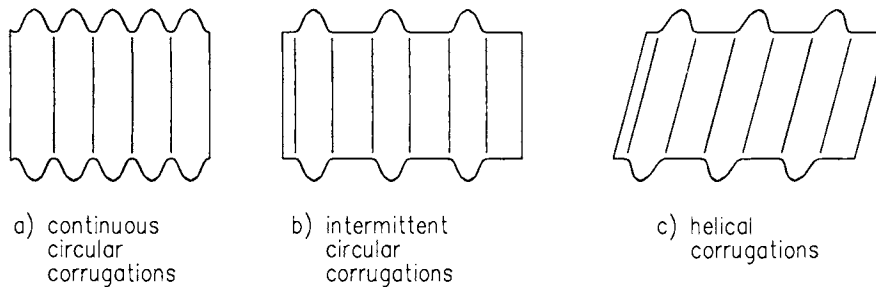


Fig. 1 : Shapes of corrugation

## 3 Material Properties and Requirements of HDPE and PP

### 3.1 General

If plastic materials made from HDPE or PP have to adopt load-bearing functions, such as for internal bonded post-tensioning, requirements for their mechanical behaviour have to be defined and guaranteed. These properties may change from the granulate to the non-moulded mass through to the final moulded shape. The influence of temperature is of special importance. The following text applies to ducts for internal, bonded post-tensioning.

### 3.2 Specifications, Properties and Requirements

For ducts, generally only new material (granulate) is suitable. Clean recycled/reprocessable material generated from the manufacturer's own production of ducts conforming to this specification may be used if it is derived from the same compound as used for the relevant production. Other recycled material shall not be used.

The producer has to specify the material in the form of granulate and once formed into the duct. In the specification the thermoplastic moulding materials have to be designated according to e.g. DIN 16 774-1 for polypropylene (PP) and according to DIN 16 776 for polyethylene (PE) and their properties have to be declared. As a minimum the properties given in Table 3.1 should be declared during the approval process. The values have to comply to the limits of Table 3.1. If the ducts are welded, the welding procedure should be specified, and the properties of added material, if any, should be declared.

P

Table 3.1 does not only list the properties of HDPE and PP, but also the different types of proof of conformity. The test methods are described in ISO-, DIN- and ASTM- standards. Equivalent British Standards (BS) and ASTM standards are listed in Section 6.2. However, test parameters and acceptance criteria may be different.

Material properties should be verified by an independent body. This should form an integral part of the approval of the plastic duct system. Such verification is indicated in Table 3.1 with a note (2).

Reference samples of production lots used for initial approval should be kept for future reference and comparison with standard production.

Material certificates during standard production should declare as a minimum the following properties: Density, Melt Mass-Flow Rate MFR 190/5, Hardness, Tensile Stress at Yield, Elongation at Yield, and Carbon Content, if applicable.

### 3.3 Test methods and Background

Below, test methods and their background are briefly explained. It should be noted that several properties are difficult to measure in practice. Production of test pieces made under pressure have been reported to be the most reliable production method. Density and elongation are properties which are sensitive to the presence of entrapped air in the specimens.

**Table 3.1****Material Specification : Properties and Requirements (HDPE and PP)**

Property	Granulate	Duct	Measuring Technique (6), (7)	Unit	Value Max. / (6), (7) Min. HDPE	Value Max. / (6), (7) Min. PP	Attestation of Conformity
Density		D	DIN 53 479	g/cm <sup>3</sup>	0,95 ± 0,01	0,90 ± 0,01	(1), (2)
Melt Mass-Flow Rate MFR 230/5	G		ISO 1133	g/10min	-	1,2 ± 0,3	(1)
Melt Mass-Flow Rate MFR 190/5	G		ISO 1133	g/10 min	0,5 ± 0,1	-	(1)
Melt Mass-Flow Rate MFR 230/5		D	ISO 1133	g/10min	-	(3)	(1), (2)
Melt Mass-Flow Rate MFR 190/5		D	ISO 1133	g/10 min	(3)	-	(1), (2)
Hardness : Ball indentation method H 132/30	G		ISO 2039-1	N/mm <sup>2</sup>	44 ± 4	50 ± 5	(1)
Indentation test dependent on time and temperature (e.g. +23°C and +60°C)		D	ISO 2039-1, at +60°C and selected load	To be declared by the manufacturer for a time of up to one hour			
Charpy impact strength of notched specimens, a <sub>cN</sub> : at +23°C	G		ISO 179/1 eA	kJ/m <sup>2</sup>	no fracture	≥ 35	(1)
Charpy impact strength of notched specimens, a <sub>cN</sub> : at -30°C	G		ISO 179/1 eA	kJ/m <sup>2</sup>	no fracture	≥ 3	(1)
Tensile impact strength of notched specimens at + 23°C	G		ISO 8256	kJ/m <sup>2</sup>	≥ 130	≥ 120	(1)
Tensile stress at yield	G		DIN 53 455	N/mm <sup>2</sup>	≥ 22	≥ 24	(1)
Elongation at yield	G		DIN 53 455	%	≥ 7	≥ 10	(1)
Environmental stress cracking (ESC)	G		ASTM-D-1693- 70 ISO 6252	hours	≥ 192 ≥ 100		(1)
Vicat VST B50	G		ISO 306	°C	≥ 70	≥ 70	(1)



Property	Granulate	Duct	Measuring Technique (6), (7)	Unit	Value Max. / (6), (7) Min. HDPE	Value Max. / (6), (7) Min. PP	Attestation of Conformity
Linear expansion-coefficient between 20° and 80° C – average value	G		DIN 53 752	K <sup>-1</sup>	To be declared by the manufacturer		
Elastic modulus at + 23°C	G		DIN 53457	N/mm <sup>2</sup>	To be declared by the manufacturer		
Carbon content (5)	G			%	≥ 2		(1)
Homogeneoususness		D	thin cut	mm <sup>2</sup>	(4)		(1), (2)

- G Granulate, specimen made of initial material  
D Duct, specimen made of material from the duct  
(1) Factory production control or guaranteed values by the manufacturer  
(2) Control by an approved body  
(3) There should be no significant increase from the values of the granulate (G) to the values of the duct (D).  
(4) Parts, which are not mixed homogeneously with carbon, having clusters of carbon, bubbles, shrinkage cavities and foreign substances, must not be larger than 0,02 mm<sup>2</sup>.  
(5) If applicable.  
(6) Or equivalent standards and acceptance criteria which are adjusted accordingly.  
(7) If other test parameters are prescribed, these may be accepted, and acceptance criteria may need to be adjusted accordingly.

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- Density (DIN 53 479) :

The density given in g/cm<sup>3</sup> is a material characteristic which can be determined in different ways. It helps to determine physical or chemical changes during production and use. Test temperature is 23°C. The density is needed to confirm that the PE is high as against medium density.

- Melt mass-flow rate (ISO 1133) :

It measures the shear speed. “MFR 230/5” for example is the amount of material in grams, which exits an extruder die in 10 minutes at a temperature of 230°C under a mass of 5 kg. It serves for quality control during production to assure a proper manufacturing process. Mass flow rate tests may be carried out on a comparative basis for standard production with the as supplied raw material. Variation from the original values greater than those indicated in Table 3.1 is an indication that some change to the material has occurred.

- Hardness (ISO 2039-1) :

With a ball-shaped penetrating stamp Ø 5 mm hardness, i.e. penetration h, is measured in mm under a test load F = 132 N, applied for 30 seconds. Hardness is determined by the

equation  $H = (1/5\pi) \times F/h$ . Other load levels than 132 N may be chosen as given in the standard.

- Indentation test dependant on time and temperature :

The hardness test as per ISO 2039-1 is carried out at 23°C and at 60°C for the determination of the influence of temperature. Duration of loading should be up to one hour.

- Charpy impact strength of notched specimens (ISO 179/1) :

With a defined notch the material should display a certain deformability in kJ/m<sup>2</sup> at bending before fracture. In this test, temperature plays a decisive roll and therefore, two levels of + 23°C and – 30°C are checked.

- Tensile impact strength of notched specimens (ISO 8256) :

In addition to Charpy test a notched sample is loaded in the longitudinal direction.

- Tensile stress at yield and elongation (DIN 53455) :

Yield stress and elongation are determined on a specifically shaped tensile test sample. Machining of the test specimens must be carried out with great care to avoid residual stresses influencing the results.

- Environmental stress cracking (ASTM-D-1693-70; ISO 6252) :

A sample has to withstand a stress near the yield point for a given number of hours at 70°C under aggressive influences. This serves as an indicator for ageing properties.

- Vicat VST B 50 (ISO 306) :

The temperature in °C is determined at which a defined penetrating stamp penetrates 1 mm into the material at a force of 50N and a heat increase of 50°C/h.

- Linear expansion coefficient (DIN 53752) :

The coefficient of expansion is in the order of  $2 \cdot 10^{-4}$ , i.e. more than 10 times higher than that of steel or concrete. This may be of importance and thus, it has to be determined.

- Elastic modulus (DIN 53457) :

This value may be important for certain design aspects of the duct, and should be declared by the manufacturer for a range of temperatures. Typical values at 23°C are 600 MPa (HDPE) and 800 MPa (PP).

- Embrittlement under UV radiation :

Addition of carbon is important for durability against UV radiation. Besides the absolute content of carbon of  $\geq 2\%$  also its distribution is of importance. Clusters of carbon, bubbles, shrinkage cavities and foreign substances must not be larger than 0.02mm<sup>2</sup>.

Light colours instead of black may be desirable to reduce the effects of temperature on the duct properties. In such cases UV stabilisers other than carbon black need to be added. Alternative materials such as titanium dioxide used instead of carbon should meet the same requirements.

## 4 Components and System Requirements

This chapter presents requirements, test methods, and acceptance criteria for different aspects of the individual plastic duct system components, and of the completely assembled system. These assessment procedures for duct components and the duct system should preferably be used as part of a System Approval procedure verified by an approval body, but may eventually also be used in parts for project specific acceptance / suitability testing verified by the project engineer.

All the tests listed below are, for practical reasons, carried out as short-term tests at room temperature. The result of these tests serve as a reference and for declaration of properties. However, the approval body or project engineer needs to assess and judge the importance and the eventual effects of elevated temperatures and long-term loading on a proposed plastic duct system, in particular if they are intended to be used in hot climates. In such particular cases, it may be necessary to carry out some of the proposed tests at higher temperature. This may include e.g. the tests described in 4.1.2, 4.1.4, and 4.1.7. Low temperatures also need to be considered in particular cases for tests such as described in 4.1.3.

The proposed tests should be carried out at an independent qualified laboratory. Tests carried out by the system supplier are acceptable if they are certified by an independent qualified witness. The approval body or project engineer may accept other types of tests if they are considered to allow assessment of the properties of the components and system to be equivalent to the ones required in this report.

### 4.1 Components Testing

Individual aspects of components should be assessed as presented in Clauses 4.1.1 to 4.1.8. Additional optional features may be assessed as presented in Clauses 4.1.9 and 4.1.10 if these options are offered by the system supplier. In general, one test per item is considered sufficient to document the performance. Indicated test temperatures should be maintained within a tolerance of about 5°C.

#### 4.1.1 Definition of Components

The main component of a plastic duct system is the duct. However, the complete system often includes such accessories as :

- duct couplers,
- duct vents and drains,
- connections of duct to anchorage,
- anchorage cap,
- sealing elements,
- special details for electrical isolation of anchorage.

As for any part of a post-tensioning system, the duct and accessories must be completely defined in terms of geometry and materials. Main dimensions of the duct, and of accessories if applicable, should be presented in data sheets, and assembly of the components should be shown on an assembly drawing.

Dimensions of duct and accessories should be suitable for proper assembly, installation, stressing, and grouting of the system. In particular, minimum cross sections of duct, vents and drains for installation of prestressing steel and for grouting should be respected, see [FIP Technical Report "Tendons" (1995)]. In general, a minimum wall thickness of the duct of 2 mm has been found to give sufficient robustness and stiffness.

Tolerances of plastic parts should be adequately limited to assure proper fit over the design range of temperature variations, and shall be within the range specified on the fabrication drawings. Deviations from the mean values of the internal diameter of the duct determined according to Annex A1 should generally not exceed  $\pm 1\%$  or  $\pm 0.5$  mm, whichever is the greater.

Ducts shall be made from HDPE or PP as specified in Chapter 3 above. Accessories should be made of the same material but may be produced from other materials if these materials are compatible.

#### **4.1.2 Flexural Behaviour of Duct**

Ducts should be sufficiently rigid to limit deflections between duct supports due to temperature variations and during concreting, both for vertical and for lateral deflections.

Depending on the system holder's specified method of tendon installation, this requirement should apply to the duct without and/or with the prestressing steel installed prior to concreting. The type and spacing of duct supports should be specified by the system holder. Typical spacing is less than that for metal ducting, and may be in the order of 5 to 10 duct diameters.

The flexural behaviour of the duct should be determined according to Annex 2. The measured load at an instantaneous deflection at mid span of 20mm as well as after 2 minutes should be documented for a temperature of 23°C. The instantaneous residual deflection after release of the load as well as after 2 minutes should also be recorded.

The flexural behaviour should be deemed acceptable if

- (1) the losses due to friction and wobble effects in actual applications, determined with site tests [FIP State of the art report (1986)], or according to Clause 4.2.3, and Annex A9, confirm the friction and wobble parameters specified by the system holder and,
- (2) the displacement of the duct during concreting is not likely to result in problems during installation/stressing of the prestressing steel.

Data of existing approved duct systems seems to indicate similar loads for plastic ducts in above test as for steel ducts.

#### **4.1.3 Flexibility of Duct**

The duct should be flexible enough to allow easy bending to the specified minimum radius of curvature in a structure without excessive deformation of the duct cross section.

The flexibility of the duct should be verified with the test described in Annex A3, at a temperature of 23°C.

The flexibility of the duct should be deemed acceptable if the duct does not suffer any visual damage. Deformations of the duct cross section should preferably not exceed 5% of the duct diameter, determined by passing a plunger through the duct.

Flat or oval ducts should be tested in the direction for which they were conceived to be bent on site. This is normally bending on the weak axis of the cross section. In this case, the duct depth should be used in lieu of the duct diameter to check acceptable deformations.

The above criteria are not meant to check the performance for plastic ducts assembled on coils, but apply strictly to site performance.

#### **4.1.4 Lateral Load Resistance of Duct**

The duct should be sufficiently strong to sustain concentrated lateral loads introduced at tendon supports, or as created during concreting including unintentional impact, without undue deformation of the duct cross section.

The lateral load resistance should be tested according to Annex A4 at a temperature of 23°C.

The lateral load resistance of the duct should be deemed acceptable if the irreversible transverse deformations of the duct, measured 2 minutes after release of the load, are not exceeding 10% of the duct diameter or 5 mm, whichever is the smaller.

Ducts not satisfying above criteria should be tested again with stiffeners placed at the location of load application which corresponds to the location of duct supports in practice. If the test criteria are then met, such stiffeners need to be specified for the system, and applied on site at relevant locations on the duct supports (e.g. near high point between Sections III and V of Fig. A 9.1).

For flat or oval ducts, the same comment applies as made in 4.1.3 above.

#### **4.1.5 Longitudinal Load Resistance of Duct System**

The duct, and in particular couplers between duct segments, and connections between duct and anchorage, should be sufficiently strong to resist restraints due to temperature variations after installation into the reinforcing steel cage of a structure but before concreting.

For duct systems which are supplied on coils to site (flat duct or small diameter round duct), the duct and any couplers/connections need to resist to loads created by the coiling and handling.

The longitudinal load resistance should be tested according to Annex A5 at a temperature of 23°C. The duct installed with a coupler and/or connection should be able to sustain an imposed longitudinal elongation (tension loading) of + 8 mm/m of duct outside connector, over a period of 10 minutes. The corresponding loads at the start and end of the 10 minutes period should be recorded. Duct systems which are intended to be supplied on coils should be



tested with an applied load as specified in Annex A5. Corresponding duct elongation should be recorded.

The longitudinal load resistance should be deemed acceptable if the applied elongation and/or load can be held during the test period without failure of the duct or slippage of the duct / coupler connection.

Duct systems not intended for coiling not satisfying the above criteria may be designed to allow movements of 8mm/m at connections without compromising their water tightness. This fact should be stated in the system documentation.

#### **4.1.6 Leak Tightness of Duct System**

The duct system including couplers and connections/vents should be sufficiently watertight when bent to the minimum radius of curvature specified in the post-tensioning system and/or duct system documentation.

The leak tightness should be tested according to Annex A6 at a temperature of 23°C, with a duct assembled with coupler and/or connection bent to a specified minimum radius curvature including an allowance for specified duct placement tolerances, using the same components previously tested under 4.1.3, 4.1.4, and 4.1.5. Leak tightness should be tested for both a differential pressure applied from outside and from inside the duct.

The leak tightness should be deemed acceptable if there is no visually detectable loss of water during the test period.

#### **4.1.7 Wear Resistance of Duct**

The duct should be sufficiently resistant to wear caused by the prestressing steel during stressing of the tendon, and the time before grouting of the tendon, when bent to the minimum radius of curvature specified in the post-tensioning system and/or duct system documentation.

The wear resistance should be tested according to Annex A7 at a temperature of 23°C for each particular design of plastic duct, i.e. particular form and spacing of corrugation, and material selection.

The wear resistance should be deemed acceptable if the minimum residual wall thickness of the duct after testing is not less than 1.0mm. A confirmation of the wear resistance during the system approval testing, Section 4.2, may be considered.

The above criteria will assure that a plastic duct system will perform satisfactorily in most applications. Particular attention should however, be applied if the duct system is intended to be stressed at elevated duct temperatures such as occurring for early stressing while the concrete may still be at elevated temperature due to the heat of hydration. Installation of the duct at elevated temperature may lead to local permanent indentations of the duct at tendon supports creating a “hard spot” which will be a source of excessive local wear.

For such particular applications, it is strongly recommended to specify and use stiffeners / half shells between the duct and duct supports at locations where the tendon deviation forces

act towards the duct supports to better distribute the local effects at the tendon supports. Such stiffeners and their intended use should be stated, if applicable, in the system documentation.

#### 4.1.8 Bond Behaviour of Tendon

It has been shown by testing that the bond between prestressing steel and grout is usually inferior to the bond between grout and duct or duct and concrete, [P. Marti (1993)]. Hence, the bond behaviour of plastic ducts to concrete often is not relevant, i.e. the bond behaviour of the tendon can be considered similar to bond with corrugated steel duct. However, the bond behaviour of the tendon inside the grouted plastic duct should be declared in the duct system documentation anyway to allow a structural engineer to assess for particular applications eventual implications for the design of the structure under service and ultimate conditions.

The bond behaviour of plastic ducts should be tested according to Annex A8 at a temperature of 23°C.

The bond behaviour should be deemed acceptable if the values measured in the test according to Annex A8.1 are not less than the corresponding values declared in the duct system documentation. In particular, the following values should be verified :

- Measured bond stress and/or corresponding tendon force at displacement  $\Delta s = 0.1\text{mm}$
- Measured bond stress and/or corresponding tendon force at displacement  $\Delta s = 1.0\text{mm}$
- Measured maximum bond stress and/or corresponding tendon force
- Ratio of measured bond stresses or tendon forces at displacements  $\Delta s = 1.0\text{mm}$  and  $\Delta s = 5.0\text{mm}$

Typical bond strength should allow to anchor the characteristic ultimate tendon force in a bond length of 50-100 duct diameters. The actual value for the particular system should be declared in the system documentation by the system holder, and should be confirmed as per Annex A8.2. In post-tensioning tendons with mechanical end anchorages, only the force beyond effective prestress after all losses needs to be transferred by bond at ultimate conditions.

#### 4.1.9 Friction Parameters

For the materials specified in Chapter 3, the friction coefficient between duct and prestressing steel are sufficiently well known. The typical range of friction coefficients is as follows :

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

The friction parameters for the duct system should be specified in the system documentation with a “range” and a “recommended design value” for friction and wobble coefficient.

The values may be confirmed with tests on actual sites as proposed in [FIP State of the art report (1986)]. In particular cases outside prior experience, a friction test should be included as part of the assembled duct system assessment, see Section 4.2.

It has been noted that tendon elongation increases over a period of a few minutes after stressing if the applied load is held constant, particularly at elevated temperature. This leads to a more uniform tendon force distribution, corresponding to a reduced friction coefficient (order of reduction is 0.02).

#### **4.1.10 Durability / Corrosion Protection**

It has been shown that corrugated steel duct will fracture at cyclically opening cracks across the duct, [H. Cordes, et. al. (1996)]. Plastic duct has been shown to perform better under similar conditions. For certain applications the designer may want to specify an option that the plastic duct system should remain intact for complete encapsulation and corrosion protection during the design life of the structure. This may be of particular interest for cracked structures in aggressive environment (de-icing salts, splash zones, etc).

If such an option is specified by the designer, tests such as used and presented in [H. Cordes, et. al. (1996)], [H. Cordes, et. al. (1996)] and [M. Abel (1996)] may be considered for verification of the performance.

Durable complete encapsulation and corrosion protection may be considered to be provided if the duct system remains intact during the test period under an applied cyclic opening of cracks in the order of 0.3 to 0.5 mm at specified minimum temperature of application for the duct system.

## **4.2 System Approval Testing**

These complementary tests should demonstrate that the assembled components act as a complete system and satisfy the requirements for which the individual components have been previously tested :

- Practicability of assembly
- Water tightness
- Stressing / Friction
- Grouting
- Electrical resistance (optional).

The tests should document the suitability of the system for practical applications and therefore, be performed as full scale tests. The installation, stressing and grouting of the tendon system should follow rigorously the method statements prepared for the system. The method statement should be adjusted, if required, until the suitability tests meet the specified requirements.

The tests proposed are not meant as project specific tests but as system approval tests and therefore, need to be carried out only once for certification or approval of the system.

Strict adherence of installation methods used on site to the method statements used for system approval, installation of the system by approved and qualified personnel, the application of quality plans, and the independent checking by the engineer on site will assure that the performance confirmed in the approval testing will be obtained also on construction sites.

The test programme should be carried out in stages. For new and innovative systems with no prior experience stages 1 to 4 should be carried out (and stage 5 if given as an option). For other systems stages 1 and 2 (and stage 5 if given as an option) may be considered to be sufficient for system approval. Each subsequent stage is an extension of the successfully performed previous one. The tests should be performed on a representative tendon size. For typical bridge applications this is equivalent to 12 to 19 numbers of 7-wire strands of 150mm<sup>2</sup> cross section, or equivalent force for other prestressing steels. For other applications the system holder should propose an appropriate tendon size. The tendon should have a realistic tendon profile according to Annex A9, comprising the following elements :

- tendon duct with stiffeners at supports, if required,
- one low point,
- one high point with minimum radius of curvature,
- vent at the high point,
- duct connectors as required,
- one fixed-end anchorage,
- stressing anchorage,
- stressable coupler, if it is part of the system approval.

#### **4.2.1 Stage 1 Test : Full Scale System Assembly**

The system should be able to be properly assembled according to the method statement.

The test should consist of assembling all the duct system components in full conformance with the method statement, to satisfy the geometrical requirements stipulated, and to demonstrate the practicability of the assembly method, inside the reinforcing steel cage of the test specimen. The prestressing steel should not be installed for the first test stage.

The assembly test should be deemed acceptable if all the components have been installed as specified in the method statement, the duct profile complies with the specified profile within specified tolerances, without any apparent tendon profile discontinuities, and without excessive duct deformations (see section 4.1).

#### **4.2.2 Stage 2 Test : Leak Tightness Test**

The test should demonstrate that the fully assembled system is sufficiently leak tight.

The following test procedure should be applied :

- The test arrangement according to Stage 1 should be used.
- The tests should be performed without the prestressing steel in the duct, but including sealed end caps at the anchorages.
- The duct should be subjected to a constant air pressure from the inside. The loss of air/leakage rate should be measured with a flowmeter, over a period of 5 minutes, and should be recorded. This test should be carried out with a pressure level of 0.1 bar.

The leak tightness test should be deemed acceptable if the pressure loss over the period of 5 minutes does not exceed 10% of the initial pressure. In the assessment of the test result, any eventual effect of extension of the plastic duct system under pressure should be considered.

If the losses exceed the value stated above, the installation method statement and/or sealing details should be revised and improved and the test repeated, until the losses are acceptable. Actual location of losses should be checked, e.g. by externally applied soap solution, and recorded.

#### **4.2.3 Stage 3 Test : Stressing / Friction Test**

This test where deemed necessary for new and innovative systems with no prior experience, should demonstrate that the system can be stressed as anticipated in the system documentation, and that the actual friction losses are within the specified range. For other systems, this test stage may be omitted.

The following test procedure should be applied :

- The test set-up according to Stage 2 should be used.
- Concrete of approximately 35 MPa cube strength at 28 days, corresponding to concrete typically used for prestressed concrete structures, should be poured around the full scale system assembly.
- The prestressing steel should be installed into the duct according to the method statement of the system supplier. If the prestressing steel is specified to be installed before concreting, this step should be performed before the step “concreting” above.
- The tendon should then be stressed from one end according to the method statement in steps of 20% of the tendon capacity up to a maximum of 80% (or to the maximum load permitted in local codes).
- Tendon forces should be determined with an accuracy of  $\pm 2\%$  at either tendon end at each step, and tendon elongation should be recorded.
- Subsequently, the tendon is released, and stressed again from the opposite end, according to the same procedure, and finally anchored at full load.

The stressing / friction test should be deemed acceptable if all the specified procedures can be applied without unforeseen incidents, and if the measured anchorage forces and tendon elongation are within the expected range and/or specified tolerances.

#### **4.2.4 Stage 4 Test : Grouting Test and Wear of Duct**

This test where deemed necessary for new and innovative systems with no prior experience, should demonstrate that the system allows proper grouting according to the method statement and complete filling of the system with its accessories and details, the grouting material and equipment specified by the system holder and/or applicable local codes. It may also be used to confirm wear of the duct during stressing, see Clause 4.1.7.



The following test procedure should be applied :

- The test arrangement according to Stage 3 should be used.
- The tendon should then be grouted according to the method statement of the system holder. Properties of grout samples should be recorded, according to the relevant specifications.
- After the grout has hardened to the specified cube strength of at least 25MPa, the tendon duct can be investigated for the presence of voids.
- For this investigation, cores of a diameter of approximately 2.5 times the duct diameter should be taken at the Sections I-I to VI-VI indicated in Annex A9 across and including the entire duct.

The grouting test should be deemed acceptable if no voids are found in the samples / cores taken which exceed a depth of 5% of the duct diameter.

This investigation should include inspection of the wear of the duct at the locations where cores are taken. Minimum remaining duct wall thickness should be measured on the duct sections removed with the cores, and recorded. Results of wear should be deemed acceptable if the minimum remaining wall thickness is not less than 1.0mm (see also Clause 4.1.7). Slippage of the tendon at the cut section should be observed and recorded.

If the voids exceed the requirements stated above, the grouting method statement should be revised and improved and the grouting test repeated, until the voids are within acceptable limits.

If actual wear exceeds the requirement stated above, the duct design and/or minimum radius of tendon curvature may need to be modified.

#### **4.2.5 Stage 5 Test: Electrical Resistance Test**

This test is optional for electrically isolated tendons and should demonstrate that a sufficient electrical resistance between the prestressing and the reinforcing steel is achieved.

- The test arrangement according to Stage 4 prior to the void investigation should be used.
- An electrical potential / alternating current should be applied between the prestressing steel and the reinforcing steel and the electrical resistance should be measured in accordance with the instructions by the “Bundesamt für Strassenbau” and “Baudirektion GD/SBB” : Richtlinie für den Korrosionsschutz von Spanngliedern im Brückenbau (“Swiss Federal Highway Administration” and “Swiss Railways Administration” : Guidelines for the Corrosion Protection of Prestressing Tendons in Bridges) , [GD/SBB (1998)].

The electrical resistance test should be deemed acceptable if a resistance of not less than 1 kilo-Ohm is achieved. If acceptable to the client, this test may also be done on a tendon installed in an actual project.

### **4.3 System Documentation**

The system supplier should provide a full documentation of the system including :

- technical documents such as general assembly drawings of the system and detailed drawings of the components
- instructions for use and method statements covering the installation, stressing and grouting of the system
- quality assurance plan covering production, storage and installation of the system. The QA plan should also contain surveillance and maintenance instructions for the in-service period of the system.

### **4.4 System Approval**

It is recommended that component tests and the results of the system approval tests are certified by an independent approved body or testing laboratory before submission of the documents to an approval body for its assessment.

### **4.5 Site Verification Tests, Recommended Specification**

A written method statement and a system assembly drawing must be available on each construction site where the system is used. Conformance of the installation of the system with the approved method statement must be verified on site.

As an additional verification of a correct assembly of the proposed system on site in compliance with the system approval, the owner or his representative may require an air-pressure leak tightness test on site similar to the one described in Section 4.2.2, with a pressure of 0.1 bar.

A summary of all the requirements, methods of verification, and acceptance criteria for the plastic duct components and systems is attached in Annex A10. This may be used as a recommended specification for corrugated plastic ducts for bonded post-tensioning.

## 5 Recommended Use

The FIP Guide to Good Practice “Grouting of Tendons in Prestressed Concrete” published in 1990 emphasises the importance of corrosion protection of tendons, [FIP Guide to Good Practice (1990)]. In the introduction to that document it is noted that metal ducts do not constitute permanent corrosion protection. The use of polyethylene or polypropylene ducts is noted as providing good long term corrosion protection for the prestressing steel.

The temporary ban of the use of grouted ducts for internal post-tensioning in the United Kingdom in 1992 resulted in many countries examining their specifications for grouting and the overall corrosion protection systems for prestressing tendons. New specifications have evolved which require use of plastic (HDPE or PP) duct material in order to provide a corrosion resistant barrier and which require enhanced performance of the grout material, [TR 47 (1996)]. Introduction of these requirements has resulted in the lifting of the ban in the UK in 1996 and other countries are adopting this philosophy.

Many structures which use prestressing tendons are subject to severe environmental attack through de-icing salts or salt water. Water leakage through cracking and breakdown of the waterproofing membrane, and blocked or failed drainage, results in penetration of the contaminants to the tendon ducts. Metal ducting is not tight to resist water penetration which can thus reach the grout and then the tendons. If there are voids in the grout the corrosion process is easier and may be more rapid. The use of plastic ducting is recommended to give extra assurance as an additional protective layer, which will prevent contaminants penetrating the ducts and ensure more durable post-tensioned structures.

Plastic ducts have the following benefits:

- Enhanced corrosion protection.
- Low and more reliable friction coefficient, beneficial for longer tendons and circular tank construction.
- Reduced risk of fretting fatigue of the tendons.
- Possibility of electrical isolation of tendons from stray currents, which is a vital aspect for railway bridges.

Suitable uses of corrugated plastic ducts are for most structures of in-situ construction where the ducts can be properly joined and sealed for their entire length and a tendon encapsulation formed. This is particularly true for tendons which are placed close to the concrete surface, and close to potential environmental attack of de-icing salts, [GD/SBB, Final Draft (1998)].

Plastic ducts also contribute to an improved corrosion protection in precast segmental construction. However, sealing details at the segment joints need particular attention to form a complete encapsulation of the prestressing tendon. Indications are that epoxy resin in the segment joints may provide a good protection of the tendon, [J. S. West, et. al. (1996)]. In some cases O-ring seals have been used for added protection of the prestressing steel across the segment joints, however, their effectiveness has been challenged. At the time of writing this report, special connections to provide continuity of the plastic duct across segment joints are being developed by system suppliers.

Cracks and joints in concrete allow a path for contaminated water to reach internal ducts and these can occur either longitudinally or transversely to the tendons. These cracks may be simply a result of the design within permissible code limits, depending on the type of design. For example:

- Longitudinal cracks along longitudinal tendons in a transversely reinforced concrete deck slab.
- Transverse cracks along transverse tendons in the slab of a steel composite bridge. In both cases the cracks could run along the line of the ducts.
- Cracks normal to tendons are less likely, unless there has been unexpected loss of prestressing force e.g. due to restrained shortening of prestressed concrete, but could also provide free passage of water to the tendons.

In these cases plastic ducting should especially be considered. Where structural elements are prestressed in both directions and designed to be crack-free, there is less risk that metal ducting would be susceptible to corrosion and penetration. However, the extra cost of plastic ducting is small compared to the added benefits, or may even be compensated by reduced need for prestressing steel.

With the added protection provided, and with the additional durability testing according to Section 4.1.10 successfully passed, the designer may choose to design a prestressed concrete structure for serviceability criteria and crack widths specified and acceptable for reinforced concrete structures, instead of applying the more severe requirements for prestressed concrete, [FIP Recommendations (1998)].

The properties of HDPE and PP materials are quite well proven in engineering applications and have been tested by major suppliers for use as post-tensioning ducts, for bond, friction, wear etc., but designers should be aware of some properties which may affect aspects of design. These include :

- Minimum thickness of the duct is dependent on the radius of the tendon because the tendon bites (wear) into the duct and reduces the wall thickness during tensioning. Designers should be careful to specify suitable radii of curvature for the tendons.
- Typically plastic duct diameters are slightly greater than metal ducts for the same tendon size. This can affect minimum spacing of ducts and therefore member thickness.
- Tests have shown that corrugated plastic ducts have good bond transmission properties and therefore design for Ultimate Limit State can use the same assumptions of increase in tendon strain as for metal ducts.
- The bond of prestressing steel in plastic ducts is softer than in corrugated steel ducts. Therefore, the contribution of the cross section of the prestressing steel for crack distribution and for fatigue checks of the non-prestressed reinforcement should be assessed conservatively with the data provided in Clause 4.1.8, or should be neglected.

It has been queried that a gap could form between plastic duct and surrounding concrete due to the difference in the coefficients of thermal expansion of these materials. It has been confirmed by testing and analysis that this is not significant, [J. Kollegger (1994)]. Typically, grouting under pressure will compensate for such an initial minor gap.

## 6 References and Standards

### 6.1 References

“Steel strip sheaths for prestressing tendons - Terminology, requirements, quality control”, European Standard EN 523 (1997).

“Steel strip sheaths for prestressing tendons - Test Methods”, European Standard EN 524, Parts 1 to 6 (1997).

R. Saul, H.S. Svensson : “On the Corrosion Protection of the Stay Cables”, Stahlbau, Heft 6, Ernst & Sohn, pp 165-176 (1990).

F. Hunkeler, H. Ungricht, P. Matt ; “Korrosionsschäden an Spannstählen in Spanngliedern und vorgespannten Boden-und Felsankern” (Corrosion damage on prestressing steels in tendons and prestressed soil and rock anchors), Forschungsauftrag Bundesamt für Strassen (ASTRA) No 86/95, VSS, Zürich (Draft 1998).

H. R. Ganz : “Plastic ducts for enhanced performance of post-tensioning tendons”, FIP Notes 1997/2, The Institution of Structural Engineers, London, pp 15-18 (1997).

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

J. Kollegger : “Untersuchungen an einem Kunststoffhüllrohr für Spannglieder mit nachträglichem Verbund” (Investigations on a plastic duct for bonded post-tensioning), Bauingenieur 69, pp 1-10, (1994).

H. Cordes, M. Abel : “Bedeutung der Hüllrohre für die Qualität der Vorspannung mit nachträglichem Verbund” (The importance of ducts for the quality of bonded post-tensioning), Beton-und Stahlbetonbau 91, Heft 5, pp 110-114, (1996).

P. Marti : “Verbundverhalten von Spanngliedern mit Kunststoff-Hüllrohren” (Bond behaviour of post-tensioning tendons in plastic ducts), Report, Institute for Structural Engineering, ETH Zürich, 16 pp (1993).

“Durable Bonded Post-tensioned Concrete Bridges”, Technical Report No 47, The Concrete Society, Slough (1996).

FIP Technical Report “Tendons”, Federation Internationale de la Precontrainte, The Institution of Structural Engineers, London, 23 pp (1995).

FIP State of the art report “Tensioning of tendons : force-elongation relationship”, Federation Internationale de la Precontrainte, The Institution of Structural Engineers, London, 18 pp (1986).

H. Cordes, M. Abel : “Sheaths for bonded tendons in post-tensioned concrete structures”, FIP Symposium “Post-Tensioned Concrete Structures”, Proceedings, The Concrete Society, Slough, Vol. 1, pp 27-36 (1996).

M. Abel : “Zur Dauerhaftigkeit von Spanngliedern in teilweise vorgespannten Bauteilen unter Betriebsbedingungen” (On the durability of post-tensioning tendons in partially prestressed structures under in service conditions), Lehrstuhl und Institut für Massivbau der RWTH Aachen (IMB), Aachen (1996).



“Richtlinie für den Korrosionsschutz von Spanngliedern im Brückenbau” (Guidelines for the corrosion protection of post-tensioning tendons in bridge construction), Bundesamt für Strassenbau und Baudirektion GD/SBB, Final Draft (1998).

FIP Guide to Good Practice “Grouting of tendons in prestressed concrete”, Fédération Internationale de la Précontrainte, The Institution of Structural Engineers, London, 10 pp (1990).

J.S. West, R.P. Vignos, J.E. Breen “Corrosion Protection Tests of Internal Tendons Across Segmental Joints”, Abstracts of 1996 ASBI Convention, American Segmental Bridge Institute, Phoenix / AZ, 6 pp (1996).

FIP Recommendations “Practical Design of Structural Concrete”, Fédération Internationale de la Précontrainte, The Institution of Structural Engineers, London (1998).

## 6.2 Standards

This is a list of standards considered to be equivalent to the ones quoted in the text.

### 6.2.1 Polyethylene/Polypropylene: Current British Standards

ISO 1133	(1993)	BS 2782 Part 7 Method 720A (1979) - 10 pages Part 7 - Rheological Properties Method 720A - Determination of melt flow rate of Thermoplastics.
ISO 2039	(1996)	BS EN ISO 2039-1 (1997) - also numbered BS 2782 Part 3 Method 365D (1997) Part 3 - Mechanical Properties Method 365D - Plastics determination of hardness, ball indentation method.
ISO 179/1	(1993)	BS 2782 Part 3 Method 359 (1993) Part 3 - Mechanical Properties Method 359 - Determination of Charpy Impact Strength
ISO 8256	(1990)	BS 2782 Part 3 Method 354A (1991) Part 3 - Mechanical Properties Method 354A - Determination of Tensile Impact Strength
ISO 6252	(1992)	BS 2782 Part 8 Method 833A (1993) Part 8 - Other Properties Method 833A - Determination of Environmental Stress Cracking (ESC) by the Constant Tensile Stress Method
ISO 306	(1987)	BS 2782 Part 1 Methods 120A and 120C (1990) Part I - Thermal Properties Method 120A - Determination of Vicat Softening Temperature of Thermoplastics

Method 120C - Determination of the 1/10 Vicat Softening Temperature of Thermoplastics

DIN 53752	No comparable British Standard
DIN 53455	Similar to BS EN ISO 527-3 (1996) Previous BS 2782 Part 3 Method 326A - 326C Test Conditions for films and sheets
DIN 53479	Similar to BS 2782 Part 6 Method 620E (1980) Determination of Density of Liquid Resins by the Pycnometer Method.

### 6.2.2 Polyethylene/Polypropylene: Current ASTM Standards

ISO 1133	ASTM D 1238	Test Method for Determination of Melt Mass-Flow Rate
ISO 2039	ASTM D 738 ASTM D 224	Test Method for Determination of Hardness – Ball Indentation Method
ISO 179	ASTM D 256	Impact Resistance of Plastics and Electrical Insulating Materials (Charpy-Test, Notched Specimen)
ISO 8256	ASTM D 1882	Determination of Tensile Impact Strength ; Notched Specimen
ISO 6252	ASTM D 1693 ASTM F 1248	Test Method for Environmental Stress Cracking of Ethylene Plastics
ISO 306	ASTM D 1525	Determination of Vicat Softening Temperature
DIN 53752	ASTM D 696	Test Method for Determination of the Coefficient of Linear Thermal Expansion
DIN 53455, DIN 53457 (ISO 527)	ASTM D 638	Tensile Properties of Plastics
DIN 53479	ASTM D 792	Test Methods for Specific Gravity (Relative Density) and Density of Plastics by Displacement
DIN 16776	ASTM D 1248	Polyethylene Plastic Moulding and Extrusion Materials
DIN 16774	ASTM D 4101	Polypropylene Plastics Moulding and Extrusion Materials
	ASTM D 1603	Test Method for Carbon Black in Olefin Plastics

### **6.2.3 Polyethylene/Polypropylene: Other Standards**

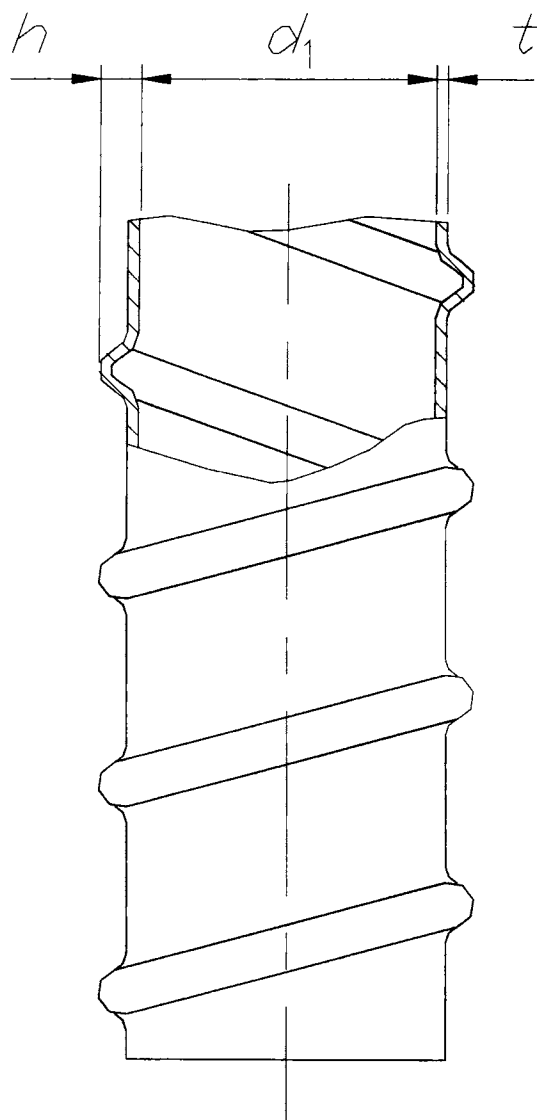
Some of the referenced standards are also available in other countries under local designations, or have local equivalent standards. This is e.g. the case in France with the following standards:

ISO 1133	NF T 51-016	Plastique. Détermination de l'Indice de fluidité à chaud des thermoplastiques, en masse (MFI) et en volume (MVI) – HOM Mars 1993
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## Annex A1 Dimensional Tolerance of Duct

### 1 Test specimen and measuring procedure :

A test specimen of duct with a length of approximately 500mm should be used. The internal diameter,  $d_1$ , should be determined by means of a vernier calliper (accuracy 0.1mm), see Fig. A1.1. Measurements should be taken at both ends of the specimen in two directions at right angles to one another. The mean values should be calculated from the values obtained. Actual and mean values should be recorded.



**Fig. A1.1 : Test specimen, definition of internal diameter  $d_1$**

## Annex A2 Flexural Behaviour of Duct

### 1 General

The flexural behaviour of ducts is characterised by their load / deformation curve when subjected to three-point-bending.

### 2 Specimen

A section of 1100 mm length of duct under consideration should be taken.

### 3 Procedure

The specimen should be subjected to three-point-bending as shown in Fig. A2.1 by increasing the load  $F$ . The distance between the supports should be 1000 mm.

### 4 Test results

The following results should be recorded :

- Load  $F$  at instantaneous mid-span deflection of  $f = 20$  mm,
- Load  $F$  after 2 minutes of mid-span deflection of  $f = 20$ mm,
- Instantaneous residual mid-span deflection,  $f$ , after release of load  $F$ ,
- Residual mid-span deflection  $f$ , 2 minutes after release of load  $F$ .

Dimensions in mm.

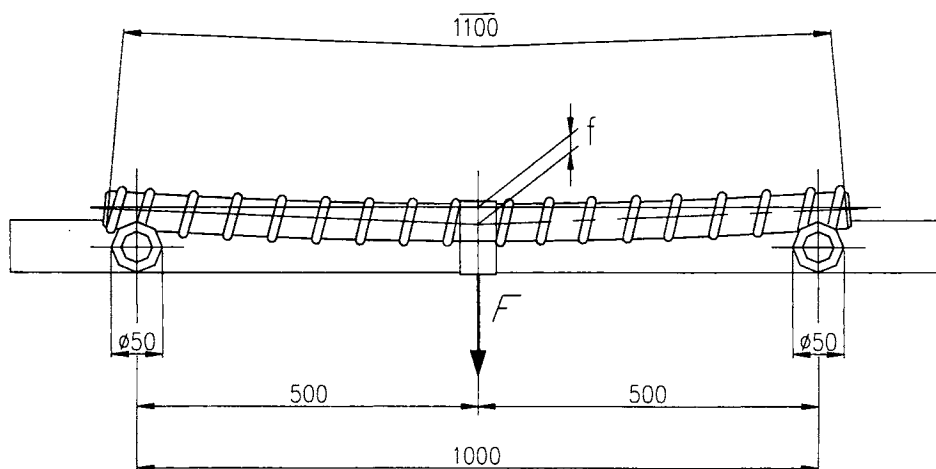


Fig. A 2.1 : Test specimen and loading

## Annex A3 Flexibility of Duct

### 1 Test set-up

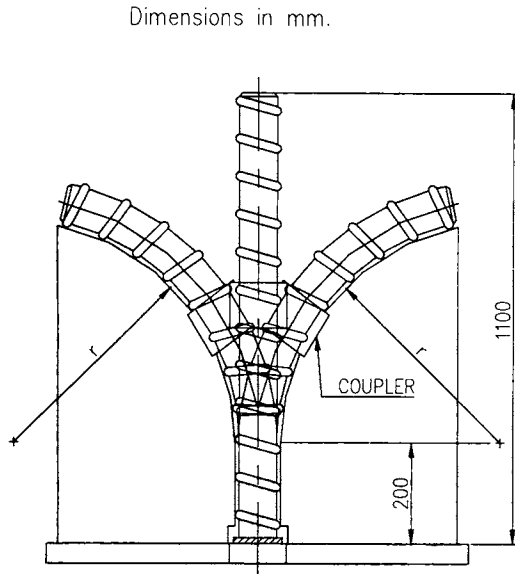
The test set-up consists of a duct specimen of 1100 mm length fixed at the centre of a base plate in an upright position in such a way that it will offer sufficient bending flexibility, see Fig. A3.1. The specimen should include one duct coupler placed at the centre of the specimen. Two curved templates which allow horizontal shift of the templates in relation to the surface of the fixed sheath are placed perpendicular to the base plate. The radius  $r$  of each bending template should correspond to the following values :

- Internal duct diameter  $d_1 \leq 85$  mm :  $r = 1500$  mm,
- Internal duct diameter  $d_1 > 85$  mm :  $r = 1800$  mm.

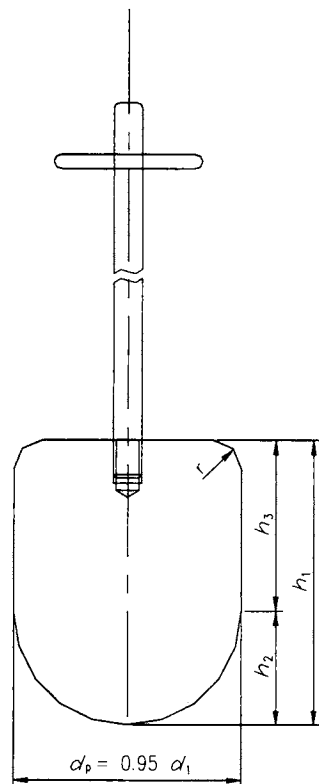
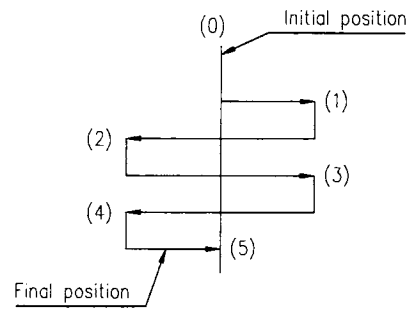
### 2 Procedure

The specimen should be bent slowly by hand to and from twice around each curved section of the templates (see figure A3.1) over a length of 800 mm. For the sequence of bending, see Fig. A3.2. While in the last bent position in either bending direction, a steel plunger with the shape and the dimensions given in Fig. A3.3 should be inserted and pass the specimen in the whole length, after the specimen has been held in the bent position for 2 minutes.

**Fig. A3.1 : Test set-up**



**Fig. A3.2 : Sequence of bending**



- $d_p$  = diameter of the plunger
- $d_1$  = nominal internal diameter of the duct
- $h_1 = 1,25 d_p$
- $h_2 = 0,5 d_p$
- $h_3 = 0,75 d_p$
- $r = 5 \text{ mm}$

**Fig. A 3.3 : Shape and dimensions of steel plunger**

## Annex A4 Lateral Load Resistance of Duct

### 1 Apparatus and accuracy

The following test equipment is required :

- a test machine or a suitable test frame with a hydraulic or mechanical drive,
- a load measuring device with an accuracy of 2% in 750N,
- a deformation measuring instrument, e.g. vernier calliper or micrometer gauge, with an accuracy of 0.1 mm.

### 2 Procedure

A 1100 mm long duct specimen is placed on a firm, 500 mm long base as shown in Fig. A4.1 and subjected to loading by means of a plunger provided with a cylindrical end with a diameter of 12 mm. Each test specimen has to be loaded twice in two different places between the ribs, where possible. The places of loading should be situated in the middle part of the specimen and should have a distance of 150 mm minimum from one another.

The time of load application should lie between 30 seconds and one minute. Immediately and 2 minutes after unloading, the smallest irreversible internal diameter of the sheath should be determined at each loading point, and should be recorded.

NOTE : This test may also be conducted using a stiffener if necessary.

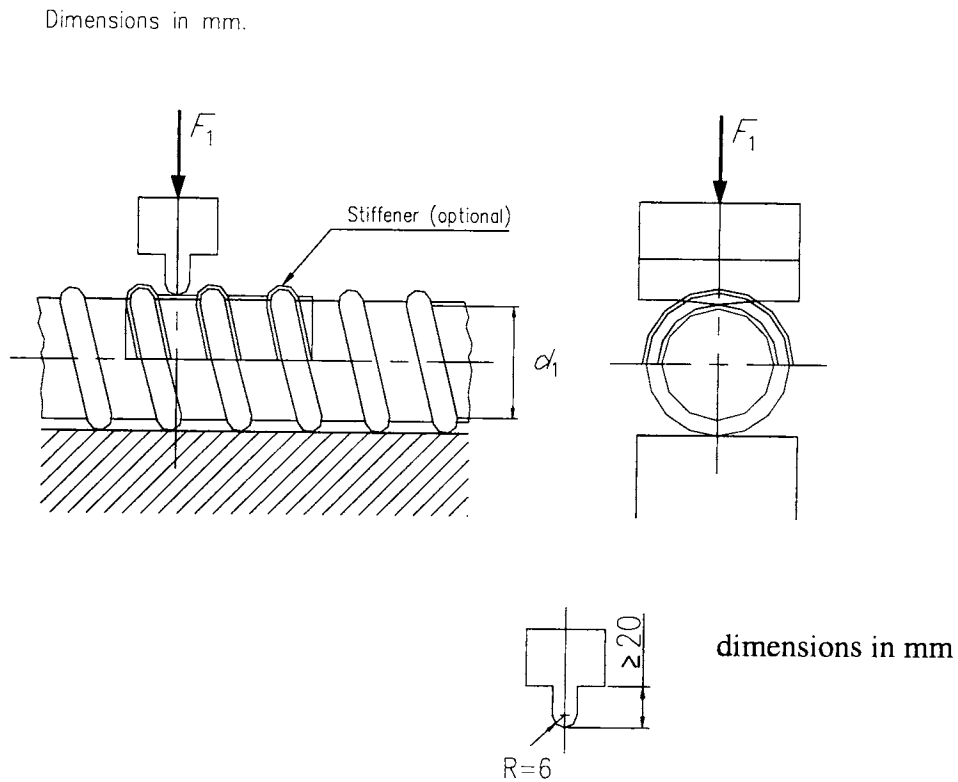
Where stiffeners are used (see Fig. A4.1) the size should not exceed half the circumference of the specimen and should have the same profile as the specimen.

The length of the stiffener should not exceed 1.5 times the nominal internal diameter  $d_1$  of the duct or 100 mm whichever is the greater.

The following loads should be applied to the specimens :

$d_1 \leq 25$ mm :	$F_1 = 500$ N,
$25$ mm < $d_1 \leq 35$ mm :	$F_1 = 600$ N,
$35$ mm < $d_1 \leq 55$ mm :	$F_1 = 750$ N,
$55$ mm < $d_1 \leq 85$ mm :	$F_1 = 950$ N,
$85$ mm < $d_1 \leq 130$ mm :	$F_1 = 1050$ N.





**Fig. A 4.1 : Test set-up, example with optional stiffener**

## Annex A5 Longitudinal Load Resistance

### 1 Apparatus and accuracy

The following test equipment is required :

- a testing machine or a suitable test frame with a hydraulic or mechanical drive
- a load measuring device with an accuracy of 2% within 750N
- a deformation measuring device such as folding rule.

### 2 Procedure

A 1100 mm long duct specimen should be connected to at least one duct coupler and/or connection to an anchorage, and be subjected to an applied elongation or an applied load as specified below over a period of 10 minutes (see Fig. A5.1). The applied deformation should be 8 mm/m of free duct length between connector and base ( $1100 \text{ mm} - l_1$ ). No internal stiffeners should be used. The displacement of the coupler or connection in relation to the duct, occurring under the applied elongation or load, should be measured. This value has to be recorded together with any unusual observations.

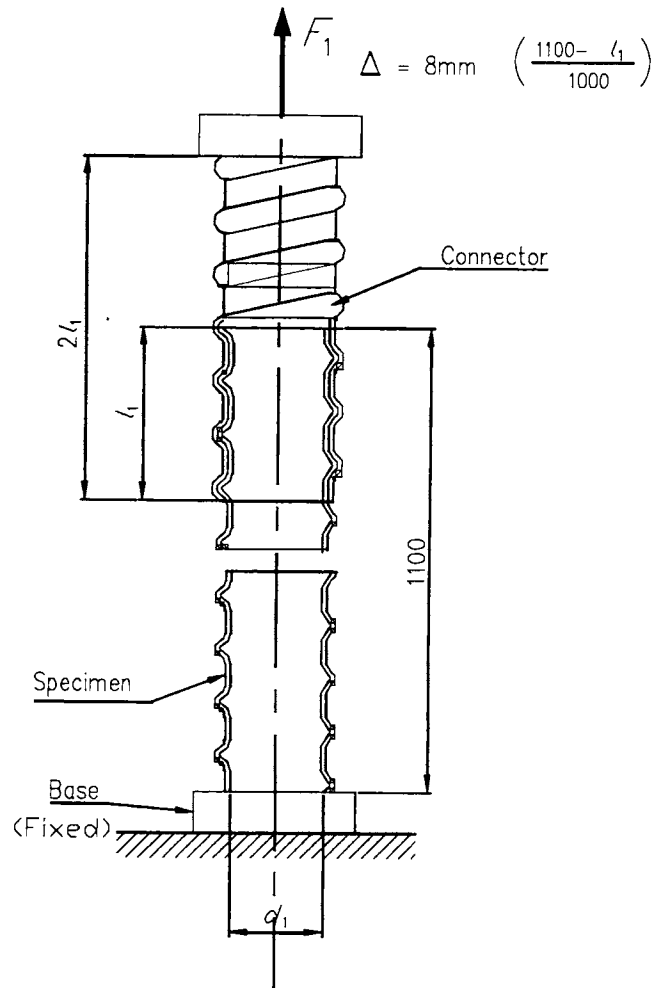
- Applied elongation :  $\Delta = 8 \text{ mm/m}$  of free duct length.  
(for general case)

Note : Corresponding loads  $F$  at the start and at the end of the 10 minutes loading period should be recorded.

- |   |  |                         |
|---|--|-------------------------|
| • Applied load :<br>(for cases where duct<br>is supplied on coil) | $d_1 \leq 25 \text{ mm}$                   | $F_1 = 250 \text{ N,}$  |
|   | $25 \text{ mm} < d_1 \leq 35 \text{ mm}$   | $F_1 = 400 \text{ N,}$  |
|   | $35 \text{ mm} < d_1 \leq 45 \text{ mm}$   | $F_1 = 600 \text{ N,}$  |
|   | $45 \text{ mm} < d_1 \leq 55 \text{ mm}$   | $F_1 = 900 \text{ N,}$  |
|   | $55 \text{ mm} < d_1 \leq 65 \text{ mm}$   | $F_1 = 1100 \text{ N,}$ |
|   | $65 \text{ mm} < d_1 \leq 75 \text{ mm}$   | $F_1 = 1400 \text{ N,}$ |
|   | $75 \text{ mm} < d_1 \leq 85 \text{ mm}$   | $F_1 = 1600 \text{ N,}$ |
|   | $85 \text{ mm} < d_1 \leq 100 \text{ mm}$  | $F_1 = 1900 \text{ N,}$ |
|   | $100 \text{ mm} < d_1 \leq 130 \text{ mm}$ | $F_1 = 2200 \text{ N.}$ |

Note : Corresponding elongation of duct at the start and at the end of the 10 minutes loading period should be recorded.

Dimensions in mm.



**Fig. A5.1 : Test set-up and loading**

## **Annex A6**    Leak Tightness of Duct System

### **1**        **Test procedure**

The test should be conducted on a 1100 mm long duct specimen which has previously been subjected to the tests required in Section 4.1.3, 4.1.4, and 4.1.5 including a connector but without re-assembly of duct/coupler connection. The duct specimen should be bent with a template as described in Annex A3, and shown in Fig. A3.1, to the minimum radius of tendon curvature specified by the system holder including an allowance for specified duct placement tolerances on tendon supports further reducing the bending radius.

The specimen should be pressure tested with water applied under a pressure of 0.5 bar (50 kPa) by adequate equipment (e.g. by sealing at both ends and inducing air pressure) over a period of 5 minutes. The water pressure should first be applied on the inside of the duct. Subsequently, the water pressure should be applied from the outside of the duct.

### **2**        **Observations**

Any leakage of water from inside out or from outside into the duct should be recorded, and the location of leakage noted.

## **Annex A7     Wear Resistance of Duct**

### **1            Test specimen**

The test specimen consists of two strips of plastic duct, cut out of an actual duct. The wall thickness of the strip should be measured in at least six locations and the values recorded. The strips are then cast each into a sufficiently rigid supporting body to suit the test frame. The strip of duct should be cut such as to consist of  $\frac{1}{8}$  of the duct circumference (45 out of 360 degrees) and have a length of a full multiple of rib/corrugation spacing of not less than 100 mm total length. The test specimen is shown in Fig. A7.1.

### **2            Apparatus and accuracy**

The following test equipment is required :

- a testing machine or a suitable test frame with a hydraulic or mechanical drive to stress one element of prestressing steel of at least 1m free length to 70% of its tensile strength
- a device, e.g. a centre hole jack, to move the test specimen along the prestressing steel
- a hydraulic jack or mechanical device to press the test specimen consisting of two strips against the prestressing steel, and a load cell to confirm the clamping force with an accuracy of 2% in 10kN
- a deformation measuring instrument, e.g. vernier calliper or micrometer gauge, with an accuracy of 0.1 mm to measure the wall thickness and wear of the duct.

### **3            Procedure**

The two duct strips mounted each in a supporting body should be installed on opposite sides across the diameter of the prestressing steel. The prestressing steel should be stressed to a force  $F$  of 70% of its tensile strength. The specimen consisting of the two strips should then be clamped by means of the hydraulic jack or mechanical device to the prestressing steel with a force  $Q$ . The specimen should then be moved along the prestressing steel over a total distance of 750 mm while maintaining the clamping force without allowing the specimen to rotate around the strand (see Fig. A7.2). The movement should be accomplished in a time frame of about 2 minutes after applying the clamping force. After the specimen has reached its final position it should be held in this position while maintaining the clamping force for another 3 minutes. The clamping force  $Q$  should then be released.

After completion of the test, the specimen should be released, the strips removed from the supporting body, and the remaining wall thickness should be measured immediately at the same locations where initial thickness measurements were made, and at the locations deemed to have the minimum remaining wall thickness. All these measurements should be recorded.

The clamping force for the test may be determined with the following equation :

$$Q = 0.7 f_{tk} \cdot A_p \cdot k \cdot l / R_{min}$$

$f_{tk}$  = specified characteristic strength of prestressing steel

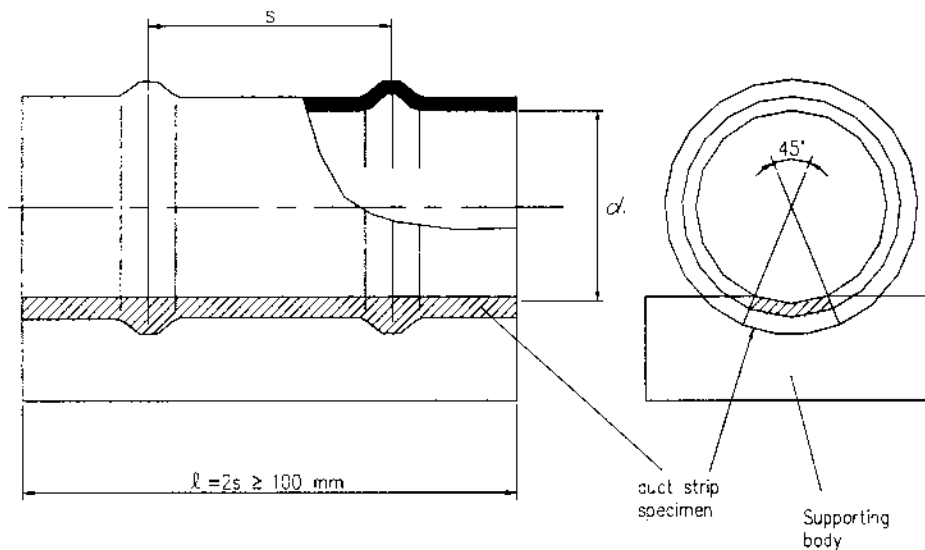
$A_p$  = specified cross section of a single tensile element of prestressing steel (e.g. strand)

$k$  = cable factor to account for effect of actual number  $n$  of tensile elements (e.g. strand) inside one duct, according to Fig. A7.3, or equivalent methods

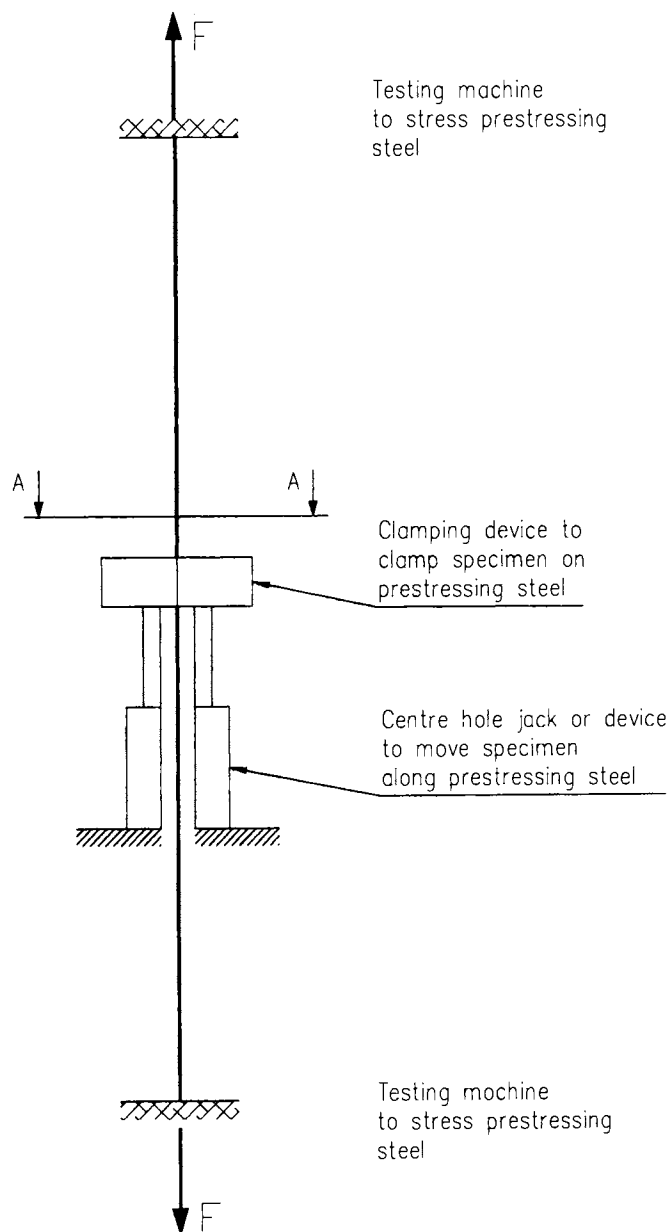
$l$  = length of specimen, according to Fig. A7.1

$R_{min}$  = minimum radius of curvature of tendon specified in the system documentation.

Note : Test set-up using one duct strip mounted in a supporting body and pressed from one side against the prestressing steel are considered equivalent to the above described. In such a set-up two strips should be tested one after the other and wall thickness in both strips should be measured as described above.

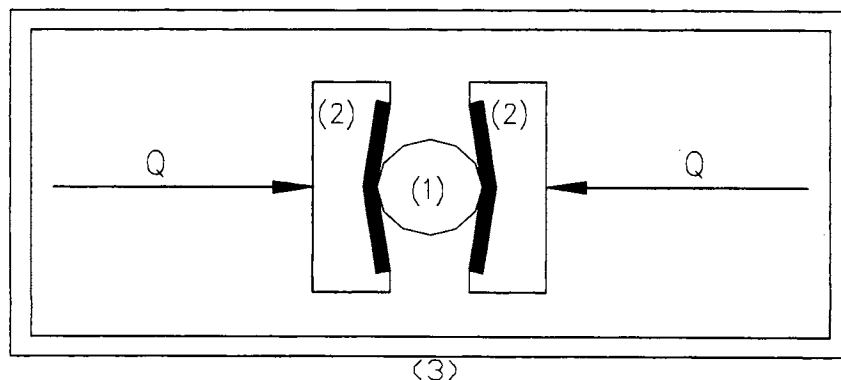


**Fig. A7.1: Test specimen  
(one strip shown only)**

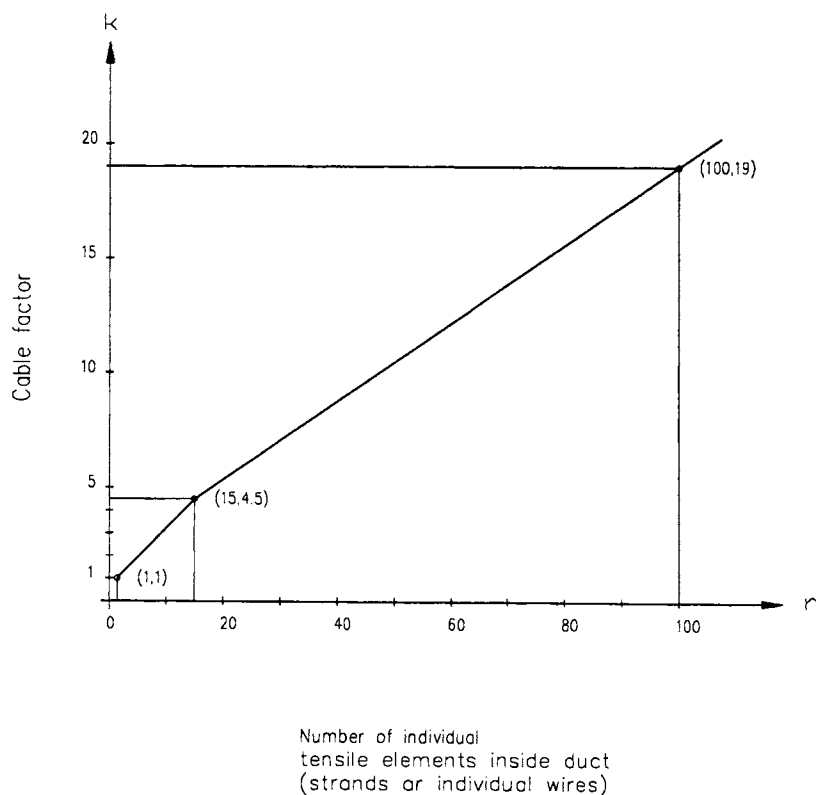


**Fig. A7.2: Test set-up**

## Section A-A, Detail:



- (1) Prestressing steel element.
- (2) Specimen mounted in supporting body.
- (3) Frame applying clamping force, including load cell.

**Fig. A7.2 : Test set-up (continued)****Fig. A7.3: Cable factor**



## Annex A8 Bond Behaviour of Tendon

### A 8.1 Bond element test

#### 1 Test specimen

The test specimen is schematically shown in Fig. A8.1. The specimen should contain the tendon duct of nominal internal diameter  $d_i$ , which will be embedded in the structural concrete away from the tendon anchorage and the prestressing steel grouted into the duct. Their arrangement and properties have to comply with the intended application and with the system documentation.

The test specimen should be a concrete cube, adequately reinforced to avoid bursting, with a side length equivalent to 10 times the equivalent diameter  $d_b$  of the tendon. The length  $l_b$  over which the tendon is bonded to the specimen should be 5 times the equivalent diameter  $d_b$  of the tendon.

$$d_b = \sqrt{\frac{4A_p}{\pi}}$$

$A_p$  = total cross section of prestressing steel in tendon.

The concrete of the test specimen should correspond to normal concrete used for prestressed concrete structures with respect to materials, composition, compaction and its characteristic strength  $f_{ck}$ . The concrete specimen should be cast with horizontal tendon duct position. After casting the specimen should be de-moulded after one day and then moist cured until testing. The cylinders or cubes cast for the determination of the compressive strength of concrete should be treated similarly.

Prestressing steel, duct, and grout used for the test should comply with the system documentation. Grouting should be done according to the specification, after the specimen has reached a sufficient strength to resist the grouting pressure. Grouting pressure should be between 0.1 MPa and 0.5 MPa. Prestressing steel should be evenly spaced and centred inside the tendon duct during grouting. Prisms cast for the determination of the compressive strength of grout should be treated as given above for the concrete.

The following data should be established particularly for this test :

- the main geometrical properties of the prestressing steel and duct
- surface characteristics of prestressing steel and duct.

If more than one grade of prestressing steel of the same type is to be used with the same type of duct and grout, the tests should be performed using the grade with the highest characteristic tensile strength, and/or largest load capacity.

## 2 Procedure

The specimen should be mounted in a calibrated test rig or testing machine with the support surface resting against a reaction frame. The load should be applied to the specimen by loading the prestressing steel at the end away from the bonded length.

The force in the prestressing steel should be increased steadily at a rate corresponding to a bond stress increase of 0.03 MPa / second until maximum tendon load is achieved. Further loading should continue at a uniform displacement rate per time equivalent to the one measured at maximum load, until complete bond failure of the tendon.

Bond stresses  $\tau_b$  should be evaluated as follows :

$$\tau_b = \frac{F}{l_b \times p_b} \quad \text{with} \quad p_b = \pi \cdot \Phi \quad \text{for a bar of diameter } \Phi$$

$$p_b = 6 (\pi - 3 + \sqrt{12m - 3}) \sqrt{\frac{A_p}{7\pi \cdot m}} \quad \text{for } m \text{ 7 - wire strands}$$

$$p_b = 2 (\pi - 3 + \sqrt{12m - 3}) \sqrt{\frac{A_p}{\pi \cdot m}} \quad \text{for } m \text{ single wires}$$

The specimen should be tested at the time when the grout has achieved the minimum required strength as per the system documentation. At that time, the concrete should have reached or exceeded its specified strength, or a minimum of 35 MPa cube strength.

The following measurements should be made and recorded :

- displacement of tendon  $\Delta l$ , grout  $\Delta M$ , and specimen  $\Delta B$  at the free end as a function of load
- displacement of the tendon  $\Delta S$ , and specimen (if any) at the loaded end as a function of load
- formation, width, and propagation of cracks in specimen, if any
- location and mode of failure
- ultimate load F.

The nominal internal diameter of the duct  $d_1$  as well as the parameters  $d_b$ ,  $l_b$  and  $p_b$  should be recorded in the report.

Fig. A8.2 schematically shows the arrangement of the deformation gauges.

Fig. A8.1 : Test specimen for bond element test

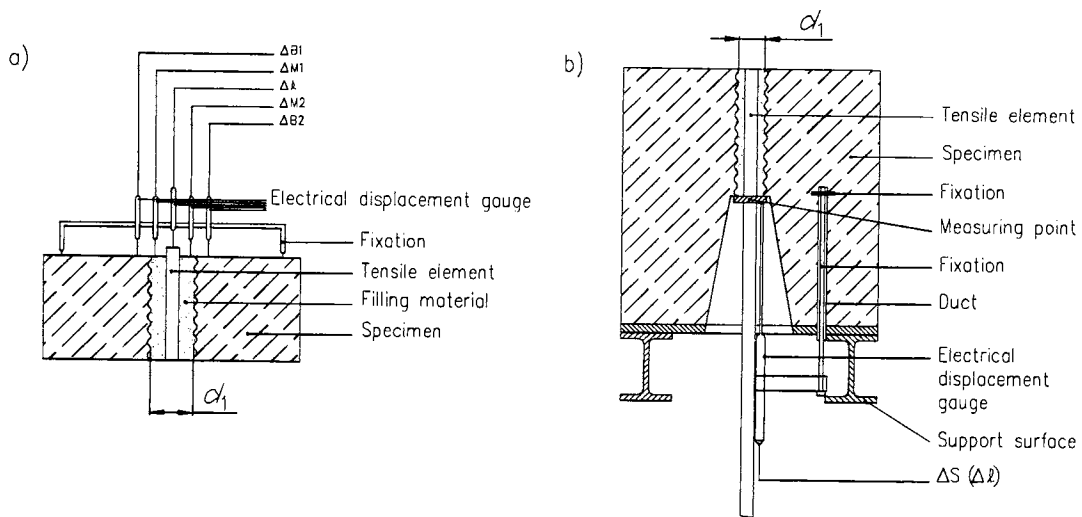
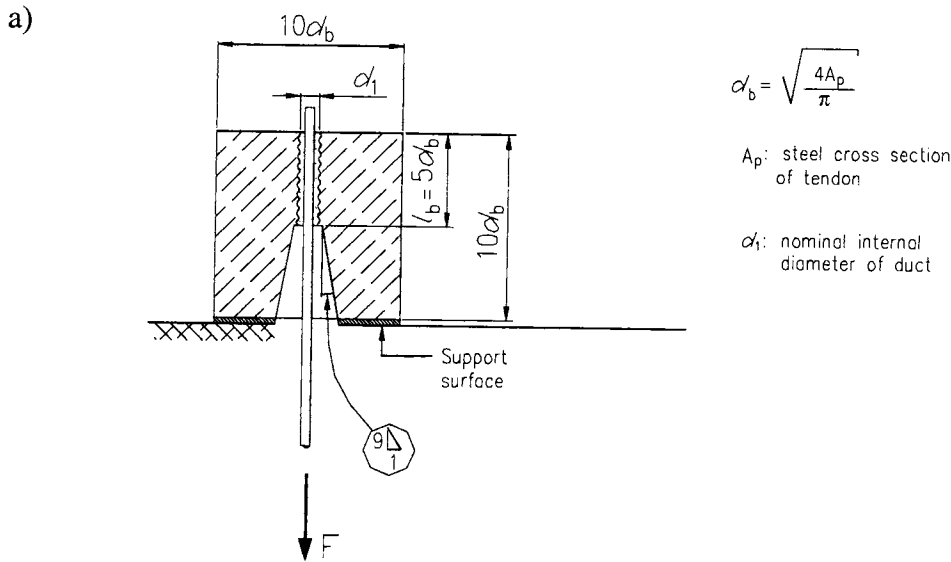


Fig. A8.2 : Measuring set-up for bond test

## A 8.2 Bond length test

### 1 Test specimen

The test specimen is schematically shown in Fig. A8.3. The specimen should contain the tendon duct of nominal internal diameter  $d_1$ , which will be embedded in the structural concrete away from the tendon anchorage and the prestressing steel grouted into the duct. Their arrangement and properties have to comply with the intended application and with the system documentation.

The test specimen should be a concrete beam with a side length equivalent to the minimum centre spacing of anchorages for the particular tendon size. The length  $l_b$  over which the tendon is bonded to the specimen should not be less than the bond length specified by the system holder for the tendon.

The free length  $l_f$  of the tendon should permit installation of an anchorage concrete block with all components necessary for anchoring the tendon, and a stressing jack with a maximum force larger than the actual breaking force of the tendon.

The concrete of the test specimen should correspond to normal concrete used for prestressed concrete structures with respect to materials, composition, compaction and its characteristic strength  $f_{ck}$ . The concrete specimen should contain reinforcing steel to limit cracking, which however, should not be considered part of the approval. The concrete specimen should be cast with horizontal tendon duct position. After casting the specimen should be de-moulded after one day and then moist cured until testing. The cylinders or cubes cast for the determination of the compressive strength of concrete should be treated similarly.

Prestressing steel, duct, and grout used for the test should comply with the system documentation. Grouting should be done according to the specification, after the specimen has reached a sufficient strength to resist the grouting pressure. Grouting pressure should be between 0.1 MPa and 0.5 MPa. Prestressing steel should be evenly spaced and centred inside the tendon duct during grouting. Prisms cast for the determination of the compressive strength of grout should be treated as given above for the concrete.

The following data should be established particularly for this test :

- the main geometrical properties of the prestressing steel and duct
- surface characteristics of prestressing steel and duct.

If more than one grade of prestressing steel of the same type is to be used with the same type of duct and grout, the tests should be performed using the grade with the highest characteristic tensile strength, and/or largest load capacity.

### 2 Procedure

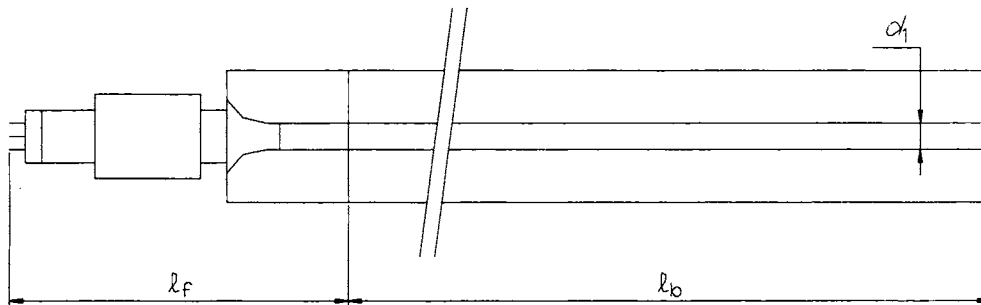
The specimen equipped with the anchorage concrete block and the stressing jack should be installed in a horizontal position. The tendon should be loaded gradually in increments of force in a minimum of four load steps until reaching failure of the tendon.

The specimen should be tested at the time when the grout has achieved the minimum required strength as per the system documentation. At that time, the concrete should have reached or exceeded its specified strength, or a minimum of 35 MPa cube strength.

The following measurements should be made and recorded :

- displacement of tendon  $\Delta l$  of at least 4 prestressing steel extremities, grout  $\Delta M$ , and specimen  $\Delta B$  at the free end at each load step
- formation, width, and propagation of cracks in specimen, if any
- location and mode of failure
- ultimate load  $F$ .

The nominal internal diameter of the duct  $d_1$  as well as the parameters  $l_b$  and  $l_f$  should be recorded in the report. Jack and tendon characteristics should also be recorded.



**Fig. A8.3 : Test specimen for bond length test**

## **Annex A9** System Approval Testing

### **1 Test specimen**

The test specimen should consist of a prismatic beam of minimum 30 m long and 1.5 m high. This beam and the associated tendon profile should represent an end span in a continuous beam including a portion of the first interior span. The tendon axis is defined by two second order parabolas through the anchorage in the end span, the low point in the end span, the transition point of the parabolas, and the high point at the fictitious support. The connection of the second transition point to the end coupler or anchorage may be straight. At the high point, the tendon should be curved to the specified minimum radius of curvature in accordance with the system documentation. The tendon profile should include intentional misalignment at tendon supports within limits specified in applicable Technical Specifications and/or the system documentation by introducing at low point and high point on consecutive tendon supports the following intended misalignment : 0, - max, + max, 0. The beam and tendon profile are schematically shown in Fig. A9.1.

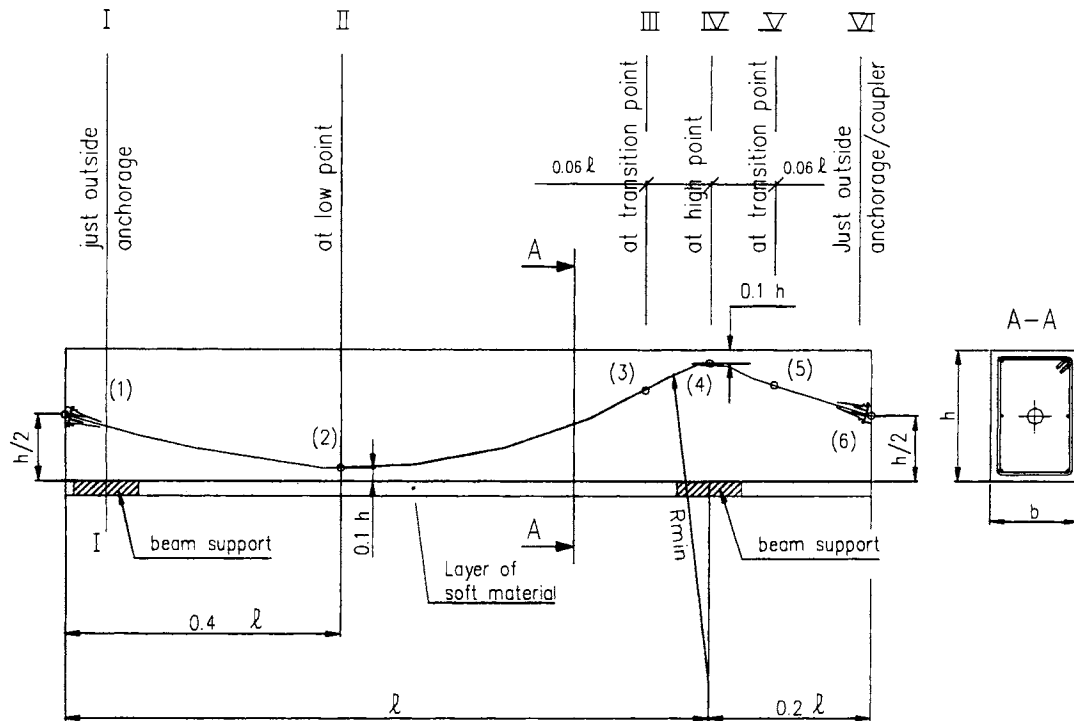
The specimen should include tendon components in accordance with the system documentation for installation, stressing and grouting.

The specimen should be reinforced in accordance with the applicable standards, and should contain anchorage bursting reinforcement in accordance with the system documentation.

### **2 Test procedure**

As per clauses 4.2.1 to 4.2.5.

Observations should include “as built” drawings of the specimen, including tendon profile and particular tendon details. A photographic documentation of each test stage should be made.



- (1) End anchorage
- (2) Low point
- (3) Transition point of parabolas
- (4) High point
- (5) Transition point of parabolas
- (6) End coupler or anchorage

Dimensions :

$l = 25\text{m}$

$h = 1.5\text{m}$

$b =$  twice the specified minimum edge distance of anchorage, but not less than  $0.5\text{m}$

I to VI: Indicates location where cores shall be taken for verification of grouting and wear of duct

**Fig. A9.1 : Test specimen**

## Annex A 10 : Summary of Requirements, Method of Verification, and Acceptance Criteria for Plastic Ducts – Recommended Specification

Requirement	Method of Verification	Acceptance Criteria	Notes for Guidance
<p><b>Component Testing</b></p> <p>4.1.1 Definition of Components</p>	<p>Data Sheets Assembly Drawings Material Certificates  Tolerance of diameter, Annex A1</p>	<p>Existence of data sheets Existence of assembly drawings Compliance with material specification, Table 3.1 <math>\pm 1\%</math> or <math>\pm 0.5</math> mm (larger limit governing)</p>	<p>Data Sheets should be presented in system supplier's information package Assembly drawings should be presented in system supplier's information package Material test results should be presented in system supplier's information package</p>
<p>4.1.2 Flexural Behaviour of Duct</p>	<p>Flexural test, Annex A2</p>	<p>Document load @ 20 mm deflection and after unloading Friction parameters satisfactory Rigidity satisfactory to retain duct profile during concreting</p>	<p>Site test as per 4.1.9 Generally it would be expected that the duct should be rigid enough not to be displaced from profile by more than about 10mm between each duct support.</p>
<p>4.1.3 Flexibility of Duct</p>	<p>Flexibility test, Annex A3</p>	<p>No visual damage, deformation of cross section <math>\leq 5\%</math></p>	<p>Duct has to be flexible enough to be able to be bent to profile</p>
<p>4.1.4 Lateral Load Resistance of Duct</p>	<p>Lateral Load test, Annex A4</p>	<p>Transverse deformations <math>\leq 10\%</math> or 5mm whichever is lesser</p>	<p>Duct must not be deeply indented at supports</p>
<p>4.1.5 Longitudinal Load Resistance of Duct System</p>	<p>Longitudinal Load test, Annex A5</p>	<p>Sustain 8 mm/m elongation or specified load for 10 minutes</p>	<p>No slippage or failure of duct/coupler connection</p>
<p>4.1.6 Leak Tightness of Duct System</p>	<p>Leak Tightness test, Annex A6</p>	<p>No visually detectable leaks with positive or negative pressure</p>	<p>Test for duct plus one duct connector</p>



4.1.7	Wear Resistance of Duct	Wear Resistance test, Annex A7	$\geq 1$ mm residual wall thickness	Residual thickness after tensioning
4.1.8	Bond Behaviour of Tendon	Bond test, Annex A8	Measured values satisfy specified values Measured values in typical range	Applies to coefficient of friction and wobble factor
4.1.9	Friction Parameter	Site tests (lift-off)	Confirmation of specified values and within range	
4.1.10	Special Durability/Corrosion Protection (optional)	Customised tests see [H. Cordes, M. Abel (1996)], [H. Cordes, M. Abel (1996)], [M. Abel (1996)]	System remains intact for specified life for crack width of 0.3-0.5 mm	
4.2.1	<b>System Testing</b> Full Scale Assembly	Assembly test, Annex A9	Successful assembly as specified	
4.2.2	Leak tightness	Leak tightness tests at 0.1 bar	Pressure loss not more than 10% in 5 minutes	
4.2.3	Stressing/Friction (if deemed necessary)	Stressing/Friction test	Measured values within expected range	
4.2.4	Grouting (if deemed necessary)	Grouting test	No voids exceeding 5% of duct diameter	Other parameters of grout to satisfy current National Standards – not covered by this document
4.2.5	Electrical Resistance (optional)	Electrical Resistance test [GD/SBB (final draft 1998)]	Resistance $\geq 1$ kilo-Ohm	Requirement if specified for particular application