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Acceptance of post-tensioning systems for cryogenic applications

Recommendation

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Acceptance of post-tensioning systems for cryogenic applications

Recommendation

Task Group 5.6

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Preface

These *fib* recommendations are concerned with the acceptance of post-tensioning systems to be used in cryogenic tanks and have been formulated on the basis of actual available knowledge with the aim to reflect the current state of the art. The recommendations are meant to be applicable for all type of on-shore cryogenic tanks such as single containment, double containment, full containment and membrane containment and where post-tensioning could be installed, regardless whether the post-tensioning tendon is never subjected to low temperatures or only subjected during an accidental event or permanently.

Since the Second World War the demand of energy has undergone an exponential growth that has led to a sharp annual increase in the use of natural gas in both, cities and thermal power stations. Nowadays, the strategic relevance of natural gas as a main source of energy is evident with a contribution of more than 20% of the total world consumption. This development in increasing demand of natural gas has led for a need of suitable storage and transportation infrastructure.

This new bulletin presents technical guidelines regarding testing, assessment, installation, inspection and maintenance of post-tensioning systems to be used on on-shore cryogenic tanks, which either during service conditions or in the case of an accident might be subjected to the effect of very low temperatures. The essential subjects include:

- Typology of cryogenic tanks used across history and their associated relevant standard. The information is complemented with new graphical information for each cryogenic tank type which is lately used as a reference to introduce the respective type of cryogenic post-tensioning tendon.
- Types of post-tensioning tendons depending on the cryogenic tank and its exposure to low temperatures, i.e., never, accidentally or permanently, respectively type 0, 1 or 2. The information is complemented with a recommendation of the applicable type of post-tensioning tendon type depending on the cryogenic tank and its location in the structure.
- Loads, design and detailing of post-tensioning tendons in cryogenic tanks.
- Requirements for materials associated to the type of exposure to low temperatures
- Testing requirements for post-tensioning systems in accordance with the different types of post-tensioning tendons and their exposure to low temperatures plus the concept of system qualification temperature.
- Installation and qualification of companies and personnel.
- Inspection, maintenance and repair.
- Assessment and verification of constancy of performance.

We would like to express our sincere thanks to the international working group comprised of more than 20 experts from administrative authorities, universities, laboratories, owners, structural designers, suppliers of prestressing steels and post-tensioning systems suppliers who actively contributed to the development these recommendations under the leadership of co-conveners Dr. Antonio Caballero and Dr. Alex Gutsch. We would also like to specifically acknowledge the contributions of the Task Group 5.6 members whose dedication and hard work made this important work possible. Finally, we would to express our appreciation for the detailed final review by Mr. Gordon Clark and Mr. Jan Piekarski.

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1. Introduction

Since the Second World War the demand of energy has undergone an exponential growth that has led to a sharp annual increase in the use of natural gas in both, cities and thermal power stations. Nowadays, the strategic relevance of natural gas as a main source of energy is evident with a contribution of more than 20% of the total world consumption. This development in increasing demand of natural gas has led for a need of suitable storage and transportation infrastructure.

Various gases, especially hydrocarbons, are preferably stored in liquid form for transportation and storage since the phase transformation from gas to liquid comes with a significant reduction of the volume (e.g. up to 600 times). Gases can be liquefied by raising the pressure or by cooling to their boiling point, which for most gases is below 0°C. This is known as cryogenic storage. The term cryogenic is derived from two Greek words, namely *kryos* meaning icy-cold and *genes* which can be translated as shape.

This *fib* recommendation is concerned about post-tensioning systems used in cryogenic tanks and has been formulated on the basis of actual available knowledge with the aim to reflect the current state of the art. Consequently, this recommendation has included a classification of the different cryogenic tanks typologies used in the past and nowadays, the associated different tendon types depending on their exposure to low temperature (e.g. never, only accidentally or during normal tank operation) and the testing regime required for acceptance of the materials and the post-tensioning system according to this document.

An international working group comprising more than 20 experts from administrative authorities, universities, laboratories, owners, structural designers, suppliers of prestressing steels and post-tensioning systems suppliers have actively contributed in order to develop this recommendation. This text has been written to cover best construction practices around the world, and to provide material specifications which are considered to be the most advanced available at the time of preparing this text. For ease of use (for Owner, Designer and Post-tensioning System Supplier), the content has been arranged systematically according to the system components into chapters focusing on performance characteristics, requirements and acceptance criteria.

References are provided with a separate section on standards.

2. Scope of the document

This document has been developed to give technical guidelines regarding testing, assessment, installation, inspection and maintenance of post-tensioning systems to be used on on-shore cryogenic tanks, which either during service conditions or in the case of an accident might be subjected to the effect of very low temperatures.

These recommendations are meant to be applicable for all type of on-shore cryogenic tanks such as single containment, double containment, full containment and membrane containment and where post-tensioning could be installed, regardless whether the post-tensioning tendon is never subjected to low temperatures or only subjected during an accidental event or permanently.

The main subject of these recommendations is internal post-tensioning systems with prestressing steel in the form of strand or wires. Although not typical, post-tensioning bars might also be found in cryogenic structures where they could be exposed, either short or long term, to very low temperatures. Post-tensioning bars are not covered in this document.

This document does not cover the technologies of wire-wrapping or strand-wrapping systems. These types of systems have been considered outdated and unable to provide enough structural redundancy and multiple corrosion protective layers.

The essential subjects are:

- Typology of cryogenic tanks
- Types of post-tensioning tendons depending on the cryogenic tank and its exposure to low temperatures, i.e. never, accidentally or permanently
- Loads, design and detailing of post-tensioning tendons in cryogenic tanks
- Requirements for materials
- Testing requirements for post-tensioning systems in accordance with the different types of post-tensioning tendons and their exposure to low temperatures
- Installation and qualification of companies and personnel
- Inspection, maintenance and repair
- Assessment and verification of constancy of performance

3. Definitions and symbols

For the purpose of this document, the following terms, definitions and symbols apply.

3.1 Definitions

This section provides selected definitions of specific terms used in this report.

Table 3-1 Definitions of specific terms

Terms	Definition
Accessories	Auxiliary components used in a PT system to facilitate installation, stressing, and duct filling such as duct vents, duct drains, specific tendon support devices, temporary or permanent caps at anchorages and couplings, connectors for duct lengths/sections or for ducts to anchorages, etc
Actual Ultimate Tensile Strength (AUTS)	Actual ultimate tensile strength is given by the mean value of the measured tensile strength of the tensile elements from a minimum of 3 single static tests
Anchor Head	Part which holds one or several tensile elements by wedges / button heads and transfers the prestressing load to the bearing plate in contact or embedded in the concrete structure, or for small tendon sizes directly into the structure. The anchor head is sometimes called “wedge plate” or “anchor block”
Anchorage	A mechanical device, usually the assembly comprising several components, designed to retain the load in the stressed tendon, and to transfer the prestressing load to the structure
Anchorage Cap	A metallic or plastic cap to encapsulate the end of the tensile elements at the anchorage
Anchorage Component, PT System Component	Part of the anchorage or coupling such as wedge/button head, anchor head, bearing plate or trumplate, and/or trumpet
Anchorage Zone, Local Zone	Local zone in the structure through which the prestressing force is transferred to the structure via the anchorage
Assessment Body	An official body that performs one or several elements of technical assessment in order to issue assessment/approval certification for a post-tensioning system. Assessment body is sometimes recognized as approval body
Bearing Plate, Trumplate, Load Transfer Element	Part which supports the anchor head and transfers the prestressing load onto or into the structure
Bonded Post-Tensioning System	Post-tensioning system comprising all components in which the tensile elements are positioned inside of a duct and are permanently bonded to the surrounding concrete by the in situ cementitious grout applied after tendon stressing
Bursting Reinforcement	Reinforcement in the local anchorage zone, just adjacent to the anchorage, to confine the concrete, and to resist transverse tensile loads due to the introduction of the prestressing load. This reinforcement forms part of the post-tensioning system

This chapter was mainly authored by Caballero, Gnägi, Manshadi, Zivanovic.

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Terms	Definition
Characteristic Tensile Strength	Minimum guaranteed ultimate tensile strength value of tensile elements
Certification Body	An official body that performs one or several elements of conformity assessment by auditing of post-tensioning supplier to ensure compliance with the issued approval
Component Manufacturer	Company, which manufactures components of the post-tensioning system according to the specifications of the system owner
Connector	Special element to join individual duct lengths/sections between each other or to join a duct segment to the anchorage
Construction Contract	An agreement between two or more parties to execute the construction works as per certain terms and conditions
Container / Containment	A steel or reinforced concrete structure which is a tight shell for storage of liquids and gas
Coupler	A device to join adjacent sections of tendons
Corrosion Protection	Techniques used to protect steel components of post tensioning system e.g. tensile elements and anchor head against corrosion
Cryogenic Condition	The condition at which a post-tensioning tendon is subjected, accidentally or permanently, to a temperature lower than -40 °C
Cryogenic Tank	A specialized type of storage tank used for the storage of gases that have been cooled down to a temperature between 0 °C and -165 °C for ease and safety of non-pressurized storage and transport
Design Engineer	The engineer responsible for the permanent work design and engineering during construction of the structure. The exact scope of work and role vary according to project
Design Temperature	The lowest temperature at which system/structure may be subjected to
Duct (Sheathing)	An enclosure in which one or several tensile elements are placed and which temporarily or permanently allows relative movement between the tensile elements and the surrounding concrete. The remaining void within the duct can subsequently be filled with filling material
Ductility	Ability of a material to undergo permanent deformation through elongation (reduction in cross-sectional area) without fracturing while loading is increasing
Ductile Failure	A type of fracture characterized by extensive plastic deformation or "necking"
Filling Material, Filler, Flexible Injection Material	A material used to completely fill the space around the tensile elements inside a duct to provide corrosion protection and bond (if applicable)
Fixed-End (Passive) Anchorage	Anchorage which does not allow stressing, or anchorage formed by bond between tensile elements and concrete (bond anchorage)
Fixed Coupling	Coupling which allows joining of adjacent tendon section stressed not at the same time
Inlet / drain / vent	Tube or hose which permits either to inject the tendon or drain the water and vent/purge the air/grout from the duct of tendon profile
Internal Post-Tensioning System	Arrangement of tendon and anchorages embedded in the concrete structures to apply post-tensioning

Terms	Definition
Loop Tendon	A symmetric tendon composed of two vertical straight parts and a curved section with tight radius at the bottom. This tendon is often used when there is no access to the dead end anchorage – e.g. vertical post-tensioning in tanks and silos
Mean Concrete Compressive Strength	Mean value of the measured compressive strength of concrete determined from a minimum of 3 compression tests
Pipe	A thick walled smooth duct made of plastic or steel
Post-Tensioning Load, Post-Tensioning Force	The prestressing force introduced into the structure by stressing the post-tensioning tendon
Post-Tensioning System Supplier	Company, which supplies components of the post-tensioning system according to the specifications of the system owner
Post-Tensioning System, Post-Tensioning Tendons	Arrangement of tensile elements, anchorage components and accessories to apply post-tensioning to the structure
Protection Level	Corrosion protection strategy applied to post-tensioning tendon which depends on the aggressivity of the environment, exposure of the structural element and corrosion protection provided by the structure
PT Specialist Company, PT Specialist	Company which carries out installation, stressing and filling of duct of the PT system. May include the supply of the PT system
PT Supervisor, PT Site Manager, PT Manager	Specialists with experience in PT site activities, and recognized by the system holder
Room Temperature	Ambient temperature, generally taken as about 20°C
Sheath	see Duct
Storage Tank	A storage system composed of one or more steel or reinforced concrete containers/containments for the storage of different kind of hazardous liquids and gas e.g. LNG, LPG, CNG
Stressing (Active) Anchorage	Anchorage allowing stressing of the tendon, also called mechanical anchorage
Tendon	A single tensile element or a bundle of tensile elements used for the prestressing of a structure, including the required protection and anchorages
Tensile Element / Prestressing Steel	Individual element such as strand and / or wire to impart stressing
Toughness	The ability of a material to deform plastically and to absorb energy in the process before fracture
Wedge / Button Head / Swage	Post-tensioning component which holds each individual tensile element and transfers the prestressing load to the anchor head, or directly to the bearing plate
Unbonded Post-Tensioning System	Post-tensioning system comprising all components in which the tensile elements are positioned inside of a duct or individual sheathing with permanent freedom of longitudinal movement of tendon between the anchorages

3.2 Notation

This section provides selected definitions of specific symbols used in the report.

Table 3-2 Definitions of specific symbols

Terms	Definition
A_p	Nominal cross-sectional area of tensile elements of tendon
A_{pm}	Mean actual cross-sectional area of tensile elements of tendon
F_{pk}	Characteristic ultimate resisting force of tensile elements of tendon: $F_{pk} = A_p \cdot f_{pk}$
F_{pm}	Actual ultimate resisting force of tensile elements of tendon: $F_{pm} = A_{pm} \cdot f_{pm}$
$F_{p0,1k}$	Characteristic yield force of tensile elements of tendon: $F_{p0,1k} = A_p \cdot f_{p0,1k}$
F_{Tu}	Measured maximum force of tensile elements in tendon assembly
F_u	Measured maximum force in load transfer test
$\max F$	Upper load in the fatigue test (dynamic load test) with tendon assembly
$\min F$	Lower load in the fatigue test (dynamic load test) with tendon assembly
ΔF	Load range in the fatigue test (dynamic load test): $\Delta F = \max F - \min F$
ε_{Tu}	Elongation of tensile elements on free length of tendon at maximum force F_{Tu}
ε_v	Longitudinal strain on surface of load transfer test specimen
ε_t	Transverse strain on surface of load transfer test specimen
$\Delta\sigma_p$	Stress range in the fatigue test (dynamic load test)
a	Reference dimension of cross section of load transfer test specimen specified by system owner, measured in x-direction
b	Reference dimension of cross section of load transfer test specimen specified by system owner, measured in y-direction
c	Concrete cover of reinforcement
h	Height of load transfer test specimen
$\max w$	Maximum crack width measured in the load transfer test
n	Maximum number of tensile elements for tendon size used in fatigue test
n'	Reduced number of tensile elements in tendon installed for fatigue test
t	Time
t_0	Time at which 80% of the characteristic tensile strength of the tensile element is reached in the static load test
f_{ck}	Characteristic compressive strength of concrete at 28 days

Terms	Definition
$f_{cm,0}$	Mean compressive strength of concrete at which full prestressing is permitted as per system owner's specifications
$f_{cm,e}$	Mean compressive strength of concrete at final test to failure in the load transfer test
f_{pk}	Characteristic tensile strength of tensile elements
f_{pm}	Mean actual tensile strength of tensile elements used for testing (mean of the results of a minimum of 3 tests)
$f_{p0,1k}$	Characteristic 0.1%-proof stress of tensile elements
f_{yk}	Characteristic yield strength of reinforcement
A_c	Cross-sectional area of load transfer test specimen
r_1	Number of full rings of holes in the anchor head of the smallest size of the series
r_2	Number of rings of holes in the anchor head for largest size of the series
x	Minimum centre or twice the basic edge distance of anchorage in the structure in x-direction, derived from reference dimensions a and b
y	Minimum centre or twice the basic edge distance of anchorage in the structure in y-direction, derived from reference dimensions a and b
Δs	Relative load -and time- dependent displacement of the tensile elements with respect to the anchorage on at least two elements
Δr	Relative load -and time- dependent displacement between the individual components of the anchorage on at least two components e.g. wedges
Δz	Deflections of the head relative to the supporting plate
r	Position of wedge relative to the supporting plate
s	Position of tensile element relative to the supporting plate
e_x	edge distance in x-direction
e_y	edge distance in y-direction
w_n	Crack widths at load cycle n
ε_n	Strain at load cycle n
$F_{p0.1, cry}$	Actual 0.1%-proof stress of the tensile element at system qualification temperature

3.3 Abbreviation

This section provides selected definitions of specific abbreviations used in the report.

Table 3-3 Definitions of specific abbreviations

Terms	Definition
AUTS	Actual Ultimate Tensile Strength
EAD	European Assessment Document
EOTA	European Organization for Technical Assessment
ETA	European Technical Assessment
LNG	Liquefied Natural Gas
NSR	Notch Sensitive Ratio
OBE	Operation Basic Earthquake
PL	Protection Level
PT	Post-Tensioning
SSE	Safe Shutdown Earthquake

4 Cryogenic structures

4.1 General

Storage tanks for organic and non-organic liquid and gases can be found in many industries, such as oil and gas (i.e. production and refinery), chemical manufacturing, bulk storage and transfer operations and others consuming or producing liquids and vapours. These tanks are typically cylindrical with size range of 2 to 60 m diameter and are generally installed inside containment basins in order to contain spills in case of leakage of the tank.

Basically, there are eight types of storage tanks:

- Fixed-roof tanks
- External floating roof tanks
- Internal floating roof tanks
- Domed external floating roof tanks
- Horizontal tanks
- Pressure tanks
- Variable vapour space tanks
- Cryogenic tanks

A cryogenic tank is a specialized type of storage tank used for the storage of gases (predominantly methane, CH_4 , with some mixture of ethane, C_2H_6) that have been cooled down to liquid state for ease and safety of non-pressurized storage and transport. The gas produced from hydrocarbon deposits typically contains a wide range of hydrocarbon products, which usually includes methane (CH_4), ethane (C_2H_6), (C_3H_8) and (C_4H_{10}). All these products have wide ranging boiling points and also different heating values allowing different routes to supply and also different uses (see Table 4-1). The gas stream is typically separated into the liquefied petroleum fractions (butane and propane), which can be stored in liquid state at relatively low pressure, and the lighter ethane and methane fractions. These lighter fractions of methane and ethane are then liquefied to make up the bulk of LNG that is shipped.

Cryogenic tanks can be found underground, above ground or in LNG carriers. The common characteristic of cryogenic tanks is the ability to store liquid at very low temperature (the lowest of -165°C for LNG) and at only about 1/600 th the volume of natural gas in the gaseous state (at standard conditions for temperature and pressure). In cryogenic tanks, if the liquid gas' vapours are not released, the pressure and temperature within the tank will continue to rise. The temperature within the tank will remain constant if the pressure is kept constant by allowing the boil off gas to escape from the tank. This is known as auto-refrigeration. Table 4-1 describes more the physical properties of pure gases e.g. boiling point temperature as well as their typical storage temperatures in cryogenic storage tanks.

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Typical product storage temperature given in Table 4-1 should be considered as reference for the design temperature (see Section 6.5.1).

Table 4-1 Physical properties of pure gases and typical storage temperature

Name	Chemical formula	Mol. mass g/mol	Boiling Point °C	Latent heat of vapour at boiling point kJ/kg	Liquid density at boiling point kg/m ³	Gas density at boiling point kg/m ³ .10 ⁸	Vol. of gas liberated by 1m ³ of liquid (exp. to 15 °C at 1 bar) m ³	Typical product storage temperature °C
N-Butane	C ₄ H ₁₀	58'123	-0.5	385	601	270	239	-10 ¹
Iso-Butane	C ₄ H ₁₀	58'123	-11.7	366	593	282	236	
Ammonia	NH ₃	17'030	-33.3	1367	682	905	910	-35
Propane ²	C ₃ H ₈	44'096	-42.0	425	582	242	311	-50
Propylene	C ₃ H ₆	42'080	-47.7	437	613	236	388	-50
Ethane	C ₂ H ₆	30'069	-88.6	487	546	205	432	-105
Ethylene	C ₂ H ₄	28'054	-103.7	482	567	208	482	-105
Methane	CH ₄	16'043	-161.5	509	422	181	630	-165

¹) Commercial butane is a mixture in N-Butane and Iso-butane with small content of propane and pentane.

²) Commercial propane is propane with small content of ethane and butane.

4.2 Above ground cryogenic tanks

Prestressed concrete cryogenic tanks have been used for storage of liquefied cooled gases since 1951. Prior to this only steel tanks were built, usually as double walled tanks but sometimes also as single walled tanks. In double walled steel tanks the primary container (inner tank), which is in contact with the cold liquid, consisted of a cryogenic steel alloy or aluminium while the outer shell served as a gas tight enclosure, for insulation and other structural functions such as support for the roof. The outer shell was designed for minimum ambient temperature, constructed in carbon steel and was therefore not suitable as a secondary barrier.

Further developments of prestressed concrete cryogenic tanks began after extensive research into the cryogenic behaviour of concrete and the prestressing steel had been carried out in the U.S. Simultaneously the philosophy of a double liquid barrier within one design was developed. Table 4-2 shows the year of publication and the tank types covered in the different related standards.

Table 4-2 History of cryogenic tank types in the respective standards

Time	Events	Tank types	Research
1958	First flat bottom LNG tank	Single containment	
End 60's	Increased construction of LNG tanks, API 620: Design and Construction of Large, Welded, Low-pressure Storage Tanks ¹	Single containment	
1977	Emphasis on risks following a spill, Review of material properties (brittle failure)	Double integrity	Damping effect of perlite, Low temperature material properties
1986	Material research, EEMUA 147: Recommendations for refrigerated liquefied gas storage tanks ²	Single containment Double containment Full containment	PUF insulation Liner system Membrane tanks
1993	BS7777: Flat-bottomed, vertical, cylindrical storage tanks for low temperature service ³	Single containment Double containment Full containment	
1997	EN 1473: Installations and equipment for liquefied natural gas - Design of onshore installations ⁴	Single containment Double containment Full containment Membrane containment Spherical storage tanks Cryogenic concrete tanks	
2003/2006	EN 14620: Design and manufacture of site built, vertical, cylindrical, flat-bottomed steel tanks for the storage of refrigerated, liquefied gases with operating temperatures between 0 °C and -165°C ⁵	Single containment Double containment Full containment Membrane containment	
2009	EEMUA 207: Recommendations on the Design, Construction and Operation of Double Concrete Tank for Refrigerated Storage ⁶	Full containment (Double Concrete)	

Time	Events	Tank types	Research
2009/2010	Revision of API 620 / API 625 ⁷ : Tank systems for Refrigerated Liquefied Gas storage	Single containment Double containment Full containment (Steel or concrete)	
2013	ACI376: Code Requirements for Design and Construction of Concrete Structures for the Containment of Refrigerated Liquefied Gases and Commentary ⁸	Full containment (Steel or concrete)	

In 1986 the Engineering Equipment and Materials Users' Association (EEMUA), published "Recommendations for the Design and Construction of refrigerated liquefied gas storage tank²", in which the cryogenic tank types were for first time classified into single, double and full containment. This tank definition has been basically followed by subsequent standards and recommendations. In 2003 a cryogenic tank type of membrane containment was introduced by EN 14620⁵.

4.2.1 Single containment

A single containment cryogenic tank consists of only one container to store the liquid product (primary container), see Fig. 4-1 to 4-4. This primary container is a self-supporting cylindrical tank made of steel.

The product's vapours are contained by either the steel dome roof of the container or, when the primary container is an open top cup, by a gas-tight metallic outer shell encompassing the primary container, but being only designed to contain the product vapours and to hold and protect the thermal insulation. The tank is surrounded by a bund wall to contain the liquid in case of an accident. Table 4-3 shows the functions of the structural components in a single containment cryogenic tank.

This cryogenic tank type has been the most popular typology until the early 1980s.

Table 4-3 Structure and function of single containment cryogenic tank

Composition	Primary container + outer shell + bund wall	
Structure	Primary: steel self-supporting	
Normal Operation	Liquid-tightness	Primary container
	Gas-tightness	Primary container
Leakage	Liquid-tightness	N/A
	Gas-tightness	N/A

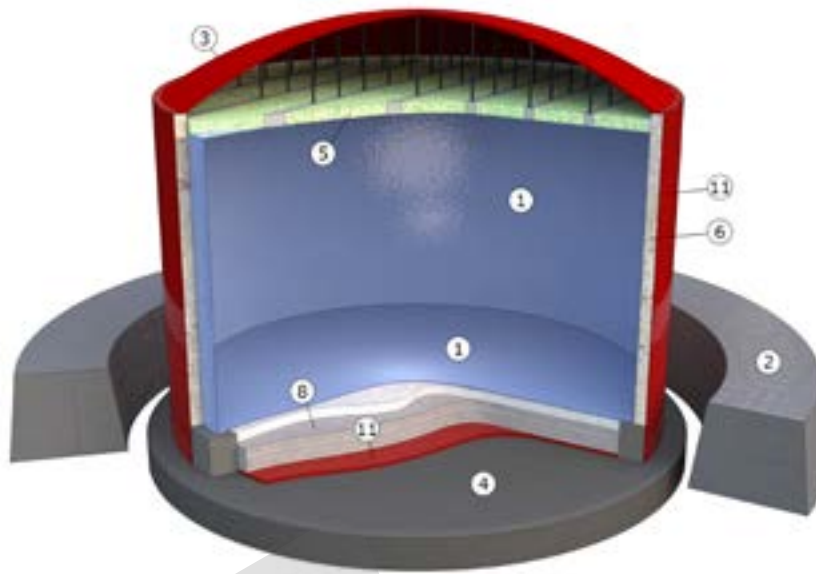


Fig. 4-1 Single containment cryogenic tank system - single wall with steel primary container and suspended deck

- | | |
|---|-----------------------------------|
| 1- primary liquid container (low temperature steel) | 5- suspended deck with insulation |
| 2- secondary liquid container (dike) | 6- insulation (external) |
| 3- warm vapor container (roof) | 8- bottom insulation |
| 4- concrete foundation | 11- moisture vapor barrier |

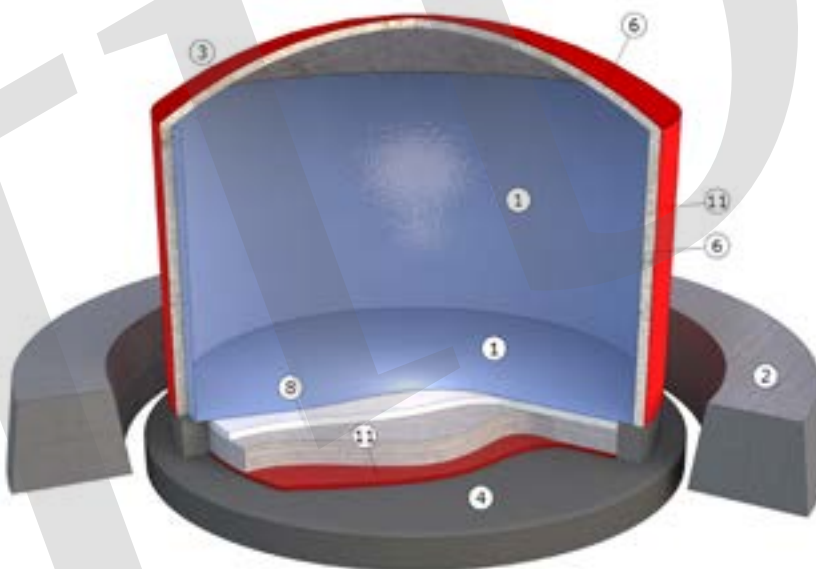


Fig. 4-2 Single containment cryogenic tank system - single wall with steel primary container and external insulation

- | | |
|---|----------------------------|
| 1- primary liquid container (low temperature steel) | 6- insulation (external) |
| 2- secondary liquid container (dike) | 8- bottom insulation |
| 3- refrigerated temperature roof | 11- moisture vapor barrier |
| 4- concrete foundation | |

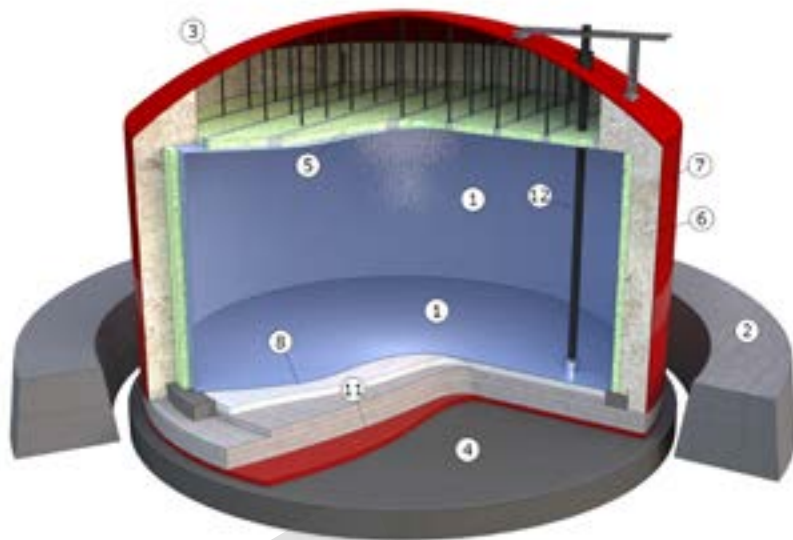


Fig. 4-3 Single containment cryogenic tank system - double wall with steel primary container and steel vapor container

Key

- | | | |
|---|---------------------------------------|---|
| 1- primary liquid container (low temperature steel) | 5- suspended deck with insulation | 8- bottom insulation |
| 2- secondary liquid container (dike) | 6- insulation (annular space) | 11- warm vapor container (outer bottom) |
| 3- warm vapor container (roof) | 7- warm vapor container (outer shell) | 12- pump column |
| 4- concrete foundation | | |

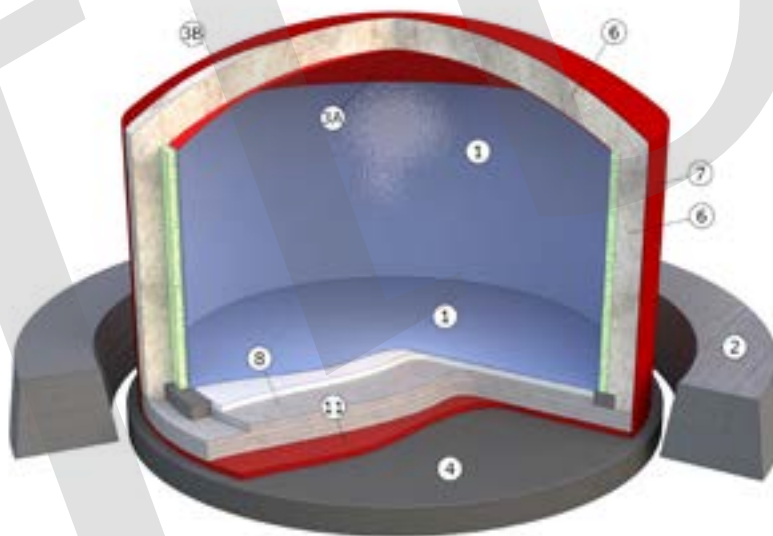


Fig. 4-4 Single containment cryogenic tank system - double wall with steel primary container and steel purge gas container

Key

- | | | |
|---|--|--|
| 1- primary liquid container (low temperature steel) | 4- concrete foundation | 8- bottom insulation |
| 2- secondary liquid container (dike) | 6- insulation (annular and roof space) | 11- purge gas container (outer bottom) |
| 3A- refrigerated temperature roof | 7- purge gas container (outer shell) | |
| 3B- purge gas container (roof) | | |

4.2.2 Double containment

A double containment cryogenic tank consists of a liquid and vapour tight primary container built inside a liquid-tight secondary container, see Fig. 4-5 and 4-6. The secondary container is designed to hold the liquid of the primary container in case of accident. The radial annular space, between the primary and secondary container, is more than 6.0 m. The space between primary and secondary container can be covered by a "rain shield" to prevent the entry of rain, snow, dirt, etc.

Table 4-4 shows the functions of the structural components in a double containment cryogenic tank.

Table 4-4 Structure and function of double containment cryogenic tank

Composition	Primary container + secondary container (within 6 m)	
Structure	Primary: steel self-supporting Secondary: steel or concrete self-supporting	
Normal Operation	Liquid-tightness	Primary container
	Gas-tightness	Primary container
Leakage	Liquid-tightness	Secondary container
	Gas-tightness	N/A

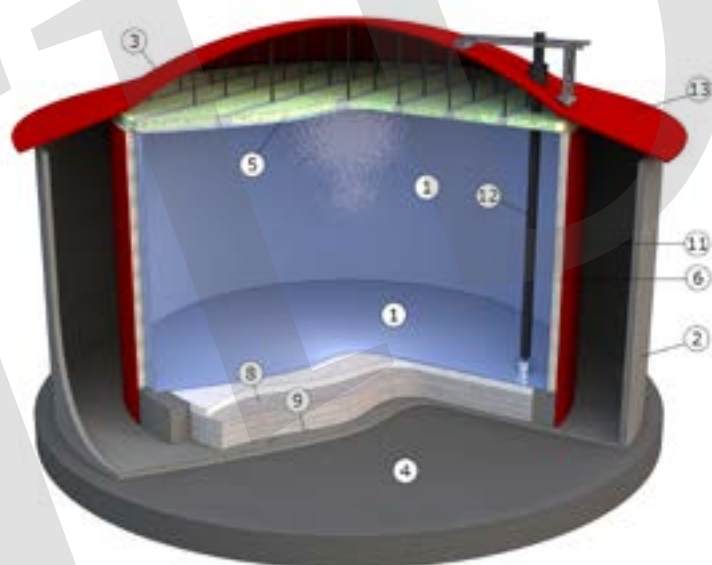


Fig. 4-5 Double containment cryogenic tank system - steel primary container and steel secondary container
Key

- | | | |
|---|---|----------------------------|
| 1- primary liquid container (low temperature steel) | 5- suspended deck with insulation | 11- moisture vapor barrier |
| 2- secondary liquid container (low temperature steel) | 6- insulation (annular space) | 12- pump column |
| 3- warm vapor container (roof) | 8- bottom insulation | 13- rain shield |
| 4- concrete foundation | 9- secondary liquid container (low temperature steel) | |

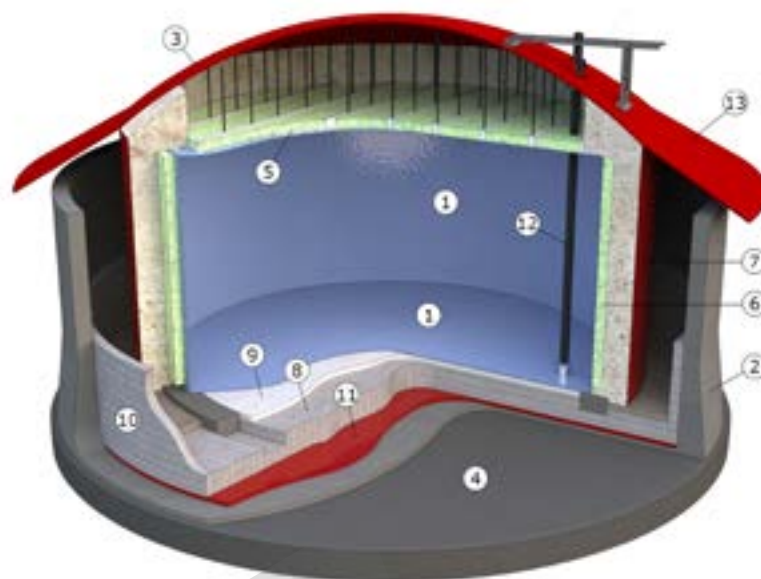


Fig. 4-6 Double containment cryogenic tank system - steel primary container, steel vapor container and concrete secondary container

Key

- | | | |
|---|---|-------------------------------|
| 1- primary liquid container (low temperature steel) | 5- suspended deck with insulation | 10- thermal corner protection |
| 2- secondary liquid container (concrete) | 6- insulation (annular space) | 11- moisture vapor barrier |
| 3- warm vapor container (roof) | 8- bottom insulation | 12- pump column |
| 4- concrete foundation | 9- secondary liquid container (low temperature steel) | 13- rain shield |

4.2.3 Full containment

Full containment has been the most common type of cryogenic tanks since 1980s. A full containment cryogenic tank consists of a primary container and a secondary container, which together form an integrated storage tank. The primary container is a self-standing steel structure and holds the liquid product, see Fig. 4-7 to 4-9. The primary container is either open at the top, in which case it does not contain the product's vapours or equipped with a dome roof so that the product vapours are contained.

The secondary container is a self-supporting steel or concrete tank equipped with a dome roof and designed to combine the following functions:

- During service: to provide the primary vapour containment of the tank (this in case of open top primary container) and to hold the thermal insulation of the primary container.
- In an accident/leakage event of the primary container: to contain all liquid product and to remain structurally vapour tight. Venting release is acceptable but shall be controlled (pressure relief system).

The annular space between the primary and secondary containers is not more than 2.0 m. Table 4-5 shows the functions of the structural components in a full containment tank.

Table 4-5 Structure and function of full containment cryogenic tank

Composition	Primary container + secondary container (within 2m)	
Structure	Primary: steel or concrete self-supporting Secondary: steel or concrete self-supporting	
Normal Operation	Liquid-tightness	Primary container
	Gas-tightness	Primary container (if dome roof) or outer shell (if suspended roof)
Leakage	Liquid-tightness	Secondary container
	Gas-tightness	Secondary container (pressure relief system)

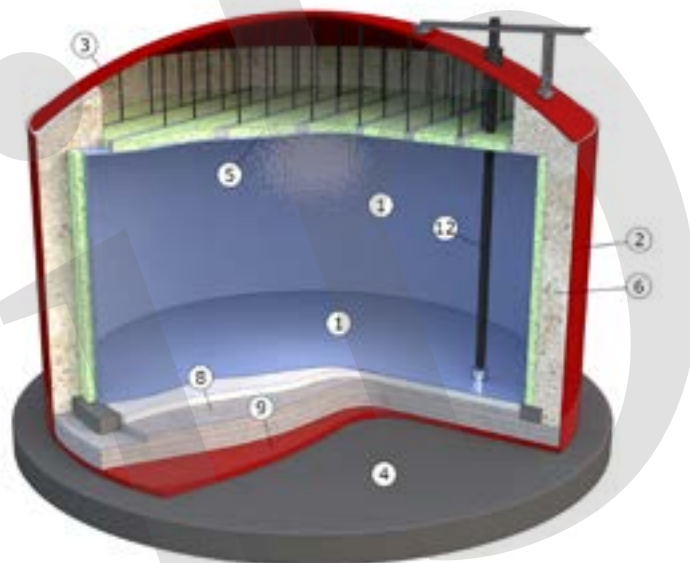


Fig. 4-7 Full containment cryogenic tank system - steel primary container, steel secondary container and steel roof

Key

- | | | |
|---|-----------------------------------|---|
| 1- primary liquid container (low temperature steel) | 4- concrete foundation | 8- bottom insulation |
| 2- secondary liquid container (low temperature steel) | 5- suspended deck with insulation | 9- secondary liquid container (low temperature steel) |
| 3- warm vapor container (roof) | 6- insulation (annular space) | 12- pump column |

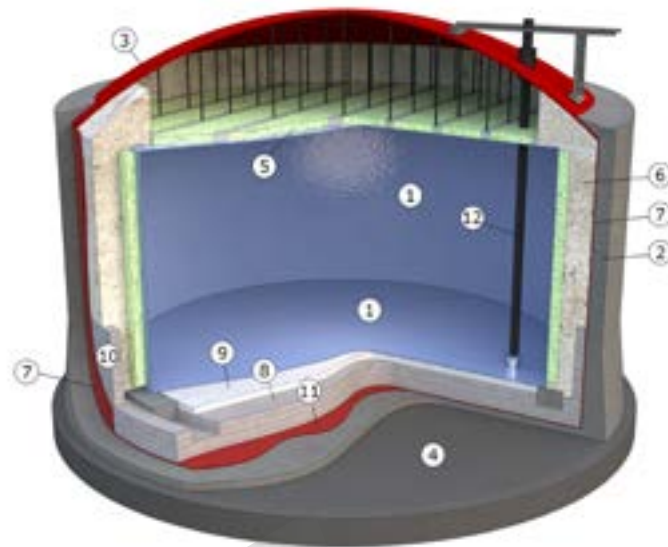


Fig. 4-8 Full containment cryogenic tank system - steel primary container, concrete secondary container and steel roof

Key

- | | | |
|---|------------------------------------|---|
| 1- primary liquid container (low temperature steel) | 5- suspended deck with insulation | 9- secondary liquid container (low temperature steel) |
| 2- secondary liquid container (concrete) | 6- insulation (annular space) | 10- thermal corner protection |
| 3- warm vapor container (roof) | 7- product vapor container (liner) | 11- moisture vapor barrier |
| 4- concrete foundation | 8- bottom insulation | 12- pump column |

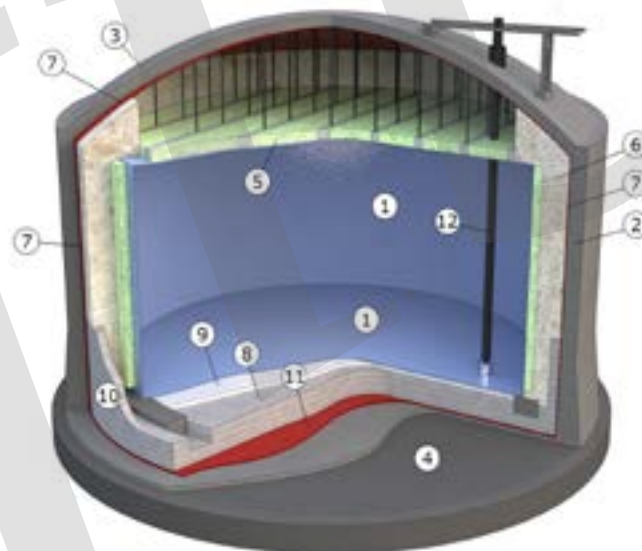


Fig. 4-9 Full containment cryogenic tank system - steel primary container, steel secondary container and steel roof

Key

- | | | |
|---|------------------------------------|---|
| 1- primary liquid container (low temperature steel) | 5- suspended deck with insulation | 9- secondary liquid container (low temperature steel) |
| 2- secondary liquid container (concrete) | 6- insulation (annular space) | 10- thermal corner protection |
| 3- warm vapor container (roof) | 7- product vapor container (liner) | 11- moisture vapor barrier |
| 4- concrete foundation | 8- bottom insulation | 12- pump column |

4.2.3.1 Full containment with concrete primary container

The scope of EN 14620⁵ is limited to full containment cryogenic tanks where the primary container is made of steel. ACI 376⁸ which was published in 2013, includes full containment cryogenic tanks where the primary container is made of concrete.

Few full containment cryogenic tanks with a concrete primary container were built in a relatively early age of gas storage history. More in particular, four cryogenic tanks of this type were built in Spain and in the USA respectively. Those cryogenic tanks consisted of a prestressed concrete inner wall, supported above a 9% nickel steel bottom plate, which allowed it to slide radially due to temperature changes. Fig. 4-10 shows the tank type.

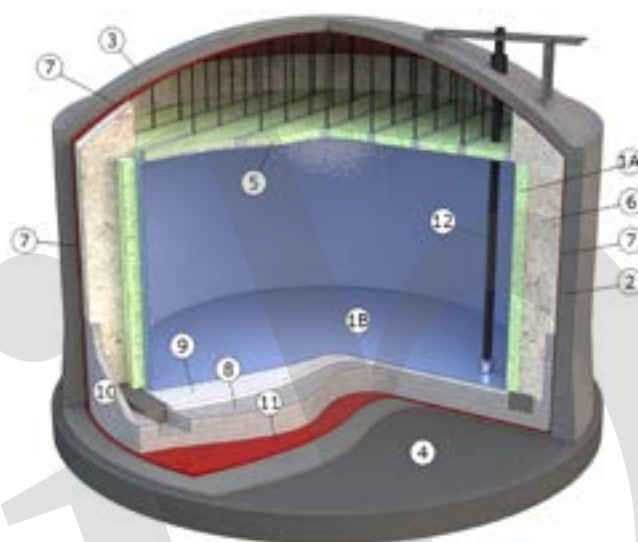


Fig. 4-10 Full containment cryogenic tank system - concrete primary container, concrete secondary container and concrete roof

Key

1A- primary liquid container (concrete)	4- concrete foundation	8- bottom insulation
1B- primary liquid container (concrete or steel)	5- suspended deck with insulation	9- secondary liquid container (low temperature steel)
2- secondary liquid container (concrete)	6- insulation (annular space)	10- thermal corner protection
3- roof (concrete)	7- product vapor container (liner)	11- moisture vapor barrier
		12- pump column

4.2.4 Membrane containment

A membrane cryogenic tank is a composite structure consisting of a thin steel primary container (membrane) together to a thermal insulation and a concrete container, all jointly integrated, see Fig. 4-11. This composite structure provides liquid and gas containment.

All hydrostatic loads and other loadings on the membrane are transferred via the load-bearing insulation to the concrete container. The vapour is contained by the tank roof, which can be either an extension of the same composite structure or a gas-tight dome roof with insulation on a suspended roof. In case of leakage of the membrane, the concrete container, in combination with the insulation system, is designed such that it can contain the liquid.

Two membrane cryogenic tanks were constructed in France before 1980 and 10 were built in Korea from mid-1980s to late-1990s. In these particular cases the membrane containment cryogenic tanks were surrounded by bund walls.

Table 4-6 shows the functions of the structural components in a membrane containment cryogenic tank.

Table 4-6 Structure and function of membrane containment cryogenic tank

Composition	Primary tank (membrane) + Insulation + Secondary container	
Structure		
Normal Operation	Liquid-tightness	Primary tank (membrane)+ Insulation + Secondary container
	Gas-tightness	Secondary container
Leakage	Liquid-tightness	Secondary container
	Gas-tightness	Secondary container (pressure relief system)

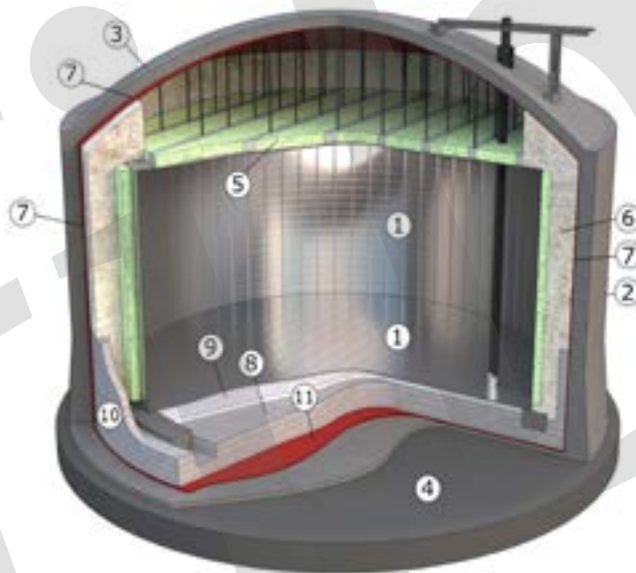


Fig. 4-11 Example of a membrane containment cryogenic tank

Key

- | | | |
|--|------------------------------------|---|
| 1- primary container (membrane) | 5- suspended deck with insulation | 8- bottom insulation |
| 2- secondary liquid container (concrete) | 6- insulation (annular space) | 9- secondary liquid container (low temperature steel) |
| 3- roof (concrete) | 7- product vapor container (liner) | 10- thermal corner protection |
| 4- foundation | | 11- moisture vapor barrier |

4.3 Containment with earth bank and underground container

A container with an earth bank, is an above-ground cryogenic tank with a secondary concrete container or external wall of concrete, against which a backfill of earth is provided forming a slope or bank over the full height or part of the height of the tank. They had been built in US, Germany, Malaysia and Australia in 1970s and 1980s.

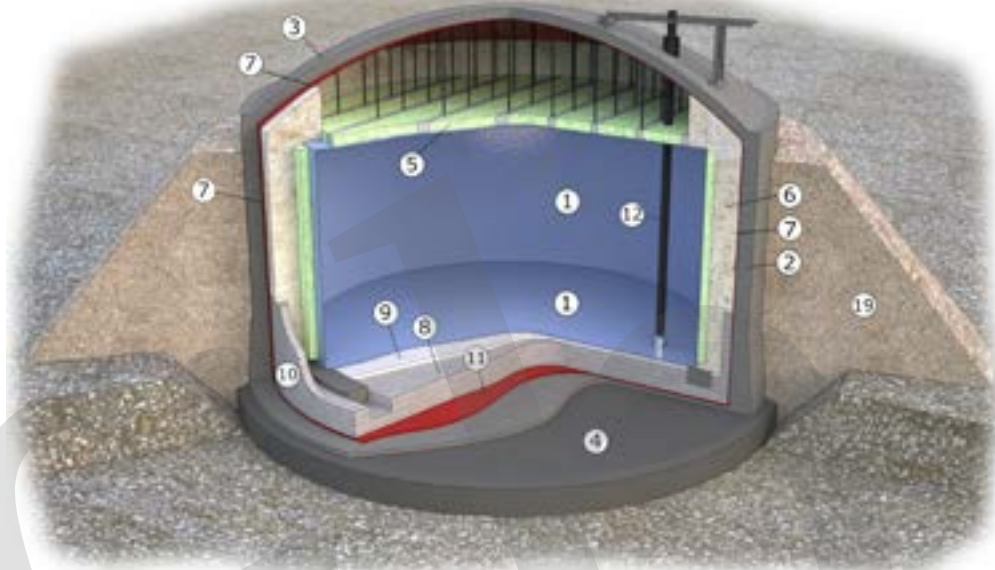


Fig. 4-12 Example of a cryogenic tank with earth bank

Key

- | | | |
|--|------------------------------------|---|
| 1- primary container (low temperature steel) | 5- suspended deck with insulation | 9- secondary liquid container (low temperature steel) |
| 2- secondary liquid container (concrete) | 6- insulation (annular space) | 10- thermal corner protection |
| 3- roof (concrete) | 7- product vapor container (liner) | 11- moisture vapor barrier |
| 4- foundation | 8- bottom insulation | 12- pump column |
| | | 19- backfill of earth |

Alternatively, an underground container is a concrete tank having primary membrane container with heating system constructed in the ground. Maximum liquid level is below the ground surface or top of the earth fill surrounding the container. They were originated in Japan in 1970s, and have been built in Japan, Korea and Taiwan until now.

5. Post-tensioning tendon typologies

5.1 General

Post-tensioning tendons are commonly specified in cryogenic tanks. The post-tensioning tendons in such structures are placed in a wide variety of locations, outer wall, slab, inner tank, roof, etc., and therefore exposed to very different thermal conditions when analyzing service loading state, ultimate loading state or accidental loading state.

Therefore, the required performance of the post-tensioning tendons shall also reflect those conditions on the structure.

This chapter provides guidance to design engineers and to suppliers of post-tensioning systems of the different typologies of post-tensioning tendons and the different requirements in terms of initial type testing depending on their thermal exposure along the full-service life of the cryogenic tank.

5.2 Description of post-tensioning tendon

5.2.1 General

Post-tensioning has been developed into a variety of forms, namely bonded or unbonded and as well internal or external to the concrete structure. For post-tensioning of cryogenic tanks predominantly internal bonded tendons are used.

A post-tensioning tendon consists of a free length and of two anchorages at the tendon extremities, see Fig. 5-1. The post-tensioning tendons might include couplers, however these are not common in cryogenic tanks. At least one of the two anchorages must allow the stressing operation (stressing anchorage) while the other fixed-end anchorage can be passive, able to anchor the force at one end of the tendon.

The duct in the free length is forming the recess in the concrete structure, in which the strands or wires (tensile elements) are installed and are free to move during the stressing operations.

After the tendon is stressed to its required final force, the remaining void in the duct and around the strands or wires, is filled with cementitious grout or grease or wax depending whether bonded or unbonded prestressing is applied. The order of stressing and filling operations might be changed for tendons with individually sheathed and greased strands.



Fig. 5-1 General post-tensioning tendon layout

Fig. 5-2 demonstrates typical post-tensioning tendons installed in vertical and horizontal directions. The vertical tendons can have different configurations: 1) loop tendon or 2) purely vertical with two anchorages.



Fig. 5-2 Typical post-tensioning tendons installed in vertical and horizontal directions

Key

- 1- vertical loop tendon
- 2- purely vertical tendon with two anchorages
- 3- horizontal tendon

5.2.2 Bonded post-tensioning tendon

A bonded post-tensioning tendon consists of bare strands or wires inside a duct filled with cementitious grout (see Chapters 7 and 9). Cementitious grout in combination with ducts made from corrugated bare or galvanized metal strips or polymeric materials are widely used and have proven to behave satisfactorily from a structural and durability point of view. In order for the bond between the tendon and the structure to be effective, the cementitious grout and the duct should have the appropriate strength and shape characteristics. Adequately grouted tendons allow a local stress transfer from the concrete to the tendon and vice versa. Full bond between the post-tensioning tendons and the concrete element can only be obtained with internal ducts.

As a result, structures with bonded tendons typically exhibit a more uniform crack distribution at ultimate load. A further advantage of cementitious grout is that the tendon injection material is achieving a stable and solid condition along the service life.

5.2.3 Unbonded post-tensioning tendon

An unbonded post-tensioning tendon can consist of bare strands or wires in a duct filled with flexible fillers (e.g. grease, wax) or individually sheathed and greased strands in a duct filled with cementitious grout. Unbonded post-tensioning tendon could also consist of a single monostrand embedded into concrete although this option is not commonly used in cryogenic tanks. Unbonded post-tensioning tendons solely rely on the transfer of the prestressing forces to the structural concrete at the anchorages. Different possibilities exist to protect the prestressing steel of unbonded post-tensioning tendons against corrosion (see Chapters 7 and 9). Unbonded post-tensioning tendons may find application in cases where the tendon force has to be adapted/controlled after initial stressing or where tendons shall be replaced in a later stage.

5.3 Durability

The durability of post-tensioning tendons is discussed in more detail in the specific *fib* Recommendation 33⁹. A summary of the main points which are influencing the durability of post-tensioning tendons installed in cryogenic tanks are:

- The location and exposure (i.e. wind-borne chlorides in the case of marine environment).
- Type of cross-section and its shape, particularly at its boundaries, to minimise the risk of contaminants penetrating the structure.
- The overall layout of the tendons to suit the methods of construction and maintenance to allow for good workmanship.
- Experience and training of engineers and workers handling specialised works.
- Location, detailing and protection of the anchorages.
- Appropriate selection and qualification of admixtures / cement for grout or flexible filler, equipment and filling operation.
- Complete filling of the tendon ducts with cementitious grout or flexible filler injection as appropriate.
- Quality assurance and testing during installation.
- Specifications for the tendon components (e.g. corrosion-resistant duct material designed to exclude contaminants).
- Detailing the roof waterproofing system and drainage design to avoid ingress of water.
- Specifications for the quality of the concrete and the cover.
- The method of construction with its associated buildability and workmanship factors.

It is highlighted that the range of parameters influencing the durability is not only limited to the hardware used to build the structure but also includes the installation methodology as well as inspection and maintenance during the operations.

Although the focus is on concrete bridges, the principles of the tendon protection strategy which is introduced in the *fib* Recommendation 33⁹, can be applied to post-tensioning tendons installed in cryogenic tanks. The objective of this strategy is to select the Protection Level (PL) of post-tensioning tendons based on:

- the aggressivity of the environment
- the exposure of the structure
- the number of protection layers provided by the structure

It is the combination of the protection level provided to the post-tensioning tendons and the protection layers provided by the structure which together provide the resistance against the aggressivity of the environment and the particular exposure condition of the cryogenic tank. Three tendon categories are defined in the abovementioned document, PL1, PL2 and PL3.

The EN 206-1¹⁰ is providing information regarding the aggressivity and exposure of structures and the classification of the principal environments to which concrete structures are exposed and the corrosivity of these environments.

When focusing on the durability of post-tensioning tendons installed in a cryogenic tank, the following subjects shall be jointly reviewed and in combination with the applicable standards and/or recommendations:

- Concrete quality, cover over the post-tensioning tendon and tendon layout
- Waterproofing systems and other surface protection systems
- Maximum crack limit
- Detailing of construction joints
- Access for inspection and maintenance

Other considerations might include the overall quality of construction, qualification of the main contractor, specific competence, workmanship certification, products availability and quality of the materials.

Following the above tendon protection strategy, the tendon category shall be reviewed for each project with its specific conditions.

Although other combinations are possible, typical details for post-tensioning tendons type PL1 and PL2 installed in cryogenic structures are:

- PL1: Bare strand + corrugated or plain metal duct + cement grout
- PL2: Bare strand + corrugated or plain polymeric duct + cement grout or other filling materials + encapsulation of anchorage zone

While the detailing of the installed tendon assembly has a major impact to the durability, it is fundamental that the installation process is prepared and executed in a careful and professional way.

5.4 Tendon type 0

5.4.1 Definition

Internal bonded or unbonded post-tensioning tendon with anchorages (e.g. anchor head, load transfer element, trumpet and wedges) never exposed, including during normal operation or accident scenario, to temperatures below $-40\text{ }^{\circ}\text{C}$.

5.4.2 Technical requirements

Post-tensioning systems installed as tendons type 0 shall fulfill:

- resistance to static load
- resistance to fatigue and
- load transfer to the structure

Initial type testing to approve post-tensioning systems for its use on tendon type 0 are given in Sections 8.2.1, 8.2.2 and 8.3.

The above requirements are usually described and covered in the corresponding standard applicable at the place of use (e.g. European Assessment Document EAD-160004-00-0301¹¹, AASHTO¹², etc.). Therefore, post-tensioning systems having a valid European Technical Assessment (ETA) for internal post-tensioning applications or post-tensioning systems, which have been tested at ambient temperature and approved according to the relevant local guideline, should be considered suitable for tendons type 0.

Post-tensioning systems that have system components made out of materials which might exhibit a brittle behavior and with no previous experience at temperatures lower than $-20\text{ }^{\circ}\text{C}$ but before the $-40\text{ }^{\circ}\text{C}$, shall be assessed as tendon type 1. However this requirement is limited only to the essential characteristic that might be compromised, e.g. resistance to static load or load transfer to the structure or both.

5.4.3 Typical examples of tendon type 0

Typical examples of tendon type 0 in cryogenic tanks might be:

- Post-tensioning tendons placed in the concrete roof
- Vertical post-tensioning tendons used in the outer concrete tank with both anchorages located at the top of the wall (e.g. loop tendon)

More detailed information is given in Table 5-1.

5.5 Tendon type 1

5.5.1 Definition

Internal bonded post-tensioning tendon with anchorages that might be exposed to temperatures below $-40\text{ }^{\circ}\text{C}$ during the occurrence of an accident but never during normal operation.

5.5.2 Technical requirements

Post-tensioning system installed in tendons type 1 shall fulfill:

- same requirements as indicated for tendon type 0, see Section 5.4.2, plus
- resistance to static load according to Section 8.4.1
- resistance to load transfer according to Section 8.4.2

5.5.3 Typical examples of tendon type 1

Typical examples of tendon type 1 in cryogenic tanks might be:

- Horizontal post-tensioning tendons placed in the outer concrete wall tank or safety concrete wall
- Vertical post-tensioning tendons placed in the outer concrete wall tank or safety concrete wall with at least one anchorage exposed to cryogenic condition

More detailed information is given in Table 5-1.

5.6 Tendon type 2

5.6.1 Definition

Internal bonded post-tensioning tendon with anchorages exposed to temperatures below $-40\text{ }^{\circ}\text{C}$ during normal operation or service.

5.6.2 Technical requirements

Post-tensioning system installed in tendons type 2 shall fulfill:

- same requirements as indicated for tendon type 1, see Section 5.3.2, plus
- resistance to load transfer according to Section 8.5

5.6.3 Typical examples of tendon type 2

Typical examples of tendon type 2 in cryogenic tanks might be:

- Horizontal post-tensioning tendons placed in the inner concrete wall tank
- Horizontal post-tensioning tendons placed in the concrete slab of the inner tank
- Vertical post-tensioning tendons placed in the inner concrete wall tank

More detailed information is given in Table 5-1.

Table 5-1 Recommended type of tendons at each tank location for each respective tank types

Tank location	Applicable post-tensioning tendon			type 2
	None	type 0	type 1	
Primary liquid container	Tank types 4.1, 4.2, 4.3, 4.4, 4.5, 4.6, 4.7, 4.8 and 4.9			Tank type 4.10
Secondary liquid container	Tank types 4.5 and 4.7		Tank types 4.1, 4.2, 4.3, 4.4, 4.6 ¹⁾ , 4.8 ¹⁾ , 4.9 ¹⁾ and 4.10 ¹⁾	
Roof	Tank types 4.1, 4.2, 4.3, 4.4, 4.5, 4.6, 4.7 and 4.8	Tank types 4.9 and 4.10		
Foundation		Tank types 4.1, 4.2, 4.3, 4.4	Tank types 4.5 ¹⁾ , 4.6 ¹⁾ , 4.7 ¹⁾ , 4.8 ¹⁾ , 4.9 ¹⁾ and 4.10 ¹⁾	

¹⁾ The Designer might consider to specify tendon Type 0 provided he furnishes the particular part of the structure with appropriate design temperature distribution condition which will avoid the temperature be lower than -40C at any point of the post-tensioning tendon.

6 Design actions and design requirements

6.1 General

This chapter does not cover generic aspects for the design of cryogenic tanks, but specific design guidelines related to post-tensioning tendons and their application in prestressed concrete cryogenic tanks, which shall be considered and specified by the design engineer. Detailed design specifications applicable in cryogenic tanks might be found in the respective codes and standards, such as EN 1473⁴, EN 14620⁵, EEMUA 207⁶ and ACI 376⁸.

Before the design stage starts, the owner shall determine the basic design data of the cryogenic tank, i.e. stored product, type of cryogenic tank, capacity of the tank, tank dimensions, construction site conditions, design service life, operation conditions, seismic conditions, etc.

The design engineer shall discuss the requirements of the cryogenic tank with the owner, and set up the performance requirements in accordance to the relevant codes. Then, the design requirements for the cryogenic tank shall be fixed to satisfy the performance requirements for all combinations of actions during the lifetime.

The design engineer selects the materials and structures, establishes the design conditions and the method of construction, and applies the appropriate analysis method.

6.2 Design action

Prestressed cryogenic tanks might be exposed to different condition states and their associated actions such as construction, testing, operation, maintenance, accidents and hazards. They shall be designed to withstand any applicable state condition and its associated actions. Normal and accidental actions in prestressed cryogenic tanks are described in Sections 6.3 and 6.4.

6.3 Normal actions

Normal actions include those permanent or variable actions existing during construction, testing, operation or maintenance condition states. Permanent actions include self-weight of concrete, steel and insulation components, piping, fittings, ancillaries, fixed equipment and as well as any effect from prestressing.

Variable actions include storage loads, imposed loads, wind loads, snow loads, insulation pressure, design internal pressure, design internal negative pressure (vacuum), settlement loads, pipe connections, loading due to construction, hydrostatic and pneumatic testing, thermal effects and Operation Basic Earthquake (OBE).

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6.4 Accidental actions

Accidental actions include leakage of the primary container, spillage from piping components, Safe Shutdown Earthquake (SSE) and external fire and explosions.

6.5 Thermal actions

For structural design and material selection the design temperature distribution and the minimum temperature shall be considered. The design temperature distribution, see Fig. 6-1, should be calculated by a heat transfer analysis using an integral model of the cryogenic tank that at least includes the primary container, the secondary container, the ground and the respective material thermal properties such as for instance the thermal conductivity and the boundary conditions for concrete surface, surrounding air, etc.

6.5.1 Under operation

Thermal actions appearing during construction, testing and operation shall be considered. The minimum design temperature to be considered for the primary container components shall be equal or lower to the storage temperature, see Table 4-1. For the design of the secondary container steady state conditions as well as daily and seasonal temperature variations shall be considered.

6.5.2 Under leakage

Thermal actions under leakage condition shall be considered. For the secondary container thermal actions at steady state condition with the maximum liquid content and as well as the transitional condition until steady state including various liquid gas levels shall be considered.

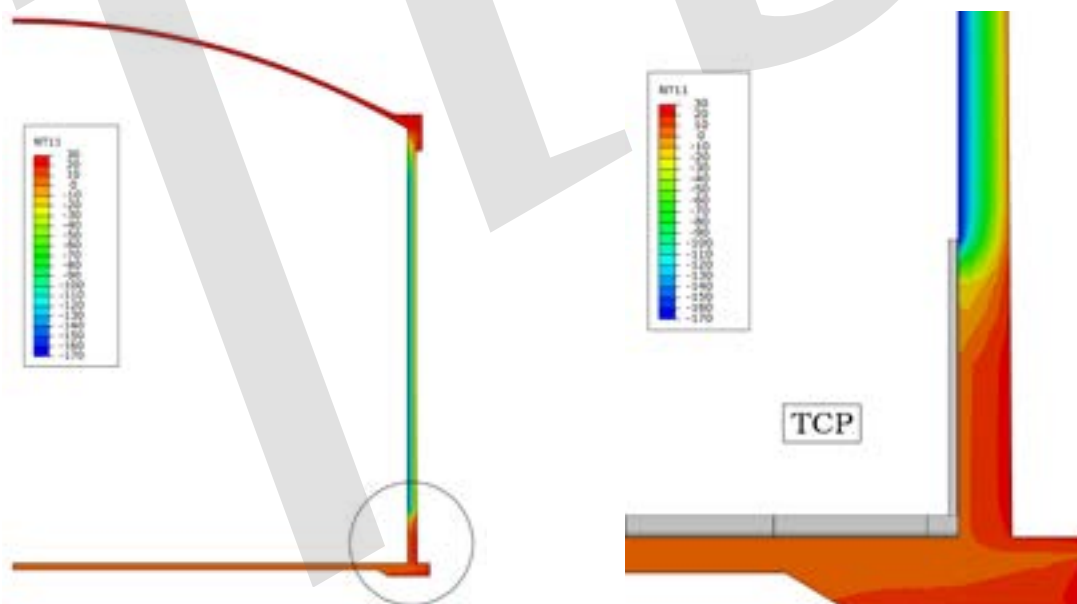


Fig. 6-1 Example of design temperature distribution (Leakage condition)
(Courtesy by Obayashi corporation and Osaka Gas company)

6.6 Design requirements of prestressed cryogenic tanks

This section provides examples of main design requirements of prestressed primary and secondary containments.

6.6.1 Secondary containment

6.6.1.1 Requirements during normal operation condition

The secondary containment shall withstand operating pressures, provide gas-tightness, hold the thermal insulation of the primary containment and support the roof and ancillary platforms, suspended deck, tank pumps, pipes, relief valves and other equipment.

6.6.1.2 Requirements during accidental condition

In case of leakage of the primary containment, the secondary containment shall contain all liquid products in the annular space. In case of a full containment cryogenic tank, the second containment shall remain structurally gas-tight including no loss of containment during and after OBE event. To fulfill the requirement, the secondary containment should be designed for OBE and SSE actions without the liquid in the secondary containment and as well as containing the full liquid volume (maximum normal operating volume) during and after OBE event.

6.6.2 Primary containment

6.6.2.1 Requirements during normal operation condition

The primary containment should remain liquid-tight during normal actions. Tightness level shall be Class 3 in accordance with EN 1992-3¹⁴ (i.e. no leakage permitted). If there is no specific information available for a particular project, the following might be taken as minimum requirements for liquid tightness:

- the net resultant force in a section shall be compressive
- a compressive zone of either 50% of the section thickness or 200 mm, whichever is greater, shall be maintained in both perpendicular directions.
- applicable to concrete wall and concrete base

6.6.2.2 Requirements during accidental condition

The primary containment shall retain its containment capability during and after a SSE. If there is no specific information available for a particular project, the following might be taken as minimum requirements for liquid tightness:

- a compressive zone of either 25% of the section thickness or 100 mm, whichever is greater, shall be maintained in both perpendicular directions.
- applicable to concrete wall and concrete base

6.7 Design and detailing of post-tensioning tendons

6.7.1 General

These provisions are based on the current state-of-the-art and the available knowledge and experience at the moment of its development. A post-tensioning system to be used in a cryogenic tank should be designed according to these guidelines and capable to meet the different performances described when applicable. The working life of the post-tensioning system for its intended use needs to be equal or greater than the expected lifetime of the cryogenic tank.

However, the working life of the post-tensioning system cannot be interpreted as a guarantee neither given by the post-tensioning systems supplier, his local representative nor the body assessing the post-tensioning system or issuing an ETA or local approval. The working life of the post-tensioning system shall be regarded only as a means for expressing its expected economically reasonable working life.

6.7.2 Definition of anchorage zone

The anchorage zone consists of local zone and general zone that surrounds it. Post-tensioning anchorages need reinforcement in the local zone, to confine the concrete, and to resist transverse tensile loads due to the introduction of the post-tensioning force.

The anchorage zone, in post-tensioning, is a region of dual responsibility shared between the design engineer and the supplier of the post-tensioning system. To prevent errors as a result of simple oversight, the division of responsibility must be clearly defined in the project plans and specifications. The design of the post-tensioning anchorage and the local zone, see Fig. 6-2, are within the scope of the supplier of the post-tensioning system.

The design engineer is responsible for the design of the structure including the general zone.

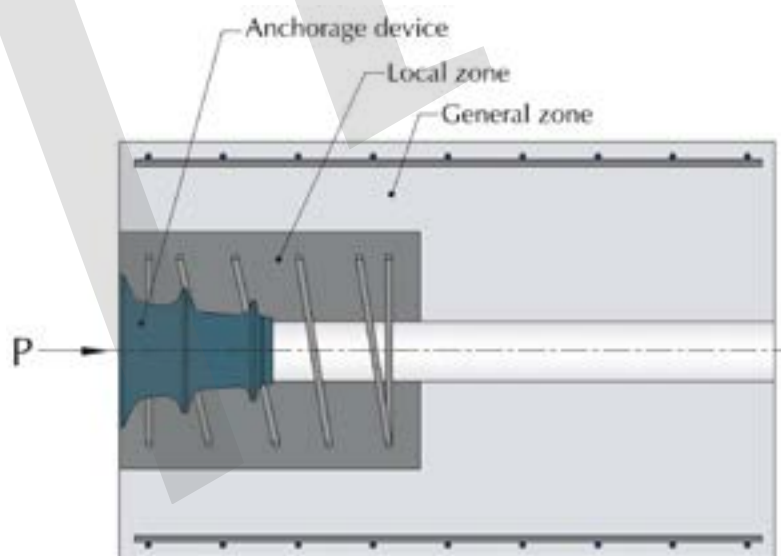


Fig. 6-2 Anchorage zone: general and local zones

6.7.3 Assessment of local zone design

6.7.3.1 Local zone in tendon type 0

In tendons type 0 it is recommended to use post-tensioning systems which have been assessed in accordance with EAD 16-0004-03.01¹¹, (European assessment document for the assessment of post-tensioning kits for prestressing of structures) or similar (e.g. AASHTO¹², PTI¹⁷, etc.).

The verification of the local zone configuration is not required if centre spacing, edge distances, grade and dimensions of reinforcement and mean concrete compressive strength are covered within the ones declared in the respective ETA of the post-tensioning system.

The verification of the local zone on those post-tensioning systems not assessed in accordance with EAD 16-0004-03.01¹¹ or similar as stated above, shall be strictly derived from the local zone configuration used for the respective load transfer to the structure test, Section 8.3.3.

6.7.3.2 Local zone in tendons type 1 and 2

In tendons type 1 and 2, the configuration of local zone shall be assessed for ambient temperature, see Section 8.3.3, and in addition for low temperature in accordance with the respective Sections 8.4.2 or 8.5.1.

6.7.4 Tendon type design

The post-tensioning tendons in the secondary containment, roof and foundation might be subjected to low temperature under leakage condition. For this scenario tendon type 1 should be considered, see Chapter 5.

The post-tensioning tendons in the primary containment are permanently subjected to low temperature under operation condition. For this scenario, tendon type 2 shall be considered, see Chapter 5.

6.7.5 Protection level design

The different protection level strategies for post-tensioning tendons are described in *fib* recommendation Bulletin 33⁹ and summarized in Section 5.3 for the specific application of cryogenic tanks. The design engineer shall define the applicable protection levels based on:

1. the aggressivity of the environment
2. the exposure of the structural element where the post-tensioning tendon is placed
3. the protection provided by the structure

Different protection levels might be chosen for different post-tensioning tendon groups provided this differentiation is technically justified in terms of points (2) and (3) above and provided enough measures are taken during design and construction to avoid confusion on site.

6.7.6 Design temperature

The design temperature in a cryogenic tank is the lowest temperature at which the tank is designed to safely operate and it mainly depends on the type of liquified gas and the temperature at which it has to be stored, see Table 4-1. The design temperature in a cryogenic tank shall be defined by the design engineer.



7. Materials: properties, requirements, and testing

7.1 General

Materials whose properties are regulated by national or international standards, including the respective test procedures shall be used. Minimum requirements are proposed below, however other relevant quality standards may be specified by the design engineer. In accordance with the scope of this recommendation, see Chapter 2, this Chapter focuses only on describing the properties, requirements and testing methods of those materials being part directly or indirectly of the post-tensioning tendons in a cryogenic tank, such as:

- Concrete in the local zone, only
- Standardized structural reinforcing steel for the local zone, only
- High-tensile prestressing steels as main tensile elements
- Steel or plastic, corrugated or smooth duct
- Filling materials (e.g. cementitious grout, wax or grease)
- Standardized structural steels used for anchorage components
- Standardized cast iron/steel used for the load transfer elements

The material requirements as well as the requirements for transport, storage and installation must be compliant with the specified quality assurance and quality control manuals. The types of test certificates to be provided by the suppliers must be specified (e.g. EN 10204¹⁵ or equivalent).

7.2 Concrete

For normal and low temperature conditions, the concrete material requirements shall be in accordance with EN 1992-1-1¹³ or equivalent standard accepted at the place of use. For the concrete performance, production, placing and compliance criteria, reference shall be made to EN 206-1¹⁰.

The moisture content of concrete proves to be the decisive factor for strength, deformation and frost damage. It is necessary to estimate the moisture content of the concrete prior to cryogenic conditions or cryogenic exposure. This is also to be considered and applied accordingly in concrete testing at low temperatures.

For prestressed concrete the class of concrete should be C40/50 or higher in accordance with EN 1992-1-1¹³ as well as EN 14620-3¹⁶. Minimum cement content should be 400 kg / m³, with a water/cement-ratio being 0.40 or less in order to reduce the pore water within the concrete matrix. The concrete mix may contain up to 5% entrained air with air entraining agents being resin based in accordance with the relevant standard. Metallic based agents shall not be used. It should be ensured though that no adverse effects from using combinations of concrete additives can take place.

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Natural uncrushed aggregates of high strength and very low porosity should be used to ensure maximum frost resistance, with aggregate size being 20 mm or less. However, more stringent requirements from governing local regulations regarding cement content, water/cement-ratio, entrained air and maximum aggregate size and the concrete mixture shall be respected accordingly.

The compressive strength of concrete increases significantly with a reduction of temperature. The strength increase is markedly influenced by the moisture content and will be less pronounced with lower moisture content. The dependence on the tensile strength – axial tensile strength and splitting strength – is similar to the compressive strength, though less pronounced. With decreasing temperature the ultimate strain at failure decreases¹⁸⁻²¹. Additional tests on the mechanical and thermal properties of concrete subjected to low temperature are recommended.

Enhanced strength of concrete at low temperature is normally not used in determining the ultimate strength of concrete sections. However, when adequate testing data is available, the low temperature properties may be utilized. Reduced expansion coefficient, thermal properties and Young's modulus should be considered for design verification. Strength increase caused by high strain rates (e.g. valve impact) should be considered when appropriate.

Ground granulated blast furnace slag or pulverized fuel ash may be used in combination with Portland cement. These materials assist in reducing the heat of hydration of thick concrete sections and thus reducing the early thermal shrinkage. Whilst the introduction of cement replacement materials may be beneficial in terms of the reduction of early shrinkage and enhanced resistance to environmental pollution, users should be aware that there may be a slower strength gain.

7.2.1 Additional requirements for concrete subject to low temperature

Concrete being subject to low temperature once, either accidentally or permanently, shall show a performance of strength not falling below that at room temperature. However, if the concrete undergoes several cycles between room and low temperature the diminution of its compressive and tensile splitting strength shall be limited. In order to fulfil those requirements additional testing should be carried out for qualification of the concrete mix. If such testing for low temperature is not provided in national codes, one may use testing procedure specified in Sections 7.2.1.1 and 7.2.1.2.

7.2.1.1 Testing of compressive and tensile splitting strength at low temperature

This section describes the testing applicable to concrete being once subjected to low temperature. Low temperature concrete specimens are cooled down to system qualification temperature with a rate of 2°C / min. Reference concrete specimens are kept at 20°C. After the cooling down phase, the low temperature specimens are kept for another 30 to 60 minutes at minimum design temperature. Right after taking the low temperature specimens out of chamber, the compression tests and tensile splitting tests are carried out. With the compressive tests also strain shall be measured.

Compressive and tensile strength measured on reference specimens shall be in compliance with the specified strength of the concrete. No individual result of the low temperature specimens shall be less than 90% of the specified strength of the concrete. The average compressive strength and the average tensile splitting strength of the low temperature specimens shall be not less than the ones of the reference specimens. The compressive strength, tensile strength and splitting strength of hardened concrete increase with decreasing temperature¹⁹⁻²¹. In general, the ultimate strain at maximum strength decreases with decreasing temperature.

7.2.1.2 Testing of compressive and tensile splitting strength after low temperature cycles

This section describes the testing applicable to concrete being permanently subjected to low temperature. Low temperature concrete specimen shall be sealed in plastic sheet and then put in a cooling chamber where they are thermally cycled with a rate of 0.5 K / min for either cooling or heating. 10 cycles between 20°C and the system qualification temperature shall be carried out. Reference concrete specimens are kept at 20°C. After the temperature cycles are completed, the compression tests and the tensile splitting tests are carried out when the specimens reach the ambient temperature. With the compressive tests also strain and Young modulus shall be measured.

Compressive and tensile strength measured on reference specimen shall be in compliance with the specified strength of the concrete. No individual result of the low temperature specimens shall be less than 80% of the specified strength of the concrete. The average compressive strength and the average tensile splitting strength of the low temperature specimens shall be not less than 90% of the ones of the reference specimens.

7.3 Reinforcing steel

One of the main requirements for reinforcement steel is the ductility, usually defined by the ratio of tensile strength to yield strength and the elongation at maximum force.

The geometrical characteristics influence the bond behaviour of the reinforcing steel with the concrete. For the local zone mainly ribbed reinforced steel is used. However, the suitability of a reinforcement type (geometry) shall be demonstrated by testing (e.g. load transfer test of the local zone for the respective tendon type, Section 8.2.2.3).

Reinforcing steel for tendons type 0 shall be according to EN 1992-1-1¹³ or equivalent accepted at the place of use. Reinforcement steel exposed to low temperatures exhibits an increase in both, yield and ultimate tensile strength and a decrease in ductility. Different types of steels exist with improved ductility and notch toughness at low temperature such as carbon-manganese steel, 9% nickel steel, austenitic stainless steel as mentioned in EN 14620-3¹⁶. Reinforcing steel for tendons type 1 and 2 shall be according to EN 1992-1-1¹³ or equivalent at the place of use plus the requirements specified in Section 7.3.1.

7.3.1 Additional requirements for reinforcing steel subject to low temperatures

Reinforcing steel for the local zone in tendon type 1 or 2 shall comply with the ductility criteria specified in EN 14620-3¹⁶. Those criteria include additional tensile tests and its comparison considering notched and un-notched reinforcing bar specimens. The tests shall be carried out at the system qualification temperature or lower, Section 8.1.4. These criteria are:

- Notch Sensitivity Ratio (NSR)
- Plastic elongation
- Yield strength

7.3.1.1 Notch Sensitivity Ratio (NSR)

The Notch Sensitivity Ratio should be:

$$NSR = \frac{\text{Tensile strength of notched bar}}{0.2\% \text{ proof stress of un-notched bar}} \quad (7-1)$$

or

$$NSR = \frac{\text{Tensile strength of notched bar}}{\text{Lower yield stress of un-notched bar}} \quad (7-2)$$

A NSR value of 1 or greater is required to achieve acceptable toughness.

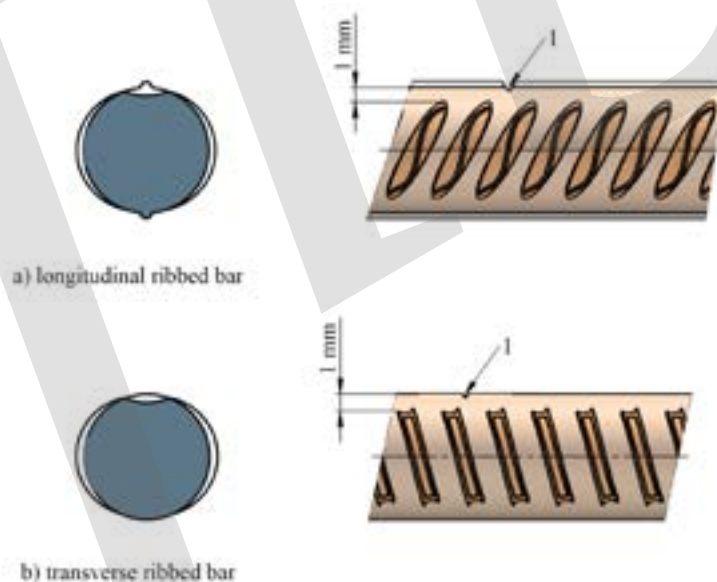


Fig. 7-1 V-notch geometry on reinforcing steels

7.3.1.2 Plastic elongation

The un-notched specimen should demonstrate a percentage plastic elongation equal or larger than the one measured at the respective load transfer test, Sections 8.4.2 and 8.5.1, or if not reported of at least 3%.

7.3.1.3 Yield strength

The yield strength of the un-notched specimen should be equal or larger than the one measured at the respective load transfer test, Sections 8.4.2 and 8.5.1, or if not reported of at least 1.15 times the minimum yield strength used in the design of the local zone.

7.3.1.4 Number of tests

Initial type testing of criteria 7.3.1.1, 7.3.1.2 and 7.3.1.3 should be carried out in accordance with EN 10080²³. Initial type testing is considered valid as long as there are no changes in relevant details related to materials and production process.

7.3.2 Corrosion protection of reinforcement steel

Alternative materials or coatings for reinforcement steel are discussed in the *fib* technical report Bulletin 49²⁴. This bulletin is focusing on the corrosion protection of reinforcing steels. Three types of reinforcing steels with alternative corrosion protection are outlined: Epoxy coated reinforcement steel, galvanised reinforcement steel and stainless reinforcement steel. As part of the documentation, the Bulletin 49 is giving information on the behaviour of these three types of reinforcement steel at extreme temperatures. While the effect of temperature on the epoxy coated and the galvanized reinforcement steel is discussed only at elevated temperature, the Bulletin 49 has a specific chapter with information on the suitability of stainless steel reinforcement for the construction of concrete containments under low design temperature. The increased ductile behaviour of austenitic stainless steel compared with classical carbon steel at low temperature is mentioned.

7.4 Prestressing steel

Prestressing steel for tendons type 0 shall be according to prEN 10138²⁵ or equivalent standard accepted at the place of use²⁶⁻²⁸. Prestressing steels with relaxation class R1 according to prEN 10138²⁵ are recommended. Requirements about welding specified in prEN 10138²⁵ shall always be respected.

The dimensions and properties given in Table 7-1 are based on prEN 10138²⁵. They may also be specified according to other standards with equivalent dimensions and properties applicable at the place of use. For cryogenic tank applications mainly prestressing steel in the form of 7-wire strands is used.

Table 7-1 Recommended values at room temperature for prestressing steels of cryogenic tanks

Type of Steel	E-modulus GPa	Diameter mm	Tensile Strength MPa	Cross section mm²	Mass per metre g/m	Recommended tolerances on mass %	Characteristic ultimate force kN
7-wire strand	195	15.3	1'860	140	1093	±2	260
		15.7		150	1172		279
Wires	205	6	1'770	28.3	221		50.1
		7	1'670	38.5	300.7		64.3
			1'770				68.1

One of the main requirements for prestressing steel is ductility. However, similarly to reinforcing steel, prestressing steel exposed to low temperatures exhibits an increase in both, yield strength and ultimate tensile strength and a decrease in ductility. Small notches or surface damage, as may occur in practice, do not seem to cause problems for static loads at low temperatures. Only deformational capacity under realistic conditions needs to be checked, see Rostasy 1982²⁹. In this sense, the notch sensitivity of prestressing steel is verified during system qualification and suitability testing, see Sections 8.2 and 8.6.

Prestressing steel for tendons type 1 and type 2 shall be according to prEN 10138²⁵ or equivalent standard accepted at the place of use plus the requirements specified in Section 7.4.1. In addition, previous comments in terms of relaxation and welding for type 0 are also applicable to type 1 and type 2.

7.4.1 Additional requirements for prestressing steel subject to low temperatures

Prestressing steel subject to low temperatures shall comply with additional strength and ductility requirements as defined below. Those requirements include additional tensile testing to be carried out at the system qualification temperature or lower, Section 8.1.4. These requirements are:

1. Yield and ultimate tensile strength
2. Elongation at maximum force
3. Failure mode

7.4.1.1 Yield and ultimate tensile strength

The minimum yield and ultimate tensile strengths at system qualification temperature shall be equal or higher than the respective characteristic strength specified at room temperature.

7.4.1.2 Elongation at maximum force

The minimum elongation at maximum force shall be equal to or higher than 3.5%.

4.4.1.3 Failure mode

Wires shall exhibit a ductile failure visible to the unaided eye. Ruptures in “arrow head” shall not be permitted. In case of dispute the percentage reduction of area shall be determined and the value shall be equal to or larger than 25%.

7.4.1.4 Number of tests

Initial type testing of criteria given in Sections 7.4.1.1, 7.4.1.2 and 7.4.1.3 should be carried out in accordance with prEN 10138²⁵. However, alternatively the number of heats might be increased up to a maximum of five provided each heat is tested three times. Initial type testing is considered valid as long as there are no changes in relevant details related to materials and production process.

7.5 Duct

The duct in post-tensioning tendons forms a conduit to allow the installation of the prestressing steel and protects it from corrosion together with the filling material. Ducts should provide a minimum cross-sectional area to facilitate the installation of the prestressing steel and to ensure the requirements of the minimum radius of the tendon are fulfilled.

In case of bonded post-tensioning, it transfers the prestressing force from the cementitious grout to the concrete. Post-tensioning duct might be in steel or plastic and be corrugated or smooth.

7.5.1 Corrugated steel duct

Corrugated steel ducts shall be in accordance with EN 523³⁰ and EN 524³¹ and these might be used in tendons type 0, 1 and 2. They are made of a continuous steel sheath roundly wrapped to form ducts by interlocking or welding. The degree of corrugation given by the manufacturing should be sufficient to ensure bond with the surrounding concrete and the cementitious grout. Sheaths shall have sufficient resistance against mechanical actions and environmental exposure and for such a reason they may be used as galvanized. Wall thickness of steel duct may vary from 0.2 mm up to 0.7 mm.

Consecutive duct sections are connected with couplers, made with the same manufacturing process and shape of ducts but with a sufficiently bigger internal diameter to allow proper overlapping and coupling. EN 523³⁰ provides guidance on dimensions of couplers. Couplers should provide a smooth interior alignment without lips or abrupt angle changes.

7.5.2 Smooth steel duct

Smooth steel ducts according to EN 10255³², EN 10216-1³³, EN 10217-1³⁴, EN 10219-1³⁵ or EN 10305-5³⁶ can be used in tendons type 0, 1 and 2. Because of their significantly larger thickness compared to corrugated ducts, these ducts might represent a better

corrosion protection barrier. Wall thickness is often specified as 2% of the pipe diameter. However, wall thickness should not be less than 3 mm to allow proper welding on site. Smooth steel ducts are usually specified for vertical tendons or when small curvature radii are required and corrugated steel ducts cannot be properly bent to meet requirements. Smooth pipes must be bent in the workshop to the specified geometry.

A typical application of smooth ducts in cryogenic tanks is the “U shaped” (loop) tube placed at the bottom of a wall where the same post-tensioning tendon goes first downwards and then upwards to the top of the wall. They are usually supplied pre-bent, free of any kinks and might be galvanized on the outside to provide corrosion protection. Inside only a temporary corrosion protection is needed which often assures low and stable friction values during stressing activities. Since a rigid steel duct is not flexible enough to accommodate for standard placing tolerances of ducts, careful detailing is needed to allow proper connections of pieces.

7.5.3 Corrugated plastic (polymer) duct

Corrugated polymer ducts shall be according to *fib* Bulletin 75³⁷ and these might be used in tendons type 0. Corrugated polymer ducts might also be used in tendons type 1 when the cryogenic tank will not be re-used after an accidental event. At the moment of developing these recommendations, there is insufficient data to determine the viability of using polymer ducts for tendons type 1 beyond an accident or for tendons type 2. For additional information regarding tendons types, see Sections 5.2, 5.3 and 5.4.

Corrugated polymer duct can be used with all tendon protection levels (PL1, PL2, and PL3), *fib* Bulletin 33⁹. When protection level PL2 is specified by the design engineer of the cryogenic tank, the use of corrugated polymer duct is required as defined in *fib* Bulletin 75³⁷ and PTI/ASBI Guide Specification¹⁷.

7.6 Filling material

7.6.1 General

Post-tensioning of structural elements requires of high-quality filling material and application methodology to ensure a long-term protection against corrosion of the prestressing steel and provide bonding when required. The filling material, regardless whether cementitious grout, grease or wax, etc., and its application methodology shall be able to ensure a complete filling of the post-tensioning tendon.

This chapter aims to propose an update in filling materials applicable to cryogenic tanks where often post-tensioning tendons exhibit large lengths ($L > 100$ m) or vertical tendons with large heights ($h > 40$ m). Application methodologies and specific solutions for injection of post-tensioning tendons is covered in Section 9.6.

7.6.2 Cementitious grout

Cementitious grout shall be in accordance with EN 445³⁸, EN 446³⁹, EN 447⁴⁰, EAD 160027-00-0301⁴⁶ or any other standard or recommendation applicable at the place of use. Several types of cementitious grouts are commonly used, fluid cementitious grout (eventually with retarding agent), expanding cementitious grout and thixotropic cementitious grout. The content in the cementitious grout of components aggressive to the prestressing steel (e.g. chlorides, sulphate, sulphides, etc.) shall be addressed using detailed chemical analysis.

The suitability of a cementitious grout formulation in the conditions of use on site shall be assessed, in accordance with the applicable standard, at least one month before the stressing operations are initiated. This limitation seeks to limit the time that the prestressing steel is unprotected and stressed.

7.6.2.1 Cementitious grout components and grout properties

Cement shall comply with EN 197-1⁴¹ type CEM I (Portland cement) or any other type of cement permitted for grouting of tendons at the place of use. The cement type shall be declared. Water shall be drinkable water or in compliance with EN 1008⁴² for cementitious grout formulation.

Admixtures shall comply with EN 934-4⁴³ or EN 934-2⁴⁴ and they could be used singly or in combination with others, but always according to the instructions of the admixture's manufacturer. The use of silica fume complying with EN 13263⁴⁵ is permitted. If permitted at the place of use grout may contain other additions intended for the use in concrete in accordance with Section 5 of EN 206-1¹⁰. The type and amount of additions shall be declared.

The use of expansive cementitious grout is tolerated if the following conditions are satisfied:

- The expansion of the cementitious grout shall not be induced by gas generation with corrosive behaviour which has not been demonstrated to be harmless to the prestressing steel (hydrogen being prohibited and nitrogen being considered as ensuring inhibition of the steel).
- The expansion phenomenon is assessed before injection on wick induced test (as per EN 445³⁸) to be controlled (at least 3 tests performed each on different grout batches) and included in the acceptance criteria defined in EN 447⁴⁰, (-1% to +5%).
- Scaling of the admixture is to be compliant with EN 447⁴⁰ requirements ($\pm 1\%$).

7.6.3 Additional requirements for cementitious grout subject to low temperature

Cementitious grout in tendon type 1 and type 2 shall show a performance of strength at low temperature not falling below that at room temperature. In addition, for tendon type 2, where the cementitious grout undergoes several cycles between room and low temperature, the diminution of its compressive strength with temperature cycles shall be limited. In order to fulfil those requirements additional testing should be carried out for qualification of the cementitious grout mix. If such testing for low temperature is not provided in national codes, one may use testing procedure specified in Sections 7.6.3.1 and 7.6.3.2.

7.6.3.1 Testing of compressive strength at low temperature

This section describes the testing applicable to cementitious grout in tendon types 1 and 2. Low temperature cementitious grout specimens are cooled down to system qualification temperature with a rate of 2°C / min. Reference cementitious grout specimens are kept at 20°C. After the cooling down phase, the low temperature specimens are kept for another 30 to 60 min at system qualification temperature. Right after taking the low temperature specimens out of chamber, the compression tests are carried out.

Compressive strength measured on reference specimens shall be in compliance with the specified compressive strength of the cementitious grout. No individual result of the low temperature specimens shall be less than 90% of the specified strength of the cementitious grout. The average compressive strength for the low temperature specimens shall be not less than the ones for the reference specimens.

7.6.3.2 Testing of compressive strength after low temperature cycles

This section describes the testing applicable to cementitious grout in tendon type 2. Low temperature cementitious grout specimen shall be sealed in plastic sheet and then put in a cooling chamber where they are thermally cycled with a rate of 0.5°C / min for either cooling or heating. 10 cycles between 20°C and the system qualification temperature shall be carried out. Reference cementitious grout specimens are kept at 20°C. After the temperature cycles are completed, the compression tests are carried out when the specimens reach the ambient temperature.

Compressive strength measured on reference specimens shall be in compliance with the specified compressive strength of the cementitious grout. No individual result of the low temperature specimens shall be less than 80% of the specified strength of the cementitious grout. The average compressive strength of the low temperature specimens shall be not less than 90% of the ones for the reference specimens.

7.6.4 Grease

Grease shall comply with EAD 160027-00-0301⁴⁶. Grease is only suitable as filling material for tendons type 0 and 1. In case of tendon type 1, the grease shall not be considered as corrosion protection layer after an accident event without further verification.

Mineral oil-based grease is used as filling material for internal post-tensioning tendons of structures, as for example grease of metallic basis such as lithium. Potash and sodium alkaline soaps are not considered as suitable for filling materials.

7.6.5 Wax

Wax shall comply with EAD 160027-00-0301⁴⁶. Petroleum-based wax is only suitable as filling material for tendons type 0 and 1. In case of tendon type 1, the wax shall not be considered as corrosion protection layer after an accident event without further verification.

7.7 Sheathed and greased prestressing steel

The sheathed and greased prestressing steel (monostrand) can be used for tendons type 0 in unbonded prestressing applications. The monostrand is a single bare strand surrounded with grease and plastic sheathing (HDPE). Prestressing steel and grease shall be in accordance with Section 7.4 and Section 7.6.4, respectively. The monostrand shall comply with the specifications given in EAD-160004-00-0301⁴⁶, PTI M10.3⁴⁷, ACI 423.7⁴⁸ or any other standard applicable at the place of use.

7.8 Quality Control

The objective of quality control testing is to demonstrate that the properties of materials and components installed in a cryogenic tank are compliant with supplier specification and project requirements. For the main tendon materials, the tests listed in Table 7-2 shall be performed with the proposed test frequency. The corresponding test reports shall be submitted to the design engineer for approval.

Other materials and components used on the project may be accepted based on quality control certificates provided by the supplier. Table 7-2 provides the additional quality control testing applicable to tendons type 1 and 2. Basic quality control testing for tendons type 0, 1 and 2 shall be found in the relevant standard applicable at the place of use.

Table 7-2 Additional quality control testing applicable to tendons type 1 and 2

Property	Test frequency
Concrete according to Section 7.2	
Water cement ratio	Per mix
7.2.1.1. Testing of compressive and tensile splitting strength at low temperature	3 compressive and 5 tensile splitting tests per new formulation, new batch of cement or if there is a significant change of origin of concrete components (e.g. aggregates)
7.2.1.2. Testing of compressive and tensile splitting strength after low temperature cycles	3 compressive and 5 tensile splitting tests per new formulation, new batch of cement or if there is a significant change of origin of concrete components (e.g. aggregates)
Reinforcing steel according to Section 7.3	
7.3.1.1. Notch sensitivity ratio	2 production heats from the max and min bar diameter for the order and from all the strength grades to be used
7.3.1.2. Plastic elongation	3 tests per diameter and 10 tensile tests per heat
7.3.1.3. Yield strength	3 tests per diameter and 10 tensile tests per heat

Property	Test frequency
Prestressing steel according to Section 7.4.1	
7.4.1.1. Yield and ultimate tensile strength	3 tests per batch of prestressing steel ¹⁾
7.4.1.2. Elongation at maximum force	
7.4.1.3. Failure mode	
Cementitious grout according to Section 7.6.2	
7.6.2.1. Testing of compressive strength at low temperature	3 compressive tests per new production lot of cement or new cementitious grout formulation
7.6.2.2. Testing of compressive strength after low temperature cycles	3 compressive tests per new production lot of cement or new cementitious grout formulation

¹⁾ Batch corresponding to one heat number, weighing not more than 200 tonnes.

8. Test and requirements of post-tensioning kits

8.1 General

8.1.1 Purpose

The purpose of this chapter is to provide standardized procedures and required performance for the different applicable levels of testing of post-tensioning systems to be used in structures subject to temperatures lower than -40°C and according to any of the scenarios defined in Chapter 5.

8.1.2 Levels of testing

Three different levels of testing of post-tensioning systems to be used in structures subject to temperatures lower than -40°C are recommended:

1. Assessment testing of the post-tensioning system (Sections 8.2, 8.3, 8.4 and 8.5) and materials (Sections 7.3 and 7.4)
2. Suitability testing (Section 8.6)
3. Quality control (Section 7.8)

8.1.3 Laboratory, testing facility

Assessment testing and suitability testing shall be executed by an independent laboratory or equivalent body according to the following qualifications:

- The laboratory shall fulfil the requirements provided in EN ISO/IEC 17025⁴⁹ or equivalent standard

In addition, the following requirements shall be considered:

- The laboratory shall have experience with testing of post-tensioning systems.
- The laboratory shall provide all needed instruments for measuring loads, displacements, etc.
- The testing machines and measuring equipment shall be calibrated in accordance with ISO 7500⁵⁰ or equivalent standards. The calibration certificates shall be included in the test report. The uncertainty of values measured with the measuring equipment shall be within $\pm 1\%$.
- The laboratory shall provide an automatic system to detect failures of tensile elements during the testing.
- The laboratory shall take all safety measures for safe conditions for its workers as well as the machines.

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8.1.4 System qualification temperature

The system qualification temperature is the lowest temperature at which the post-tensioning system is subjected to when carrying the assessment testing (e.g. static load test and load transfer test). Therefore the system qualification temperature is associated to each post-tensioning system and dictates the lowest temperature at which the post-tensioning system is approved to deliver the required performance as described in Sections 8.4 and 8.5.

The system qualification temperature shall always be lower or equal than the design temperature considered in a particular project where the post-tensioning system is deemed to be installed.

8.1.5 Concept of series

A specific post-tensioning system is typically encompassing different unit sizes (e.g. number of strands or wires) across a range. A series is therefore that group of anchorages of different sizes of a same post-tensioning system, which follow the same design concept, use same materials and have a similar geometrical shape.

8.2 Assessment testing

8.2.1 Type of tests

The objective of assessment testing is to verify and demonstrate the ability of a proposed post-tensioning system to meet the minimum specified requirements under pre-defined loading conditions which safely cover the various service and ultimate states of the real structure. Assessment testing of post-tensioning systems to be used in structures shall include:

- Resistance to static load: the post-tensioning system shall be able to develop an ultimate breaking load which satisfies a minimum percentage of the characteristic and actual strength of the tensile elements, with a minimum elongation, without premature failure or undue deformations of the anchorage components.
- Resistance to fatigue: the post-tensioning system shall be able to resist fatigue loading (dynamic strength) without excessive damage on the tensile elements measured as a specified percentage loss of tensile element cross section. Fatigue load test is part of the assessment testing and regardless of the actual loading conditions of the structure. Despite structures under cryogenic conditions might not be subjected to fatigue conditions, the resistance to fatigue testing is part of the assessment testing since this assures good detailing and robustness of the anchorage in general for prestressed concrete structures.
- Load transfer to the structure: the post-tensioning system shall be able to transfer a specified percentage of the tensile element ultimate strength from the anchorage into the concrete structure, at a defined concrete strength, without excessive concrete cracking at the local zone.

Assessment testing has to be precisely documented, including all relevant information about test specimen, testing procedure and measurement and observations as described in Sections 8.3, 8.4 and 8.5.

In case the post-tensioning system has not a valid European Technical Assessment for the respective tendon type, the above-mentioned test reports shall be made available to the design engineer for the system assessment.

8.2.2 Testing requirements and number of tests

A summary of the assessment testing and the respective tendon type is given in Table 8-1.

Table 8-1 Summary of assessment testing for the different type of tendon

Essential characteristic	Section	Intended tendon type use		
		type 0	type 1	type 2
Resistance to static load (ambient temperature)	8.3.1	+	+	+
Resistance to fatigue (ambient temperature)	8.3.2	+	+	+
Load transfer to the structure (ambient temperature)	8.3.3	+	+	+
Resistance to static load (accidental cryogenic)	8.4.1	–	+	+
Load transfer to the structure (accidental cryogenic)	8.4.2	–	+	+
Load transfer to the structure (service cryogenic)	8.5.1	–	–	+

+: Essential characteristic relevant for the intended tendon type use

– : Essential characteristic not relevant for the intended tendon type use

The number of tests specified in Sections 8.2.2.1 to 8.2.2.3 are required to each series of a same post-tensioning system, see Section 8.1.5.

Assessment tests are considered valid as long as there are no changes in relevant details of the post-tensioning system. All tests shall pass the acceptance criteria. For each type of test in accordance with Sections 8.3 to 8.5 it is acceptable if only one test fails and two additional tests are performed and pass the acceptance criteria.

Analysis is accepted for interpolation between tested sizes following same design principle. However, stresses in the components of interpolated sizes of the post-tensioning system shall not be larger than those of components verified by tests.

8.2.2.1 Resistance to static load

The number of sizes to be tested per each series, N , and its choice depends, among others, on the highest characteristic ultimate resisting force of the series and the tendon type under evaluation.

For tendon type 0 it shall be as follows:

- $F_{pk} \leq 10'500$ kN: $N = 3$ covering the largest, the intermediate and the small size of the series. The largest size is tested twice. Out of the small and the intermediate sizes, the one exhibiting higher stresses is tested twice, the other once
- $F_{pk} > 10'500$ kN: $N = (r_2 - r_1 + 1)$, where r_1 is the number of full rings of holes in the anchor head of the smallest size of the series but $r_1 \geq 2$, and r_2 is the number of rings of holes in the anchor head for largest size of the series. See Fig. 8-1 for examples of rings and full rings of holes in the anchor head. The largest size is tested twice. Out of small and intermediate sizes, the one exhibiting higher stresses is tested twice, the others once

For tendon type 1 or type 2, one additional resistance to static load test in accordance with Section 8.4.1 shall be performed per each series. The characteristic ultimate resisting force of the tendon size to be tested shall at least represent 60% of the highest characteristic ultimate resisting force of the series to be assessed for cryogenic applications.

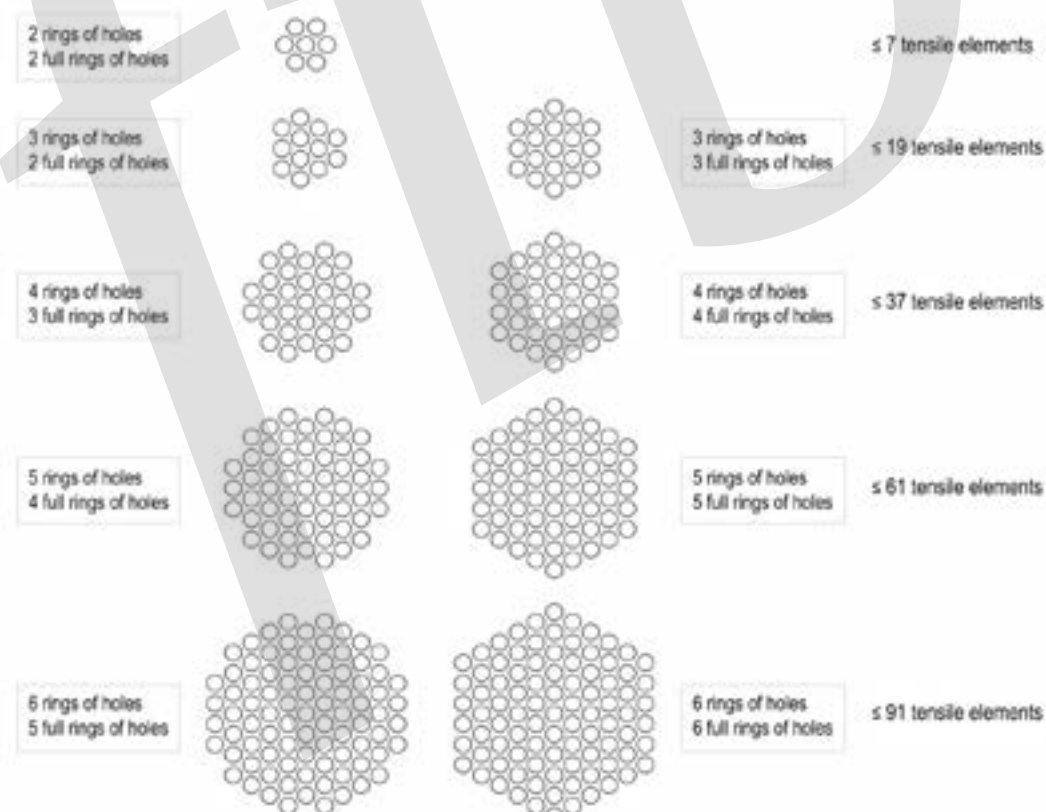


Fig. 8-1 Examples of rings of holes in an anchor head

8.2.2.2 Resistance to fatigue

The number of sizes to be tested per each series and for tendon type 0 is $N = 3$. The largest size is tested twice. The small and the intermediate sizes are tested once each.

For tendon type 1 or type 2, no additional resistance to fatigue tests are required.

8.2.2.3 Load transfer to the structure

For type 0 the number of sizes to be tested per each series, N , and its choice for the lowest mean concrete strength, $f_{cm,0'}$, declared by the post-tensioning system supplier shall be the same as specified for resistance to static load, see Section 8.2.2.1. For the highest mean concrete strength declared by the post-tensioning system supplier, one additional set of tests of the same sizes shall be performed per each series.

If there are more than two declared mean concrete strengths, and the lowest and highest mean concrete strengths differ by more than 20 MPa one or more additional set of tests with an intermediate mean concrete strength are required per each series. In any case the difference of mean concrete strength between two sets of tests shall not be higher than 20 MPa.

For tendon type 1 one additional resistance to load transfer to the structure test in accordance with Section 8.4.2 shall be performed per each series and for a mean concrete strength in the medium range. The characteristic ultimate resisting force of the tendon size to be tested shall at least represent 60% of the highest characteristic ultimate resisting force of the series to be assessed for cryogenic applications.

For tendon type 2 same requirements as for tendon type 1 apply but in accordance with Section 8.5.2.

8.2.2.4 Summary numbers of tests

Table 8-2 Summary of number of tests for assessment testing for the different type of tendon

Characteristic	Number of tests for intended tendon type use				
	Section		type 0	type 1	type 2
Resistance to static load (ambient temperature)	8.3.1	$F_{pk,max} \leq 10'500$ kN	5 ¹⁾	5 ¹⁾	5 ¹⁾
		$F_{pk,max} > 10'500$ kN	$r_2 - r_1 + 3^{2) 3)}$	$r_2 - r_1 + 3^{2) 3)}$	$r_2 - r_1 + 3^{2) 3)}$
Resistance to fatigue (ambient temperature)	8.3.2	-	4 ⁴⁾	4 ⁴⁾	4 ⁴⁾

Characteristic	Number of tests for intended tendon type use				
Load transfer to the structure (ambient temperature) ⁷⁾⁸⁾	8.3.3	$F_{pk,max} \leq 10'500$ kN	4 ⁴⁾	4 ⁴⁾	4 ⁴⁾
		$F_{pk,max} > 10'500$ kN	$r_2 - r_1 + 1$ ²⁾⁵⁾	$r_2 - r_1 + 1$ ²⁾⁵⁾	$r_2 - r_1 + 1$ ²⁾⁵⁾
Resistance to static load (service & accidental cryogenic)	8.4.1	-	0	1 ⁶⁾	1 ⁶⁾
Load transfer to the structure (accidental cryogenic) ⁹⁾	8.4.2	-	0	1 ⁶⁾	0
Load transfer to the structure (service cryogenic) ⁹⁾	8.5.2	-	0	0	1 ⁶⁾

¹⁾ It is covering largest, intermediate and small sizes. Largest size is always tested twice. Out of small and intermediate sizes, the one with higher stresses is tested twice, the other once.

²⁾ Where r_1 is the number of full rings of holes in the anchor head of the smallest size of the series but $r_1 \geq 2$, and r_2 is the number of rings of holes in the anchor head for largest size of the series.

³⁾ Largest size is always tested twice. Out of small and intermediate sizes, the one with highest stresses is tested twice, the others once.

⁴⁾ It is covering largest, intermediate and small sizes. Largest size is always tested twice. Small and intermediate sizes are tested once each.

⁵⁾ Largest size is always tested twice. Small and intermediate sizes are tested once each.

⁶⁾ The tendon size to be tested shall at least represent 60% of the highest characteristic ultimate resisting force of the series that is subject to be assessed for cryogenic applications.

⁷⁾ For the highest mean concrete compressive strength declared by the post-tensioning system supplier, one additional set of tests of the same sizes shall be performed per each series.

⁸⁾ If there are more than two declared mean concrete compressive strengths, and the lowest and highest mean concrete compressive strengths differ by more than 20 MPa one or more additional set of tests with an intermediate mean concrete compressive strength are required per each series. In any case the difference of mean concrete compressive strength between two sets of tests shall not be higher than 20 MPa.

⁹⁾ It shall be performed for a mean concrete compressive strength in the medium range.

8.3 Tendon type 0

8.3.1 Resistance to static load – tendon type 0

8.3.1.1 Test specimen

The post-tensioning tendon to be tested shall be assembled according to the envisaged application, using all components necessary for anchoring the tendon. Components for testing shall be randomly selected. The geometrical configuration of the individual tensile elements in the specimen shall be identical to that of the specified tendon assembly given in the post-tensioning system supplier's documentation.

The following data of the tensile elements shall be established:

- the main mechanical and geometrical properties of the tensile elements, including the actual ultimate strength
- calculated actual ultimate force F_{pm}
- mean total cross-section of tensile elements A_{pm}
- surface characteristics of tensile elements

Relevant geometrical and mechanical properties of anchorage components shall also be determined. The free length of the tensile elements in the tendon specimen to be tested shall be not less than 3.0 m. If an anchorage or coupling device is specified for use with different strength grades of the same type of tensile element, the test should be done with the strength grade which produces the highest load applied to the anchorage or coupling device. However, testing of more than one strength grade may be required if the geometry of the interface between tensile element and anchorage or coupling device is different for different strength grades.

Note: This rule applies e.g. in the case where one type/size of wedge is specified to be used with two or more different nominal diameters of strands, e.g. 15.3 mm and 15.7 mm.

Anchor heads that do not feature a flat contact surface to place on a steel plate may be tested embedded in a concrete body. A concrete body similar to the specimen for load transfer test, see Fig. 8-4, has been proven suitable for that purpose. The dimensions shall be at least same in cross section and additional reinforcement, but height may be reduced to the upper reinforced part. Concrete compressive strength should be not more than 20 % above $f_{cm,0}$. Different suitable concrete bodies are acceptable as well.

8.3.1.2 Test procedure

The tendon specimen is mounted in the test rig or testing machine, observing the same geometrical configuration of the individual tensile elements in the specimen to that specified in the post-tensioning system supplier's documentation.

The tendon is stressed at one end with representative equipment comparable to the one used on construction site, and specified in the post-tensioning system supplier's documentation, in steps corresponding to 20%, 40%, 60% and 80% of the characteristic tensile strength of the tensile elements. The load is increased at a constant rate corresponding to about 100 MPa per minute. At 80% level, the load is transferred from the equipment to the anchorage and test rig and then held constant at 80% level for one hour. Subsequently, the load is gradually increased with the test rig to failure at a maximum strain rate of 0.002 per minute.

Note: for internal unbonded tendons, it is suggested to held load constant at 80% level for 130 minutes.

The uncertainty of values measured with the measuring equipment shall be within $\pm 1\%$. Loads shall be maintained with a maximum tolerance of $\pm 2\%$. The load measured in the jack shall be adjusted for estimated friction losses in the anchorages to assure that the specified load has been applied to the anchor head used for measurement.

8.3.1.3 Measurements and observations

The following measurements and observations shall be made and recorded:

- Determination of actual material characteristics of tested components
- Compliance checking of the components (materials, machining, geometry, hardness, etc.) against the specifications and documentation defined by the post-tensioning system supplier on components as will be delivered on actual job sites.
- Relative load -and time- dependent displacement Δs of the tensile elements with respect to the anchorage on at least two elements (Fig. 8-2). The measurement of the relative displacement Δs shall in general be done on two tensile elements. If the tensile elements are strands, the measurement shall be done on the king wire and one external wire each.
- Relative load -and time- dependent displacement Δr between the individual components of the anchorage on at least two components e.g. wedges (Fig. 8-2), or as applicable for other methods of anchoring the tensile elements. Δr shall be measured on the same components of the two tensile elements as used for Δs .
- For internal unbonded tendons only, deformations of one anchor head in circumferential direction Δt , and deflections of the head relative to the supporting plate Δz , see Fig. 8-3, in seven measurement series as follows:
 1. At 20% level
 2. At 40% level
 3. At 80% level between time $t_0 + 10$ minutes, where t_0 is time when 80% level was reached
 4. At 80% level between time $t_0 + 30$ minutes and $t_0 + 40$ minutes
 5. At 80% level between time $t_0 + 60$ minutes and $t_0 + 70$ minutes
 6. At 80% level between time $t_0 + 120$ minutes and $t_0 + 130$ minutes
 7. At 20% level
- Complete load-elongation diagram, continuously recorded during the test
- Elongation of the tensile elements ε_{Tu} on free length at measured maximum force F_{Tu}
- Measured maximum force F_{Tu}
- Location and mode of failure
- Examination of components after dismantling, photographic documentation, comments, including residual deformations of the anchor head. Any unusual deformation of anchor head after the end of the test should be reported (if measurements of deformations are made, they shall have resolution lower or equal than 10 μm).

8.3.1.4 Acceptance criteria

- Measured maximum load shall not be less than 95.0% of the actual ultimate strength, $A_{pm} \cdot f_{pm}$, nor less than 95.0% of the specified characteristic strength, $A_p \cdot f_{pk}$, of the tensile elements, both measured at room temperature.

- Total elongation, $\varepsilon_{Tu'}$ of tensile elements on the free length at measured maximum load shall be at least 2.0%.
- Failure shall be by fracture of the tensile elements. Failure of the tendon shall not be induced by the failure of anchorage components (small longitudinal cracking or splitting of wedges shall not be considered as a failure of the anchorage).
- Residual deformations of anchorage components after testing shall confirm the reliability of the anchorage.
- With the load held at 80% of the tensile element characteristic strength the relative movements between anchorage components as well as between tensile elements and anchorage components shall stabilize within the first 30 minutes.

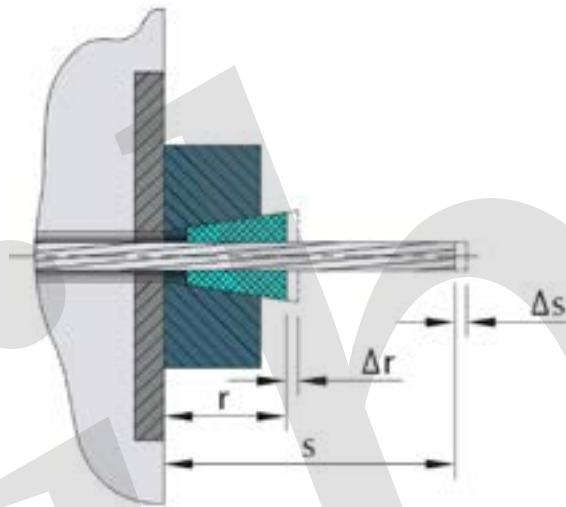


Fig. 8-2 Displacements during testing (shown for wedge anchorage; to be adapted for other methods of anchoring the tensile elements)

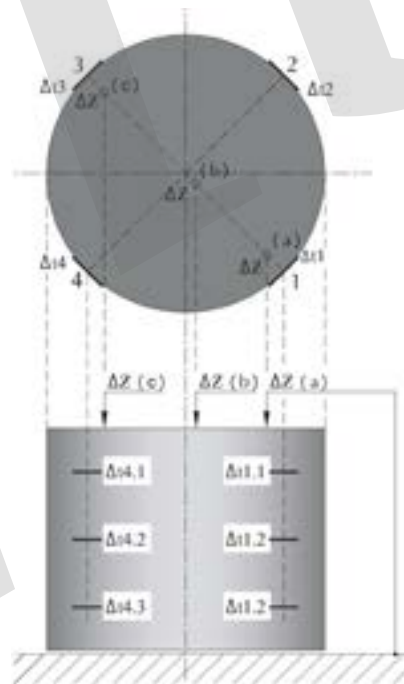


Fig. 8-3 Deformation readings on anchor head

8.3.2 Resistance to fatigue – tendon type 0

8.3.2.1 Test specimen

The type of specimen corresponds to the one described in Section 8.3.1.1. At least at one tendon end the anchorage with all components which deviate the tensile elements in the anchorage and at the entrance into the duct shall be provided identical to the assembly specified in the post-tensioning system supplier's documentation, with no change to their geometry, their material, and their machining. These components, which deviate the tensile elements shall be kept at a fixed distance from the anchorage to duplicate the actual deviation and the relative movements to the tensile elements. If both tendon ends have such anchorage details as specified above, the specimen shall count as two tests.

If an anchorage or coupling device is specified for use with different strength grades of the same type of tensile element, the test should be done with the strength grade which produces the highest load applied to the anchorage or coupling device. However, testing of more than one strength grade may be required if the geometry of the interface between tensile element and anchorage or coupling device is different for different strength grades.

This rule applies e.g. in the case where one type/size of wedge is specified to be used with two or more different nominal diameters of strands, e.g. 15.3 mm and 15.7 mm.

The number of tensile elements in the tendon-anchorage assembly to be tested may be reduced as follows. For a tendon of n tensile elements, the reduced number n' of tensile elements installed for the test shall comply with:

- if $n \leq 12$: no reduction is allowed
- if $n \geq 12$: $n' \geq \max(12; 6 + (n - 12) / 3)$

The tensile elements with the most severe angular deviation from the tendon axis shall be included.

8.3.2.2 Test procedure

The test shall be performed in a testing machine with a constant load frequency of not more than 30 Hz, and with a constant upper load of 65% of the characteristic strength of the tensile elements. Range of loads $\Delta F = \max F - \min F$ shall be maintained constant throughout the testing, at a level corresponding to 80 MPa stress amplitude in the nominal cross section of tensile elements for 2 million cycles. On its free length the specimen is without duct and filling material.

The specimen shall be tested in such a way that secondary oscillations are precluded. When assembling the specimen and fitting it in the testing machine, special care should be taken to ensure that the load is evenly distributed to all the tensile elements of the tendon.

8.3.2.3 Measurements and observations

The following measurements and observations shall be made and recorded:

- Determination of actual material characteristics of tested components.
- Compliance checking of the components (materials, machining, geometry, hardness, etc.) against the specifications and documentation defined by the post-

tensioning system supplier on components as will be delivered on actual job sites.

- Relative displacement between tensile elements and individual anchorage components as well as between the anchorage components, dependent on load and on number of load cycles on at least two tensile elements (Fig. 8-2). The measurement of the relative displacement Δs shall in general be done on two tensile elements. If the tensile elements are strands, the measurement shall be done on the king wire and one external wire each. Δr shall be measured on the same component of the two tensile elements as used for Δs .
- Examination of anchorage components and tensile elements after test with respect to fatigue damage and deformation.
- Record of fracture location and number of tensile elements which have failed by fatigue, as a function of the number of load cycles.
- Examination of components after dismantling, photographic documentation, comments.

8.3.2.4 Acceptance criteria

- No fatigue failure in anchorage components shall occur.
- No more than 5% of tensile element cross section shall be lost during fatigue testing with 2 million cycles with a minimum stress range of $\Delta\sigma_p = 80$ MPa at maximum load of 65% of tensile element characteristic strength, f_{pk} .
- The relative displacements between anchorage components as well as between tensile elements and anchorage components shall stabilize during the test.

8.3.3 Load transfer to the structure – tendon type 0

8.3.3.1 Test specimen

The test specimen is schematically shown in Fig. 8-4. The specimen shall contain those anchorage components and bursting reinforcement that will be embedded in the structural concrete, and their arrangement has to comply with the intended application and with the specification as per the post-tensioning system supplier's documentation. Components shall be randomly selected.

If an anchorage or coupling device is specified for use with different strength grades of the same type of tensile element, the test should be done with the strength grade that produces the highest load applied to the anchorage or coupling device.

The test specimen shall be a concrete prism tested in axial compression. Its concrete cross-section $A_c = a \cdot b$ shall correspond to the minimum cross-section in axial compression for the particular tendon and concrete strength class in the structure permitted by the post-tensioning system supplier's documentation.

From these reference dimensions a and b , minimum anchorage centre spacing in the structure in x - and y -directions, x and y , and minimum edge distances, shall be derived according to scientifically justified rules defined by the post-tensioning system owner. Without specific testing, the following rule may be applied:

$$A_c = x \cdot y \geq a \cdot b$$

The actual spacing / centre distance and edge distance in the structure shall comply with:

$$x \geq 0.85 a$$

$$y \geq 0.85 b$$

where a, b : side lengths of test specimen (reference dimensions given in the post-tensioning system documentation);

x, y : minimum specified centre spacing of the particular tendon in the structure whichever is smaller, $x \leq y$.

Edge distances in the structure are calculated with centre spacing in x - and y -direction by:

$$e_x = \frac{x}{2} - 10 \text{ mm} + c \quad (8-1)$$

$$e_y = \frac{y}{2} - 10 \text{ mm} + c \quad (8-2)$$

where e_x, e_y : edge distance in x - and y -direction respectively;

c : concrete cover of reinforcement in the structure as required at the place of use.

The height, h , of the specimen shall be at least twice the longer of the two side lengths a or b , see Fig. 8-4. The height of the lower, nominally reinforced part of the specimen shall be at least $0.5h$ long.

The part of the specimen containing the anchorage components shall be provided with bursting reinforcement of the same magnitude and configuration as specified for the particular system and tendon in the post-tensioning system supplier's documentation. For the assembly of the bursting reinforcement, auxiliary reinforcement may be used. It will not be part of the technical approval if the following conditions are met:

- longitudinal bars with a total cross-section of $\leq 0.003 A_c$
- stirrups, uniformly distributed along the height of specimen, with $\leq 50 \text{ kg steel} / \text{m}^3 \text{ concrete}$

The $50 \text{ kg} / \text{m}^3$ stirrups, uniformly distributed along the height of specimen, can be placed over the entire height of the specimen. They can also be combined with the local anchorage zone reinforcement. However, only the reinforcement beyond the $50 \text{ kg} / \text{m}^3$ needs to be declared.

The concrete of the test specimen shall correspond to normal concrete used for prestressed concrete structures with respect to materials, composition, compaction and its characteristic strength f_{ck} .

The composition of the concrete used for the load transfer test specimen shall be given in the test report. The test specimen should be concreted normally in a horizontal position.

After casting the specimen shall be de-moulded after one day and then moist-cured until testing. The test cylinders or cubes cast for the determination of the compressive strength of concrete shall be cured in the same manner.

The concrete cover to the reinforcement shall typically be 10 mm.

8.3.3.2 Test procedure

The specimen shall be mounted in a calibrated test rig or testing machine. The load shall be applied to the specimen on an area that simulates the loading condition in a complete anchorage.

The load is increased in steps: $0.2 F_{pk}$, $0.4 F_{pk}$, $0.6 F_{pk}$ and $0.8 F_{pk}$ (Fig. 8-5). After reaching the load $0.8 F_{pk}$ at least ten slow load cycles have to be performed, with $0.8 F_{pk}$ and $0.12 F_{pk}$ being the upper and the lower load limits, respectively. The necessary number of load cycles depends upon stabilization of strain readings and crack widths as described below. Following cyclic loading, the specimen shall be loaded continuously to failure.

During cyclic loading measurements shall be taken at the upper and lower loads of several cycles in order to decide whether satisfactory stabilization of strains and widths of cracks is being attained. Cyclic loading shall be continued to n cycles until stabilization is satisfactory, see Section 8.3.3.3. Fig. 8-5 shows the sequence of loading and measurements. Fig. 8-6 schematically shows the arrangement of the gauge points for the strain measurement on each side of the specimen, etc. At the final test to failure the mean compressive strength of concrete of specimen shall be:

$$f_{cm,e} \leq f_{cm,0} + 3 \text{ MPa}$$

8.3.3.3 Stabilization criteria

- Crack widths can be considered to have stabilized if their width under upper load complies with:

$$w_n - w_{n-4} \leq 1/3 (w_{n-4} - w_0), n \geq 10$$

- The stabilization criterion for the crack widths shall, however, only apply for crack widths larger than 0.1 mm

Longitudinal and transverse strains can be considered to have stabilized if the increase of strain under the upper load complies with:

$$\epsilon_n - \epsilon_{n-4} \leq 1/3 (\epsilon_{n-4} - \epsilon_0), n \geq 10$$

See Fig. 8-7 for details on how to assess stabilization criteria.

8.3.3.4 Measurements and observations

The following measurements and observations shall be made and recorded:

- Determination of actual material characteristics of tested components.
- Compliance checking of the components including reinforcing steel (materials, machining, geometry, hardness, etc.) against the specifications and documentation defined by the post-tensioning system supplier on components as will be delivered on actual job sites.

- Longitudinal and transverse concrete strains on at least two side faces of the specimen in the region of maximum bursting effect under the upper and lower load, dependent on number of load cycles. Longitudinal and transverse concrete strains and crack width and propagation shall also be recorded at measuring points 1, 2, 3 indicated in Fig. 8-5.
- Formation, width and propagation of cracks on the side faces of the specimen, as mentioned above.
- Visual inspection and/or measurement of deformation of anchorage components in contact with concrete. Any unusual or excessive deformation, such as large permanent deformations, shall be reported in the test report, and such actual deformation may be measured.
- Location and mode of failure.
- Measured ultimate force F_u .
- Examination of components and specimen after testing, photographic documentation, comments.

8.3.3.5 Acceptance criteria

- Crack widths max w :
 - upon first attainment of upper load of 80% of tensile element characteristic strength not more than 0.15 mm
 - upon last attainment of lower load of 12% of tensile element characteristic strength not more than 0.15 mm
 - upon last attainment of upper load of 80% of tensile element characteristic strength not more than 0.25 mm
- Readings of longitudinal and transverse strains shall stabilize during cyclic loading
- Readings of crack widths shall stabilize during cyclic loading
- Measured ultimate force of at least:
 - $F_u \geq 1.1 F_{pk} (f_{cm,e} / f_{cm,0})$
 - Anchorages intended to be placed into concrete with brittle behaviour, like unreinforced concrete without any supplementary reinforcement other than the 50 kg/m³ shall have a measured ultimate force of at least: $F_u \geq 1.3 F_{pk} (f_{cm,e} / f_{cm,0})$

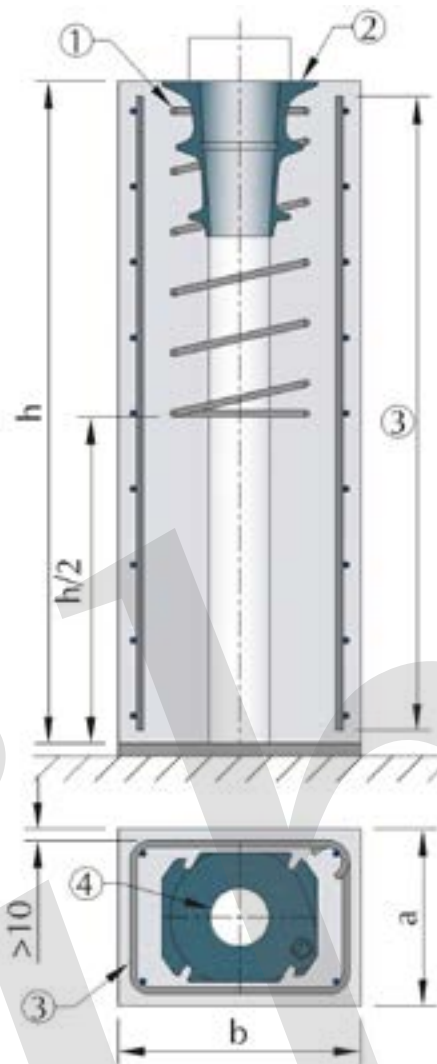


Fig. 8-4 Test specimen for load transfer test

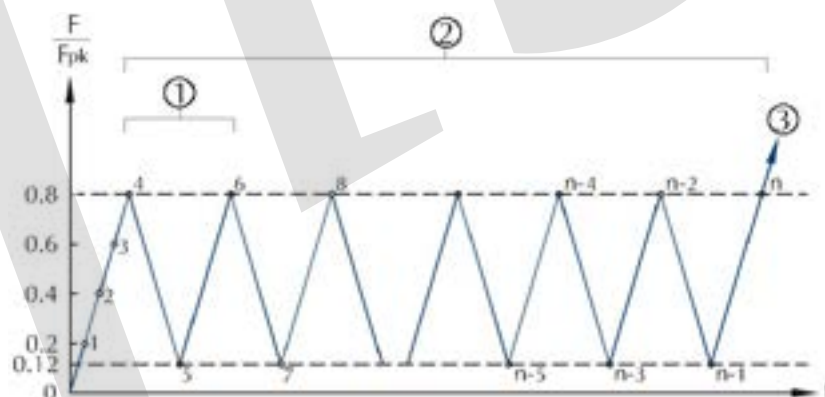


Fig. 8-5 Procedure of load transfer test – tendon type 0

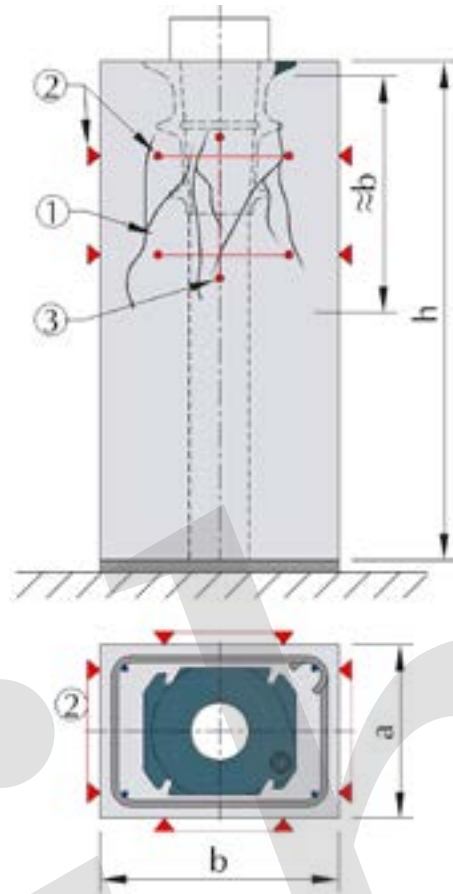


Fig. 8-6 Measuring set-up for load transfer test to be placed on at least 2 side faces

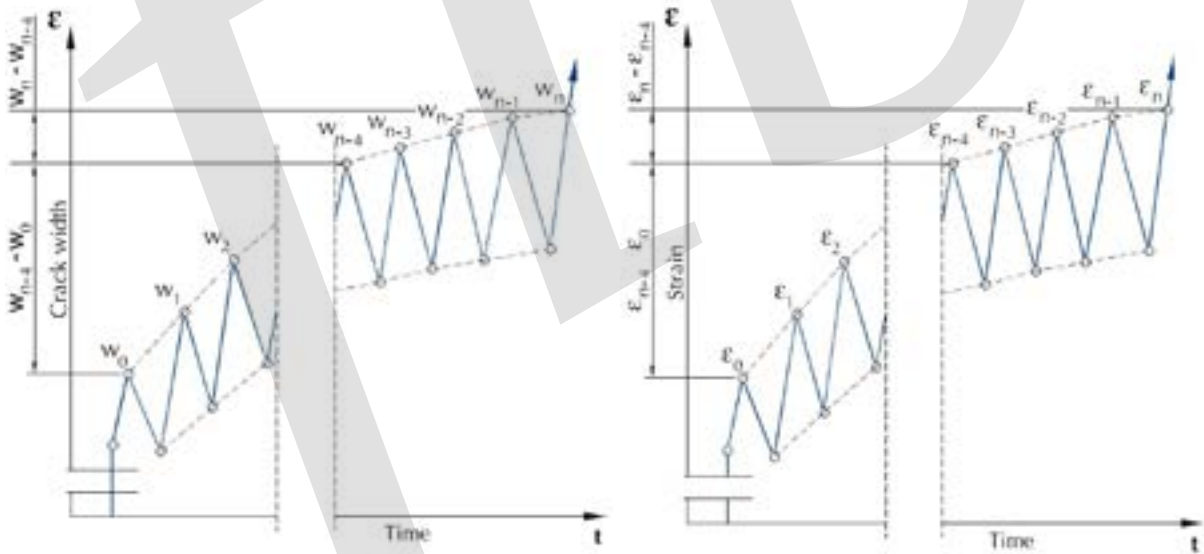


Fig. 8-7 Assessment of a) crack width and b) strain stabilization

8.4 Tendon type 1

8.4.1 Resistance to static load – tendon type 1

8.4.1.1 Test specimen

The type of specimen corresponds to the one described in Section 8.3.1.1.

8.4.1.2 Test procedure

The tendon specimen is mounted in the test rig or testing machine, observing the same geometrical configuration of the individual tensile elements in the specimen to that specified in the post-tensioning system supplier's documentation.

The tendon is stressed in steps corresponding to 20 %, 40 %, 60 % and 80 % of the characteristic tensile strength of the tensile elements f_{pk} at room temperature. The load is increased at a constant rate corresponding to about 100 MPa per minute. At the 80 % level, the load is held constant for one hour. The load is then adjusted to $0.9 F_{p0.1k}$.

Subsequently, the entire tendon including both anchorages, free length and regions where the tensile elements are deviated is immersed into liquid nitrogen or similar liquid gas appropriate to achieve the system qualification temperature for which the post-tensioning system supplier attempts to approve the system for. During the transient cooling phase the load in the tensile elements shall be maintained constant. It is important to note that the requirement of submerging the entire tendon including both anchorages is more severe than the testing conditions specified in EAD 160004-00-0301¹¹ section 2.2.9 where only one anchorage is required to be subjected to cryogenic conditions.

The transient cooling phase is deemed completed once the temperature of the testing specimen, at all different locations (e.g. anchor head, wedges, strand, etc.), has stably achieved the system qualification temperature with a temperature variation of no more than $\pm 5^{\circ}\text{C}$ from test temperature or between individual measuring points.

Note: Stable temperature is normally achieved in the specimen 1 hour after filling.

After completion of the transient cooling phase ten load cycles between the characteristic yield force $F_{p0.1k}$ of the tensile element at room temperature and $0.9 F_{p0.1k}$ at room temperature are executed.

Finally, the tendon load is increased gradually to failure (or at least until the criteria are met) at a maximum strain rate of 0.002 per minute.

8.4.1.3 Measurements and observations

The following measurements and observations shall be made and recorded:

- Determination of actual material characteristics of tested components including 3 tensile tests of prestressing steel at low temperature according to Section 7.4.1.
- Compliance checking of the components (materials, machining, geometry, hardness, etc.) against the specifications and documentation defined by the post-tensioning system supplier on components as will be delivered on actual job sites.

- Relative load -and time- dependent displacement Δs of the tensile elements with respect to the anchorage on at least two elements (Fig. 8-2), only prior to the cooling phase. The measurement of the relative displacement Δs shall in general be done on two tensile elements. If the tensile elements are strands, the measurement shall be done on the king wire and one external wire each.
- Relative load -and time- dependent displacement Δr between the individual components of the anchorage on at least two components e.g. wedges (Fig. 8-2), or as applicable for other methods of anchoring the tensile elements, only prior to the cooling phase. Δr shall be measured on the same components of the two tensile elements as used for Δs .
- Measured temperature on the outside surface of one of the anchorages over the duration of the test.
- Complete load-elongation diagram, continuously recorded during the test.
- Elongation of the tensile elements ε_{Tu} on free length at measured maximum force F_{Tu} .
- Measured maximum force F_{Tu} .
- Location and mode of failure (if applicable).
- Examination of components after dismantling, photographic documentation, comments, including residual deformations of the anchor head.

8.4.1.4 Acceptance criteria

- With the load held at 80% of the tensile element characteristic strength the displacements Δs and Δr shall stabilize within the first 30 minutes at room temperature.
- Measured maximum load shall not be less than 95% of the actual ultimate strength, $A_{pm} \cdot f_{pm}$, i.e. achieve an anchorage efficiency of 95%, nor less than 95% of the specified characteristic strength, $A_p \cdot f_{pk}$, of the tensile elements, both measured at room temperature.
- Measured maximum load F_{Tu} shall not be less than the actual 0.1%-proof stress $F_{p0.1, cry}$ of the tensile element at system qualification temperature (without anchorage effect). The test may be stopped when this criterion is met.
- If the test is continued to failure then this shall be by fracture of the tensile elements. Failure of the tendon shall not be induced by the failure of anchorage components.
- Residual deformations of anchorage components after testing shall confirm the reliability of the anchorage.

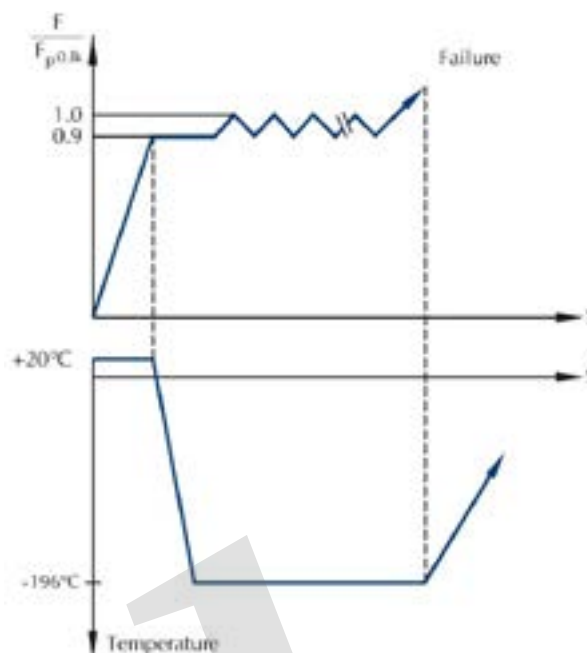


Fig. 8-8 Procedure of static load test – tendon type

8.4.2 Load transfer to the structure – tendon type 1

8.4.2.1 Test specimen

The type of specimen corresponds to the one described in Section 8.3.3.1. Reference dimensions a and b , design of bursting reinforcement (e.g. magnitude and configuration) and load transfer element shall be the same as specified in the post-tensioning system supplier's documentation for non-cryogenic applications (e.g. for tendon type 0 applications).

Replacing standard bursting reinforcement for bursting reinforcement specially manufactured (e.g. with higher content of nickel) for cryogenic applications might be possible provided that this type of bursting reinforcement provides equivalent performance and that is always used on actual projects. The above does not apply to the auxiliary reinforcement, which shall always be of the normal grade. Components shall be randomly selected.

8.4.2.2 Test procedure

The specimen shall be mounted in a calibrated test rig or testing machine. The load shall be applied to the specimen on an area which simulates the loading condition in a complete anchorage.

The load is increased in steps: $0.2 F_{pk}$, $0.4 F_{pk}$, $0.6 F_{pk}$ and $0.8 F_{pk}$ (Fig. 8-9). After reaching the load $0.8 F_{pk}$ at least ten slow load cycles have to be performed, with $0.8 F_{pk}$ and $0.12 F_{pk}$ being the upper and the lower load limits, respectively. The necessary number of load cycles depends upon stabilization of strain readings and crack widths as described below. During cyclic loading measurements shall be taken at the upper and lower loads of several cycles in order to decide whether satisfactory stabilization of strains and widths of cracks is being attained. Cyclic loading shall be continued to n cycles until stabilization is satisfactory.

Subsequently to the cyclic loading the entire specimen is immersed into liquid nitrogen or similar liquid gas appropriate to achieve the system qualification temperature for which the supplier attempts to approve the system for. During the transient cooling phase the load in the specimen should be kept constant at 80% of the characteristic tensile strength of the tensile elements.

The transient cooling phase is deemed completed once the temperature of the testing specimen, at all different locations (e.g. inner concrete, bursting reinforcement, load bearing element (casting), etc.) has stably achieved the system qualification temperature with a temperature variation of no more than $\pm 5^{\circ}\text{C}$ from test temperature or between individual measuring points.

After completion of the transient cooling phase the specimen shall be loaded continuously to failure (or at least until the criteria are met).

At the final test to failure the mean compressive strength of concrete of specimen at room temperature shall be:

$$f_{cm,e} \leq f_{cm,0} + 3 \text{ MPa}$$

8.4.2.3 Stabilization criteria

Same as given in Section 8.3.3.3

8.4.2.4 Measurements and observations

The following measurements and observations shall be made and recorded:

- Same as given in Section 8.3.3.4.
- Determination of actual material characteristics of tested components including 3 tensile tests of reinforcing steel at low temperature according to Sections 7.3.1.2 and 7.3.1.3.
- Measured temperature inside the concrete prism, next to the load transfer element and next to the surface of the bursting reinforcement.

NOTE: if the same configuration (e.g. same tendon size with same dimensions, same reinforcement, same concrete strength etc.) has been successfully tested as per 8.3.3 or if this configuration is covered by a valid European Technical Assessment (ETA), then crack widths and strain measurements and their respective assessment may be omitted.

8.4.2.5 Acceptance criteria

- Same as given in Section 8.3.3.5
- The test may be stopped when the F_u criterion is met.

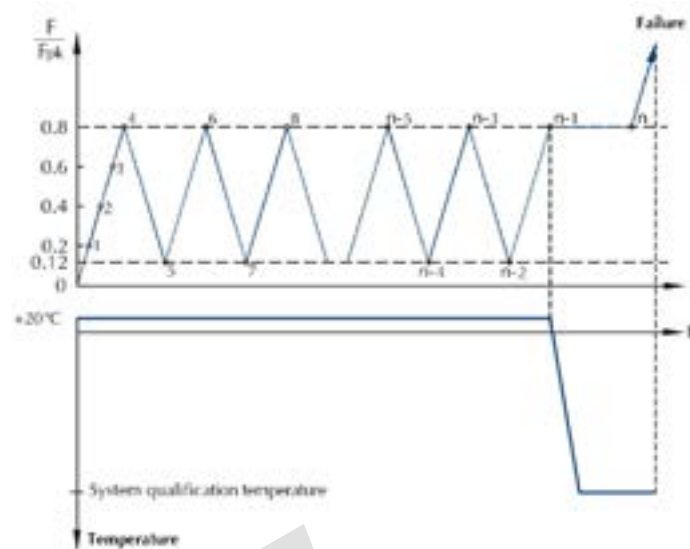


Fig. 8-9 Procedure of load transfer test – tendon type 1

8.5 Tendon type 2

8.5.1 Load transfer to the structure – tendon type 2

8.5.1.1 Test specimen

Same as given in Section 8.3.3.1.

8.5.1.2 Test procedure

The specimen shall be mounted in a calibrated test rig or testing machine. The load shall be applied to the specimen on an area which simulates the loading condition in a complete anchorage.

The load is increased in steps: $0.2 F_{pk}$, $0.4 F_{pk}$, $0.6 F_{pk}$ and $0.8 F_{pk}$ (Fig. 8-10). After reaching the load $0.8 F_{pk}$ at least ten slow load cycles have to be performed, with $0.8 F_{pk}$ and $0.12 F_{pk}$ being the upper and the lower load limits, respectively. The necessary number of load cycles depends upon stabilization of strain readings and crack widths as described below.

During cyclic loading measurements shall be taken at the upper and lower loads of several cycles in order to decide whether satisfactory stabilization of strains and widths of cracks is being attained. Cyclic loading shall be continued to n cycles until stabilization is satisfactory, see Section 8.3.3.3. Fig. 8-5 shows the sequence of loading and measurements. Fig. 8-6 schematically shows the arrangement of the gauge points for the strain measurement on each side of the specimen, etc.

After the initial load cycling between $0.12 F_{pk}$ and $0.8 F_{pk}$ the mean compressive strength of concrete of specimen shall be:

$$f_{cm,e} \leq f_{cm,0} + 3 \text{ MPa}$$

Following cyclic loading the entire specimen is immersed into liquid nitrogen or similar liquid gas appropriate to achieve the minimum design temperature for which the supplier attempts to approve the system for. During the transient cooling phase the load in the specimen should be kept constant at 80% of the characteristic tensile strength of the tensile elements.

The transient cooling phase is deemed completed once the temperature of the testing specimen, at all different locations (e.g. inner concrete, bursting reinforcement, load bearing element (casting), etc.), has stably achieved the minimum design temperature with a temperature variation of no more than 5°C from test temperature or between individual points.

After completion of the transient cooling phase the load is adjusted to $0.9 F_{p0,1k}$ and then ten load cycles between the characteristic yield force $F_{p0,1k}$ of the tensile element at room temperature and $0.9 F_{p0,1k}$ at room temperature are executed.

After completion of the cyclic loading phase the load is adjusted to $0.8 F_{pk}$. Subsequently the specimen is warmed up to ambient temperature. The transient warming phase is deemed completed once the temperature of the testing specimen, at all different locations (e.g. inner concrete, bursting reinforcement, load bearing element (casting), etc.), has stably achieved the ambient temperature with a variation of no more than 5°C from test temperature or between individual points. Finally, the specimen shall be loaded continuously to failure. The measured ultimate force test is made at ambient temperature because this condition is considered the most unfavourable for the test specimen since concrete and steel reinforcement will not exhibit any strength increase due to low temperature effects.

8.5.1.3 Measurements and observations

The following measurements and observations shall be made and recorded:

- Determination of actual material characteristics of tested components including 3 tensile tests of reinforcing steel at low temperature according to Sections 7.3.1.2 and 7.3.1.3.
- Compliance checking of the components including reinforcing steel (materials, machining, geometry, hardness, etc.) against the specifications and documentation defined by the post-tensioning system supplier on components as will be delivered on actual job sites.
- During initial load cycling between $0.12 F_{pk}$ and $0.8 F_{pk}$ longitudinal and transverse concrete strains on at least two side faces of the specimen in the region of maximum bursting effect under the upper and lower load, dependent on number of load cycles. Longitudinal and transverse concrete strains and crack width and propagation shall also be recorded at measuring points 1, 2, 3 indicated in Fig. 8-5.
- Formation, width and propagation of cracks on the side faces of the specimen, as mentioned above.
- After initial load cycling at ambient temperature and after second load cycling under cryogenic conditions: Visual inspection and/or measurement of deformation of anchorage components in contact with concrete. Any unusual or excessive deformation, such as large permanent deformations, shall be reported in the test report, and such actual deformation may be measured.

- Location and mode of failure.
- Complete load-history-diagram, continuously recorded during the test.
- Measured ultimate force F_u .
- Examination of components and specimen after testing, photographic documentation, comments.

8.5.1.4 Acceptance criteria

- Crack widths max w during initial cyclic loading:
 - upon first attainment of upper load of 80% of tensile element characteristic strength not more than 0.15 mm
 - upon last attainment of lower load of 12% of tensile element characteristic strength not more than 0.15 mm
 - upon last attainment of upper load of 80% of tensile element characteristic strength not more than 0.25 mm
- Readings of longitudinal and transverse strains shall stabilize during initial cyclic loading
- Readings of crack widths shall stabilize during initial cyclic loading
- Measured ultimate force of at least: $F_u \geq 1.1 F_{pk} (f_{cm,e} / f_{cm,0})$

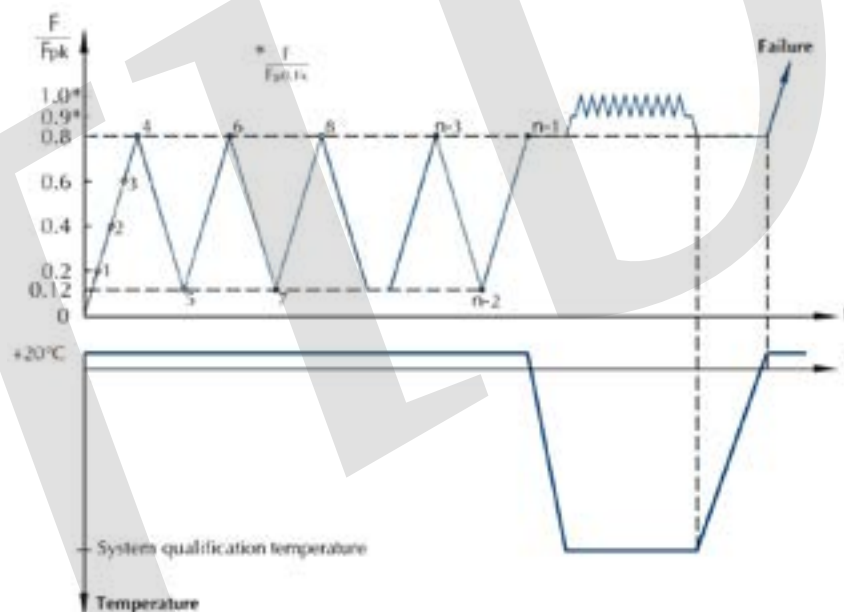


Fig. 8-10 Procedure of load transfer test – tendon type 2

8.6 Suitability Test

Basic materials and components of the post-tensioning system such as main tensile elements, anchorage components and local zone reinforcement shall satisfy the same specifications as the components used for the initial assessment. However, they may be fabricated by different suppliers or processes than those used for the testing during the

initial assessment. In the particular case of main tensile elements, only suppliers that have undergone the initial type testing shall be considered, see Section 7.4.1.

The objective of suitability testing is to demonstrate the satisfactory performance at the minimum design temperature of critical components. Suitability testing of anchorage system including strand, shall be done for each project and with the same source for the components as used for the particular project.

8.6.1 Suitability testing of anchorage system

Suitability testing is not required for tendon type 0. Suitability testing for tendon type 1 and 2 shall include:

- 3 single strand tests at room temperature, using lab anchorages. The mean value of the three tests shall be used as actual strength of the strand (AUTS).
- 3 single strand tensile tests at the minimum design temperature using lab anchorages, Section 8.1.4. The maximum load F_{Tu} and the actual 0.1% - proof stress $F_{p0.1, cry}$ of the tensile element at minimum design temperature or lower shall be measured.
- 3 single strand tensile tests at the minimum design temperature with single strand anchor head and wedge. The measured maximum load F_{Tu} shall not be less than the actual 0.1% - proof stress $F_{p0.1, cry}$ of the tensile element.

Testing of single strand only with lab anchorages shall be in accordance with Section 7.4.1.

Testing of the single strand with anchor head and wedge shall be in accordance with Section 8.4.1.

8.6.2 Suitability testing of reinforcement bar of the local anchorage zone

For tendon type 2, additional testing shall include:

- 3 tensile tests at the minimum design temperature or lower on the reinforcement bar used for the local anchorage zone reinforcement. If several reinforcement bar sizes are used, 3 tensile tests on the smallest and 3 tensile tests on the largest reinforcement bar shall be done.

Testing and verification shall be in accordance with Section 7.3.1.

8.6.3 Evaluation and conformity of post-tensioning systems and reinforcing steel

If the suitability test does not satisfy the acceptance criteria for a particular material batch, the post-tensioning system supplier and/or the reinforcing steel supplier have the choice between the following two options:

- Replace such batch of material (e.g. tensile elements or reinforcing steel) and repeat the suitability tests associated to the new material batch or
- Do not replace such batch of material (e.g. tensile elements or reinforcing steel) and repeat twice more each failed test. If any of repeated tests is failed again, then the batch of material shall be rejected.

9 Inspection and qualification of companies and personnel

9.1 General

The installation of post-tensioning system is part of the construction contract. The post-tensioning system has to be designed, assessed and delivered by the post-tensioning system supplier and installed by the PT specialist. The quality of the installed post-tensioning system highly depends on the assembly and installation activities performed on site. Therefore, the PT specialist shall be trained, certified and technically supported during construction by the post-tensioning system supplier.

The design engineer is responsible for the design of the cryogenic structure, including the construction engineering and sequence. The design engineer shall determine the prestressing forces and define the post-tensioning tendon's layout in accordance with post-tensioning systems.

The main contractor is responsible for planning all the steps necessary for the installation of the post-tensioning system.

9.2 PT specialist

9.2.1 Quality management system

The PT specialist responsible for the installation of the post-tensioning system shall have a quality management system in compliance with ISO 9000 standards⁵¹, or equivalent, covering all aspects of quality control and installation. Comprehensive literature on the subject exists, see for instance FIP Report⁵² and CWA 14646⁵³.

9.2.2 Certification of PT specialist

The PT specialist should be certified by a qualified accredited body in accordance with CWA 14646⁵³ or equivalent and is responsible for providing site specialists.

9.2.3 Qualification of personnel

The PT specialist is responsible for providing site specialists, PT manager and PT supervisors. The site shall be headed by a PT site manager. The PT site manager shall have a minimum of 5 years site experience in post-tensioning activities, with a minimum of 12 months experience with the specific post-tensioning system to be used on site. The PT supervisors shall have a minimum of 2 years site experience in PT activities, with a minimum of 6 months experience with the specific post-tensioning system.

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Both shall be familiar with matters relating to:

- materials, components and equipment for the post-tensioning system
- storage, handling and installation of components and post-tensioning system
- safety conditions for personnel
- stressing
- temporary and/or permanent protection procedures, e.g. filling of post-tensioning tendons

All site staff shall be given regular training to keep up to date with the technology, design, procedures, as well as activities to be performed on site in accordance with⁵³. The training program should be available.

9.2.4 Execution documents

The following documents should be made available by the PT specialist and be approved by the owner and design engineer before the start of post-tensioning system installation:

- Method statement of post-tensioning works on site
- Inspection and test plan and the quality management plan of the post-tensioning components (traceability)
- Assembly drawings of the post-tensioning system
- post-tensioning system installation program based on all the stages of construction
- Installation tolerance requirements, if any, on the structural parts in interaction with post-tensioning system

The method statement should include:

- Site preparation: Definition of the storage areas, access and platforms including the space requirements for the post-tensioning system installation
- Procedures for transport, storage and handling of the individual components
- Procedures for acceptance inspection of material
- Procedures for prefabrication of the post-tensioning tendon, if applicable
- Procedures for site assembly before installation, if applicable
- Procedures for the post-tensioning system components and tendon installation
- Procedures for temporary corrosion protection, if applicable
- Procedures for stressing, including measures to be taken in case of deviations from specified force or elongation values
- Procedures for filling of post-tensioning tendon, including control during injection
- Procedures for final protection of anchorages
- Procedures for inspection at the end of construction for hand-over

9.3 Shipment and storage of components

It is the responsibility of post-tensioning system supplier to undertake appropriate measures and to advise the PT specialist and the clients on the packaging, transport and storage of the product.

The post-tensioning system supplier shall have instructions related to temporary protection of prestressing steel and components in order to prevent corrosion during transportation from the production site to the job site. Furthermore, the post-tensioning system components shall be suitably packed for shipment and storage on site to protect them against harmful deformation, mechanical damage, chemical or electrochemical changes and corrosion. Prefabricated post-tensioning tendons are usually transported to the site on reels with size depending on duct diameter and length of the post-tensioning tendon. In case of land transportation, it is important to consider law restrictions in advance.

Storage conditions shall ensure that they are kept within an acceptable range of temperature, humidity and UV exposure. This applies in particular to:

- Main tensile elements packaging to avoid damage to steel and sheathing during transportation and storage, as applicable.
- Post-tensioning anchorage components to avoid damage to corrosion protection and sealing, as applicable.
- Sheathing duct to avoid excessive and/or permanent deformations such as longitudinal curvature and/or deformations of the cross section, or damage to surface features.
- Prefabricated post-tensioning tendons, if used, shall be coiled with sufficiently large diameter which do not cause harmful deformations to the duct. Coils shall have a minimum diameter as specified in the post-tensioning system specification.

Metallic surfaces of components shall be protected against corrosion during shipment and storage. This may be achieved by applying the permanent protection in the factory or, if this is not the case, by applying a suitable temporary corrosion protection to the surfaces. Storage on site shall protect post-tensioning system components from direct exposure to rain, dust and site activities. This specially applies to site fabricated post-tensioning tendons.

9.4 Assembly and installation of post-tensioning tendon

The post-tensioning tendon includes the anchorages, the reinforcing steel in the local zone, the duct, duct coupling, duct supports, duct vents, the prestressing steel and the filler. The assembly of the post-tensioning tendon shall be in accordance with the general instructions by the post-tensioning system supplier, the specific method statements prepared for the site by the specialist company, the relevant shop drawings, and the provisions valid at the construction site.

The construction sequence of cryogenic tanks may require specific adapted installation methods to ensure that the components of the post-tensioning tendon are not damaged. Any damaged component in the post-tensioning tendon which cannot be adequately repaired shall be replaced.

Installation procedures of post-tensioning tendons should be developed to minimize the influence in the general construction sequence.

9.4.1 Traceability of installation work

The type, grade and traceability reference of the prestressing steel shall be recorded for each post-tensioning tendon.

Other post-tensioning system components shall be traceable as specified for the project.

9.4.2 Specific aspects of duct installation

The installation of the ducts needs specific attention by all parties involved. Damaged ducts may lead to significant repair work. It is important that the installation of the duct and the works in the vicinity of the duct are done in such a way that the duct is not damaged or protection measures are taken to avoid damages.

The PT specialist should have a documented procedure for the installation and checking of the duct system which comprises: ducts, duct connectors, grouting connections, vents, vent connections, drains if any (e.g. in climates with risk of water freezing), transitions to anchorages and anchorage caps.

Ducts and their coupling should be sealed against the ingress of water during installation and against ingress of laitance during pouring of concrete. An acceptance procedure verifying the cross section and the leak tightness of the installed duct shall be applied before the concrete is poured.

Post-tensioning tendons and components should be placed and secured in a manner that maintains their location during concreting within permissible tolerances. Installation tolerances may be found in PTI¹⁷, ACI⁸, EN and ISO documents. The fixing should also avoid buoyancy of the duct during pouring of concrete. Duct supports should be designed and spaced such as to avoid damage to the ducts and to limit the wobble effect. Spacing of duct supports should be designed for the type of duct used. Round steel bars are suitable for corrugated steel and plastic ducts. However, additional measures to avoid deformations such as indentations of the duct are necessary for polymeric ducts at the location of duct deviation with tight post-tensioning tendon curvatures (i.e. less than achievable based upon *fib* Bulletin 75³⁷ wear resistance performance testing). At such locations, placing of half-shells between the plastic duct and the support is necessary to protect the duct, see Fig. 9-1. The post-tensioning tendon's axis should be coincident and parallel with the axis of the anchorage and couplers, in their vicinity.

The post-tensioning tendon's profile should be checked to avoid any kinks. Such kinks in metal ducts may cause breakage of the prestressing steel wire during stressing. Kinks in plastic ducts may cause leakage at duct couplers and wear-through of the duct.

Vents on the ducts should be provided at both tendon ends and at the points of the post-tensioning tendon where air or water may accumulate. Each vent shall be properly marked to identify the tendon it belongs to and its position along the tendon. During the construction, post-tensioning tendons should be adequately sealed against penetration of moisture.

During the construction process, cryogenic tanks may require a temporary opening in the wall to give access to the inside of the tank. These wall openings are closed in a later stage during construction. The continuity of the vertical and horizontal post-tensioning tendons at these temporary openings require a defined procedure for the duct. Work sequence and duct coupling may be different from duct coupling in the continuous wall section. Mockup trials to confirm the detail may be required.



Fig. 9-1 Half-shell between the plastic duct and the support in order to protect the duct

9.4.3 Specific aspects on installation of prestressing steel and anchorages

After installation of the anchorages and ducts and before concreting, the tendons may be subjected to an air pressure testing to confirm the leak tightness for tendons⁵⁴.

The installation of prestressing steel is often a dynamic process on a critical timeline. Therefore, the method for the installation of the prestressing steel shall ensure that the duct is not damaged.

Welding of prestressing steel and anchor heads is not permitted. Oxygen cutting or welding in the vicinity of pre-stressing steel is not permitted unless special provisions have been implemented to protect the steel.

The stressed post-tensioning tendon shall be left as short as possible not grouted (except tendons composed of individually sheathed and greased strands as they are cement grouted before stressing). The temporary corrosion protection shall be adapted to the time where the stressed tendon is left not grouted and the environmental condition, see Section 9.6.

Post-tensioning tendons (except tendons composed of individually sheathed and greased strands as they are cement grouted before stressing) shall be grouted as soon as possible after stressing. The penetration of water into the post-tensioning tendon shall be prevented by protecting and sealing the anchorages and vents, especially when there is a risk of frost and bursting or cracking of the concrete by the formation of ice. Therefore, it is recommended to cut the prestressing steel ends and install the protection caps as soon as possible after the stressing operations have finalized and approved.

9.4.4 Inspection of post-tensioning tendons prior to concreting

The post-tensioning tendon shall be inspected before concrete pouring operations start. The inspection should include among others the following:

- the position of the post-tensioning tendons, ducts, vents, drains if any, anchorages and couplers in respect of the project specification, including the concrete cover and the spacing of the tendons.
- checking the post-tensioning tendon's alignment for any local kinks in the ducts.
- the fixation of the post-tensioning tendons and ducts, including the provision of adequate resistance against buoyancy and the stability of their supports.
- the duct vents, anchorages, couplers and their sealing to ensure that they are undamaged.
- the tendons, anchorages and/or couplers to ensure that they are not corroded.
- the cleanliness of the ducts, anchorages and couplers preventing any blockage.
- the leak tightness between anchorages and ducts, couplers and ducts⁵⁴.

For encapsulated post-tensioning tendons, see PL2 in Section 5.3, the following additional procedures should be applied:

- verification that duct supports have not created indentations into the plastic duct which will cause a hard spot in the tendon during stressing.
- leak-tightness testing with air pressure test or verification for defects by light during the night or by smoke aerosol (dry ice).

9.4.5 Specific aspects to casting of concrete

The casting of concrete shall be performed in such a way that the concrete in the local zone is well compacted and free of voids. Experience has shown that voids in concrete occur more frequently in upper anchorages of vertical tendons. Moreover, the excessive falling height of concrete during casting should be avoided since it can dislocate or create damage to tendon components.

9.5 Stressing operation

The prestressing forces shall be applied in accordance with a prescribed and approved stressing program available at site and including at least:

- required mean cube or cylinder compressive strength of the concrete at time of stressing.
- inside each stage, time and sequence in which the tendons have to be stressed successively and, if required, indication of partial stressing of tendons.
- for every post-tensioning tendon, the prestressing forces and calculated corresponding elongations.
- time and kind of shuttering lowering and removal.

9.5.1 Preparations for stressing

Before starting with the actual stressing operation, certain preparations and working conditions as well as the safety concerns must be coordinated and confirmed:

- safe access to the stressing points for personnel and equipment
- space for the anchorage or coupler, components available at stressing points
- workspace and platforms for personnel, jack, pump, and lifts
- clearance for the jack
- equipment adequate for lifting, holding and positioning the jack
- power supply with compatible connection for hydraulic pump
- illumination for jobsite and accesses

9.5.2 Specific aspects on hydraulic and auxiliary equipment

Regularly maintained equipment and accessories with valid calibration records for the stressing jack as well as for the force (pressure) and elongation measuring devices shall be provided. The records must be available on site before stressing starts. Jacks shall be compatible with the post-tensioning system and with the size and strength of the prestressing steel. Hydraulic hoses have to be provided in sufficient length. Oil level in the pump reservoir has to be checked before stressing starts. During stressing operation temperature of hydraulic oil should be controlled.

Safety-at-work and health protection shall be available with manual of hydraulic jack. During stressing, nobody is allowed to stand behind or underneath the jack. Attachment eyes and points on the cylinder housing facilitate lifting and transportation of the jack. The jack shall never be lifted by the hoses. When setting it down, care must be taken not to damage the connections for the hydraulic hoses.

9.5.3 Stressing

Stressing operation may start provided that required concrete compressive strength in the structural member is obtained. After installation of anchor head components on both tendon ends, the prestressing steel at the stressing end is arranged in compatible order to mount the jack. Stressing shall be executed according to the specified data. Support of jack onto anchor or structure during stressing shall be aligned and must not be impaired by no means. Stressing force is applied according to the stressing programme and controlled by calibrated pressure gauge. During stressing operations, the pressure gauge and elongation shall always be monitored. Any important observation during the stressing operation, in particular prestressing forces actually applied and corresponding elongation measurements shall be documented in a stressing record for each post-tensioning tendon. This record shall also include the determined actual concrete compressive strength, and type and identification of jack with the related identification of post-tensioning tendons being stressed. Any deviation of prestressing force and elongations shall be recorded, too. Cutting the ends of the post-tensioning tendon or any preparation of subsequent working steps must not proceed until stressing records have been approved. For assessment of deviations of elongation respective regulations in the place of use (e.g. EN 13670⁵⁵) shall be referred to. In this regard the actual values of the prestressing steel's cross section and

Young modulus should be considered. Accordingly, the design engineer shall approve the stressing records or initiate the respective corrective actions. In latter case stressing programme and records shall be adapted if applicable.

A typical application for vertical post-tensioning tendons in cryogenic tanks is the “U shaped” (loop) tube placed at the bottom end of the tank wall. Stressing of the loop tendons should be applied simultaneously from both ends at the top of the tank wall, i.e. the loop tube at the bottom should serve as fixed anchor for both tendons. Special care shall be taken during this stressing operation.

Horizontal post-tensioning tendons in cryogenic tanks typically extend for half ring, covering 180° of the cryogenic tank’s perimeter. If stressing is applied from both sides, it should be carried out consecutively. During stressing operations site staff present at both ends and without direct sight contact must be in direct radio contact. Safety-at-work measures and clearance at both tendon ends, also if one is just passive anchor at that time, shall be strictly observed.

After the stressing operation has been completed and approved, the corrosion protection of the post-tensioning tendons shall be applied. If the final corrosion protection cannot be applied in due time, temporary corrosion protection measures shall be taken, see Section 9.6.



a) Installation of ducts for loop tendons



b) Installation of duct for horizontal tendons



c) Stressing of vertical tendons



d) Stressing of horizontal tendons



e) Testing of grout before grouting



Fig.9-2 Different operations of post-tensioning tendons installation and stressing in cryogenic tanks

9.6 Corrosion protection

9.6.1 Temporary corrosion protection

The corrosion behavior of the prestressing steel varies with the level of ambient aggressiveness (e.g. project environment, proximity to a chemical factory, maritime area, etc.) as well as the humidity level. The risk and speed of corrosion significantly increase in environments with humidity levels above 60%⁵⁵.

Using a temporary corrosion protection system allows to continue with anchoring and stressing operations with a limited impact from weather conditions. In addition, it provides more flexibility with the planning adaptation since the post-tensioning tendons do not require cementitious injections immediately after stressing and could remain protected against corrosion during several months depending on the used system.

The temporary corrosion protection applied to prestressing steel shall be reviewed regularly and renewed in accordance to project specifications, specifications of the supplier and the regulations at the place of use.

In case of absence of those specifications and/or regulation the following measures should be considered:

- The temporary corrosion protection of prestressing steel is applied within two weeks after the stressing operations by spraying soluble oil. Only oils that have been shown to have minimal effect on the bond between the steel and grout shall be used.
- The temporary corrosion protection is then renewed every two weeks and as many times as required.
- The initial application and renewal periods of the temporary corrosion protection can be extended from two to four weeks provided all the following conditions are fulfilled:
 - the environment is not aggressive
 - the prestressing steel is not exposed to the outside of the structure
 - all the sealing and protection caps are installed, and
 - the ducts are continuous

When spraying soluble oil as temporary corrosion protection, this shall cover the prestressing steel over the full post-tensioning tendon including the opposite end. In case of limited access or difficulty in spraying the soluble oil from one side, e.g. for long or U tendons, the soluble oil shall be applied from both tendon ends.

Circulation of dried air/inactive gas inside the duct could be used as an alternative solution for temporary protection of the prestressing steel. This temporary protection could be in place for several months before grouting operations or even as permanent protection of the post-tensioning tendon.

In this temporary solution a drying system and an air pressure pump are connected together to a piping network which is feeding each post-tensioning tendon individually. The post-tensioning tendons are capped at both extremities to limit the required flow rate as well as to avoid the increase of humidity inside the duct. In addition, the circulation of

dried air/inactive gas gives the possibility of anchoring and stressing campaigns all over the year, and planning the cementitious grout injection to be performed at any suitable time i.e. warmer and drier seasons like spring and summer time.

In order to implement a continuous assessment of the circulation of dry air/inactive gas for temporary protection, a humidity sensor should be placed at the tendon outlet positioned opposite to the injection entrance. The humidity sensor could be connected to an acquisition network unit issuing a warning signal in case the humidity measured value exceeds a defined threshold. However, due to economical and practicability concerns, the implementation of this semi-autonomous solution is often governed by a third party's acceptance.

9.6.2 Permanent corrosion protection

9.6.2.1 Cementitious grout injection

The grouting procedure and equipment shall be in accordance with EN 446³⁹ requirements or any equivalent standard applicable at the place of use.

In order to ensure an optimal grouting injection, the following measures shall be implemented:

- The complete volume of grout necessary to inject the post-tensioning tendon(s) shall be produced in advance to avoid any interruption on the grouting operation.
- Horizontal tendons are typically grouted from one end to the other.
- Vertical post-tensioning tendons shall be injected from the lowest extremity. In addition, specific measures shall be implemented at the upper extremity in order to remove the concentration of bleed water. These measures shall be defined by the PT specialist company.

9.6.2.1.1 Grouting procedure requirements

The design of the structure shall take into consideration a potential grouting pressure of 10 bars in horizontal tendons and 20 bars in vertical tendons.

The suitability of a cementitious grout formulation in the conditions of use on site (e.g. temperature) shall be assessed at least one month before the stressing operations are initiated.

In general, it is recommended to perform grouting operations when the temperature of structure is above 3°C and below 35 °C.

Grouting operation with cementitious grout temperature below 5°C needs a longer setting time which increases the risk of bleed pocket and/or voids in the post-tensioning tendon due to migration of bleeding water. This phenomenon is increased for structure temperature conditions below 3°C.

In case the temperature of the structure surrounding post-tensioning tendon is below 3°C, the post-tensioning tendon can be pre-conditioned to ensure the temperature of the cementitious grout remains at least at 5 °C for minimum 48 hours after injection.

In case the pre-conditioning is not possible, the grouting operation shall be postponed until the situation reverts or additional measures are taken, e.g. special grout mix or special equipment.

Contrarily, an ambient temperature higher than 35°C may induce acceleration of setting time of the cementitious grout which increase the risk of interruptions of grouting. In such conditions, it is recommended to precondition the grouting mixture by cooling down the water and controlling the cement temperature.

9.6.2.1.2 Duct filling requirements

In order to ensure the durability of post-tensioning tendon, the cementitious grout filling process of the duct shall:

- Be able to completely fill the free space inside the duct.
- Enable embedment of prestressing steel with bonding resistance capacity.
- Ensure the required compressive strength of cementitious grout (design assumptions) is achieved.

The suitability of the grouting procedure of the duct shall be checked during the grouting mock-up tests according to the following table criteria:

Table 9-1 Criteria for suitability of duct filling

Property	Requirement	Standard or recommendation	Test method
Void volume	Shall not exceed 1% of the volume of grout	EN 447 ⁴⁰ , EN 445 ³⁸	EN 445 ³⁸ Mock-up ²⁾
Void deepness	Shall not exceed 5% of the duct diameter	<i>fib</i> Bulletin 20 ⁵⁶	Mock-up ²⁾
Void section (in lateral and longitudinal directions of tendon)	Shall not exceed 2% of the duct section	<i>fib</i> Bulletin 20 ⁵⁶	Mock-up ²⁾
Tensile element exposure	No tensile element shall be visible ¹⁾	PTI M55.1-19 ⁵⁷	Mock-up ²⁾
Free water	No free water within the duct after hardening of cementitious grout	EN 447 ⁴⁰ , EN 445 ³⁸ and EAD 160027-00-0301 ⁴⁶	Inclined tube test

¹⁾ The positions of the tensile elements have to represent their final position in the structure (when the tensile elements are tensioned)

²⁾ Cracks in cementitious grout are generally induced during opening operation of mock-up and shall not lead to the rejection of the mock-up test

Small bubbling on the cementitious grout surface may occur which is not harmful for the durability of post-tensioning tendons. In case of mock-up test, establishing a pre-agreement on requirements for individual bubbles / voids is recommended.

9.6.2.1.3 Injection method in accordance with tendon layout and cementitious grout properties

Three main items should be considered when defining the injection procedure of the cementitious grout:

- Tendon layout and vertical variation (vertical tendons, horizontal vertically deviated tendons, etc.)
- Physical properties of the cement assessed during suitability and formulation testing (grout workability period, bleed resistance, volume change during setting)
- Quality of the duct installation (e.g. tightness) and position of the vents

Grouting operations shall be considered at the beginning of the construction phase in order to determine the vent positions and as well as the tightness requirements for the duct installation (Section 9.4.2). Similarly, the cementitious grout formulation shall be defined at an early stage of the project considering the cement type available at the project location, the injection procedure and the specific project requirements for the validation.

The main phenomenon occurring during grouting operations which shall be considered into the definition of acceptable quality filling requirements in LNG tank contracts (as per PTI introduction commentary¹⁷) and in the work procedure:

1. Air entrainment within the duct due to insufficiently tight ducts in case of vacuum grouting.
2. Porosity of the cement grout induced either by the hardening of the cement grout, the presence of gas generation or air entrapment within the product.
3. Bleeding water concentration at the highest points of the tendons due to both gradient of pressure going from bottom to top induced by the self-weight of the cement grout, and wick induced effect of the water migrating along the strand wire interspaces.
4. Air bubble entrapment when cement grout crosses the high points.
5. Air bubble entrapment within the pumping equipment.

Item 1 is one of the indirect impacts of the duct installation activities, which justify that grouting technique shall be determined as early as possible in the project, since the duct installation is often performed in absence of the PT specialist company / PT system supplier. A frequent and suitable procedure calls for vacuum assisted grouting of the tendons. This procedure requires a vacuum test which shows tightness behaviour of duct after installation. This test consists in applying vacuum inside the duct using a vacuum pump plugged on one of the vents. Once depressurization is stabilized, around -0.95 bar depending on site atmospheric pressure, the tendon is fully isolated from the vacuum pump and measurement of the increasing pressure is performed. A duct presenting a pressure raise smaller than 100 mbar by minute with a progressing pressure increase, can be considered as airtight. Unless the leaking area can be patched, in the case of leaking duct, the vacuum assisted grouting is to be avoided in order not to suck in air from the outside.

The risk of concentration of bleeding water in long vertical post-tensioning tendons or horizontal post-tensioning tendons with a large vertical profile deviation must be

addressed, either with a specific cementitious grout formulation or by a specially defined cementitious grout injection procedure.

In long vertical post-tensioning tendons, the grouting operation should be divided into two phases. In a first phase, the lower part of the vertical tendon is injected with cementitious grout. Subsequently, the highest part is purged in order to eliminate that grouted section with air bubbles and bleeding water pockets. After the hardening of the cementitious grout in the lower part, the last few meters of the post-tensioning tendon can then be injected through specifically located grouting vents.

In horizontal post-tensioning tendons, the re-grouting operation from the opposite end is used as procedure to push out the air bubbles and the bleeding water pockets throughout the vent. Such a vent disposition is also used to evacuate the air bubble induced by the passage of cementitious grout through at high deviated point in the post-tensioning tendon layout, see Fig. 9-3.

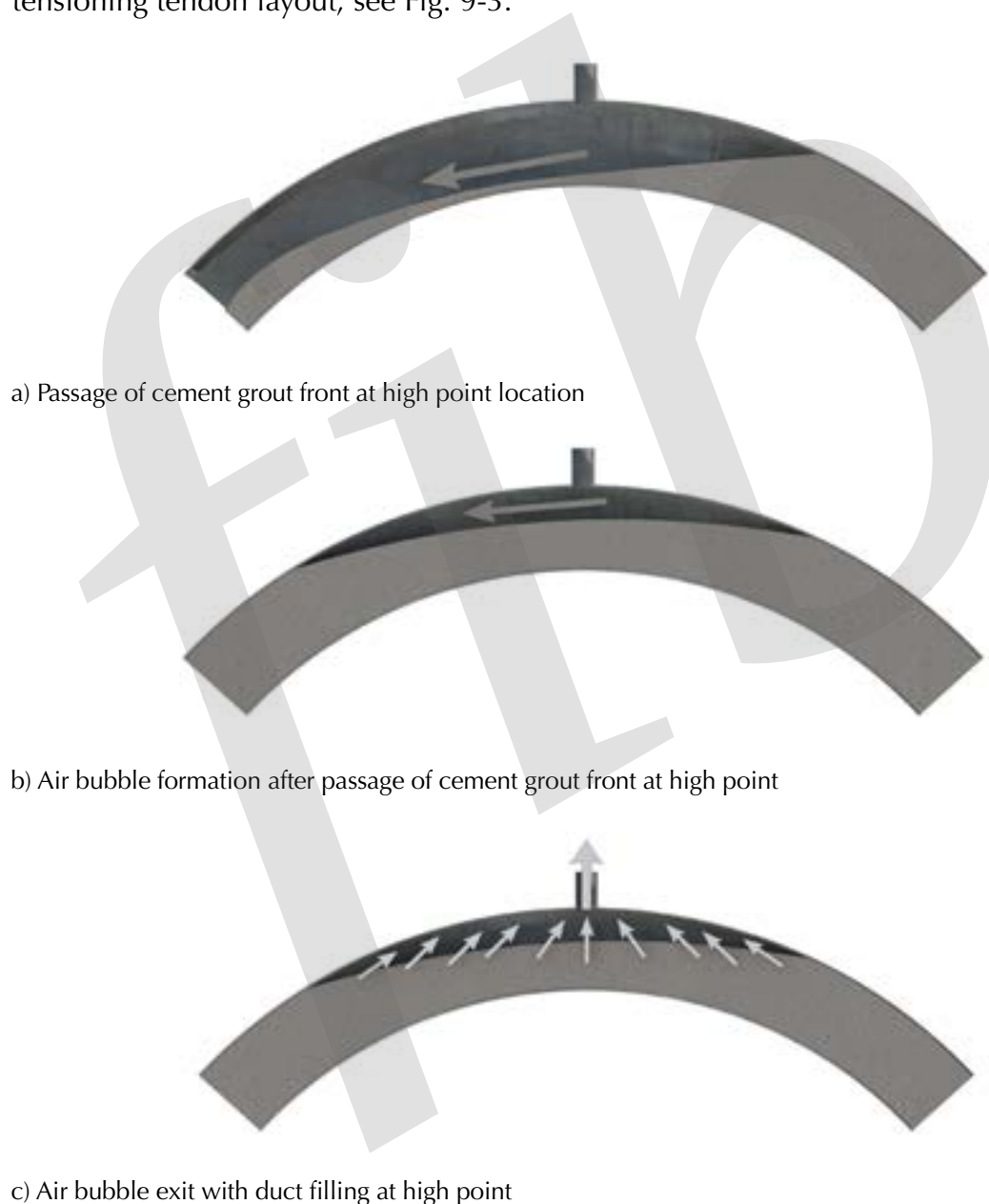


Fig. 9-3 Air bubble and bleeding water drainage through vent

Another alternative for horizontal tendons with large vertical deviation is the use of thixotropic cementitious grout.

Wick induced effect is in general not existing when injecting cementitious grout in post-tensioning tendons composed of duct and sheathed strands.

9.6.2.2 Wax and grease injection

9.6.2.2.1 Wax

The wax injection procedure needs to ensure the complete filling of the post-tensioning tendon including the free length and the anchorage zones. The wax injection of post-tensioning tendons can be carried out by vacuum assisted method.

Prior the wax injection start, the duct air tightness shall be verified by appropriate testing and as well respective health and safety measures shall be put on place. The duct air tightness is checked during a vacuum test similarly as described in Section 9.6.2.1.3 for cement grout injection.

Subsequently, the wax shall be heated up in accordance with the specifications provided by the wax supplier in order that it becomes liquid for injection and remains liquid while moving through the post-tensioning tendon. It needs to be verified that the wax temperature is exceeding the minimum temperature to remain liquid even at the end of the injection section. It is required to have a heated tank with the required volume of wax to completely inject those tendons according to the schedule.

9.6.2.2.2 Grease

The grease injection procedure needs to ensure the complete filling of the post-tensioning tendon including the free length and the anchorage zones. The grease injection procedure is mostly applied to horizontal post-tensioning tendons whereas the experience in vertical post-tensioning tendons is limited.

10 Inspection, maintenance, and repair

10.1 General

While inspection applies to the entire structure, this chapter focuses only on the post-tensioning tendon and its components. A post-tensioning tendon comprises strand/wires, anchorages, duct, fillers, etc.

The type of inspection, the inspection items and methods shall be developed and documented in the inspection and maintenance manual provided by the post-tensioning system supplier. In case of old structures, when such documentation is not available, a new documentation shall be developed by a qualified expert engineer in the field of post-tensioned cryogenic tanks. The inspections during construction are described in the relevant sections of Chapter 9.

Post-tensioned cryogenic tanks should be designed and detailed to permit adequate inspection of the relevant post-tensioning system components. At the end of construction, an initial inspection should be performed to comprehensively document the as-built conditions of the post-tensioned cryogenic tank and the post-tensioning system components, see also *fib* Bulletin 33⁹ and DIN 1076⁵⁸.

During the service life of the structure the post-tensioning tendon shall be inspected, as applicable, at regular intervals to either confirm the good behavior or to detect any relevant damage at early stage. If any damage is detected, this may be reason for an exceptional inspection, and the relevant component(s) shall be subjected to maintenance, repair and / or replacement as applicable.

Four different types of inspection are typically applied:

- Initial inspection (at the completion of construction)
- Routine inspection
- Detailed inspection
- Exceptional inspection

Documentation of inspections may include, but may not be limited to, the following information:

- Date of inspection, name of inspectors
- Program of inspection
- Data collected during the inspection and / or monitoring
- Observation of damages, photographic documentation, video, etc
- Precise location of where the data, observation of damages, photographic documentation and videos were taken
- Evaluation of results of the inspection

These inspections have to be performed supervised by certified engineers having knowledge and experience of post-tensioned cryogenic tanks.

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Table 10-1 presents the types of inspections, the possible inspection method for each component of the post-tensioning system, including the type of post-tensioning (bonded and unbonded).

Table 10-1 Recommendation of inspection of post-tensioning tendons for cryogenic tank applications

Components	Inspection item	Inspection method	System type	Type of inspection			
				Initial inspection	Routine inspection	Detailed inspection	Exceptional inspection
Free length	Wire fracture	Magnetic induction / Ultrasonic flaw detectors	Unbonded	-	-	Δ	Δ
	Tendon load	Load cell / Lift off / Electromagnetic sensor / Rayleigh-radiation ¹⁾	Unbonded and bonded ¹⁾		-	Δ	Δ
	Corrosion	Single strand replacement ¹⁾ / eddy current / ultrasonic pulse echo / glass fibre optic	Unbonded ¹⁾ and bonded	-	-	Δ	Δ
	Grout	Ultrasound	Bonded	-	-	Δ	Δ
Anchorage zone	General condition (e.g. corrosion, wedges, cap, etc.)	Visual external ¹⁾ / Visual internal ²⁾	Unbonded and bonded (if applicable)	O ¹⁾	O ¹⁾	O ²⁾	Δ ²⁾
	Water infiltration inside anchorages	Visual internal	Unbonded and bonded	-	-	O	Δ
	Conditions of filler	Visual internal ¹⁾ / Chemical ²⁾	Unbonded and bonded	-	-	O ¹⁾	Δ ²⁾
	Filler leakage	Visual internal	Unbonded	O	O	O	Δ
	Absence of strand slippage	Visual internal	Unbonded	-	-	O	Δ
	Crack pattern and width	Visual caliper, computer vision / AI tool	Unbonded and bonded	O	O	O	Δ
	Crack depth	Ultrasonic pulse velocity	Unbonded and bonded	O	O	O	Δ
	Concrete condition	Visual and rebound hammer	Unbonded and bonded	O	O	O	Δ

O: Mandatory inspection items,

Δ: Inspected if determined necessary by expert engineer

10.2 Initial inspection

The initial inspection shall be performed at the end of construction, at the time of hand-over of the structure to the owner. This initial inspection shall establish a proper reference (“initial certificate”) of the structure and the post-tensioning system for future inspections, and should include at least the following:

- Document initial inspection investigation content:
 - Latest version of complete method statement including, inspection and maintenance manual, monitoring plan documentation and general assembly drawing of the post-tensioning system, As-Built
 - Record of the actual stressing forces and elongations
 - Record of the tendon tightness checking
 - Record of the filling injection report, as applicable (i.e. grout, wax, grease)
 - Record of temperatures (ambient, structure and post-tensioning system components at the time of the survey)
 - Records of any major repairs done during construction
 - Records of As-Built material properties, suitability test data, traceability, QC of components and material certificates or CE Marking which is covering all these documents
 - Records of position of both anchorages after construction
- Initial Inspection report according to Table 10-1

10.3 Routine inspection

Routine inspection is achieved as “walk-through” inspection on the structure typically performed once a year or specifically after a significant event (e.g. storm, earthquake, etc.). This inspection aims to detect deterioration or damage within the inspected areas at an early stage. Routine inspection is usually made without the use of auxiliary instruments and should at least include items reflected in Table 10-1.

10.4 Detailed inspection

Detailed inspection is suggested to be performed every five years on about 10% of the tendons. The number of cables to be inspected should be increased in case of a significant damage is found in comparison between previous inspections. The amount / frequency of inspection should be such that all components are inspected at least once within their specified period between subsequent maintenance operations.

For detailed inspections specific measuring tools and adequate access means such as trolleys, scaffolding, etc. should be used. The scope of detailed inspection shall be developed by the post-tensioning system supplier and be included in the inspection and maintenance manual. In addition to the controls for routine inspection, detailed inspection should include items reflected in Table 10-1 and also the details defined in

the inspection and maintenance manual provided by the post-tensioning system supplier.

In addition, a topographic control of the structure is recommended and can be probably done in regard to the maintenance management of the whole cryogenic tank.

10.5 Exceptional inspection

Exceptional inspections should be carried out in case of damage due to sudden events as accidents, vandalism or catastrophes. They may also be performed in case unexpected damage is detected during either a routine or detailed inspection. The program of the exceptional inspection should include items reflected in Table 10-1 which are adapted to the specific event or detected damage.

10.6 Monitoring

Suitable monitoring equipment and tools for transmittal of the data to the owner, designer, or specialist companies are becoming more easily available and may offer additional important data on the behavior of the post-tensioning tendons and the structure during time. The program of monitoring can include the items reflected in Table 10-2.

Table 10-2 Recommendation of monitoring methods of post-tensioning tendons for cryogenic tank applications

System type	Monitoring item	Monitoring method	System type
Free length & Anchorage zone (if applicable)	Wire fracture	Acoustic/ magnetic induction / ultrasonic flaw detectors	Unbonded and bonded
	Tendon load	Load cell / Electromagnetic sensor	Unbonded only
	Corrosion	Ultrasonic pulse echo / Eddy current	Unbonded and bonded

10.7 Evaluation for results of inspection

Results of the inspection shall be evaluated by a qualified expert engineer in the field of post-tensioned cryogenic tanks and systems. The expert engineer shall submit a recommendation for actions i.e. maintenance, repair, replacement or strengthening depending on the situation and the corresponding bonded or unbonded post-tensioning systems. Recommendation from the expert engineer shall include the urgent actions to be taken and distinguish between durability issues, load bearing capacity issues and other issues.

10.8 Repair, replacement and strengthening

In case any damage is detected during the inspection of the post-tensioning system, this, its components and/or the corresponding structure shall be repaired, replaced or strengthened with the procedure planned by the designer and in accordance with the method statement of the post-tensioning system supplier.

In any case, all works carried out on the cryogenic tank shall be documented, including the following information:

- Date, location and type of repair, replacement or strengthening work
- List and certificates of materials used, list of contractors, and stressing records if applies
- Details of structural modifications if any
- Name of the responsible person in charge of the repair, replacement and strengthening



11. Assessment and verification of constancy of performance

Despite other recommendations and guidelines (e.g. EAD 160004-00-0301¹¹, PTI/ASBI¹⁷), which are available for prestressing of structures in general, this recommendation is focused on post-tensioning systems used in cryogenic tanks and includes a classification of the different cryogenic tanks typologies, the associated different tendon types depending on their exposure to low temperature (e.g. never, only accidentally or during normal tank operation) and the testing regime required for the acceptance of the materials and the post-tensioning system.

Focusing on the post-tensioning systems used in cryogenic tanks, this document aims to cover best construction practices and to provide all required aspects in a systematically manner for ease of use (for owner, design engineer and post-tensioning system supplier), from performance characteristics, requirements and acceptance criteria up to the verification and assessment process.

Therefore, this chapter provides some brief information and guideline about how such assessment/approval process may be set up, in particular for countries which and owners who have little experience with such process. This information is based on the process applied in European Technical Assessments for Post-tensioning systems¹¹.

11.1 General

Post-tensioning systems to be assessed/approved according to these recommendations shall undergo both, the technical assessment process and the verification of constancy of performance.

The technical assessment consists of a defined series of testing and its evaluation by an assessment body, see Sections 11.2 and 11.3. The verification of constancy of performance consists of a defined series of tasks for the post-tensioning system supplier and a certification body to ensure that the post-tensioning system delivered to site is fulfilling the same technical specification of the one used during the technical assessment, see Sections 11.5 and 11.6.

Post-tensioning systems having a valid CE marking fulfill these two requirements. Post-tensioning systems without a valid CE marking need to undergo the process for technical assessment and verification of constancy of performance as explained in Sections 11.2 to 11.6.

11.2 Technical assessment process

The technical assessment process consists of the assessment testing as described in Chapter 8 and a subsequent evaluation of the results against the acceptance criteria by the assessment body. The post-tensioning system supplier foreseeing the assessment shall introduce the post-tensioning system to the assessment body. The testing laboratory(ies)

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and program should be agreed upon in advance. Then, the post-tensioning system supplier shall perform the required testing, prepare and submit all the required documentation of the post-tensioning system to the assessment body. Once the assessment body has evaluated and confirmed that all the requirements are satisfied, the technical assessment is granted.

The technical assessment remains valid as long as there are no changes in the post-tensioning system. If any relevant detail, likely affecting the performance of the post-tensioning system, is changed, a new or amended technical assessment shall be made.

Before using the post-tensioning system on the site, the post-tensioning system supplier needs to contract an independent body/certification body that will verify the compliance of that system with the specifications and conditions under which the technical assessment has been granted.

11.3 Assessment / approval body

In Europe the governments of the different countries designate assessment bodies for the technical assessment of post-tensioning systems. Similar bodies exist in other countries (e.g. FDOT in the U.S.). If such a system of designation does not exist, owners or professional organizations may designate such assessment/approval body for specific task as well. The assessment body needs to be independent and technically qualified for the task of assessing post-tensioning systems. Other set-ups for assessment bodies and assessment committees may be possible.

11.4 Certification body

Similarly, to assessment/approval bodies, in Europe the designation of certification bodies is directly made by the government of different countries. Likewise, equivalent bodies might exist in other countries. If such a system of designation does not exist, owners or professional organizations may designate such certification body for specific task as well. The certification body needs to be independent and technically qualified for the task of auditing of post-tensioning systems.

11.5 Verification of constancy of performance

The verification of constancy of performance consists of a series of tasks to be performed by the post-tensioning system supplier (which is in Europe called technical assessment holder) and the certification body. As a result, the certification body will issue a verification document that the post-tensioning system is fulfilling the same technical specification of the one used during the technical assessment. The verification document should be valid by a limited period of time (e.g. two years). Exceeded that time the post-tensioning system supplier shall seek for renewal of the verification document.

The tasks defined for the verification of constancy of performance shall be carried out during the entire period of the validity of the verification document.

If a deviation from the assessed post-tensioning system is detected within the period of the validity of the verification document and that cannot be corrected satisfactorily, the certification body may suspend the validity of verification document.

11.5.1 Tasks of the post-tensioning system supplier

In general, the post-tensioning system supplier is requested to perform the following tasks:

- Audit of the component manufacturers
- Permanent control of the factory production control (FPC)

The post-tensioning system supplier shall keep record of relevant results concerning the technical assessment and the audit reports concerning the components manufacturers for at least the last 10 years.

11.5.2 Audit of the component manufacturers

The post-tensioning system supplier shall keep available an updated list of all components manufacturers. A copy of this list shall be made available to the certification body. At least once a year, each components manufacturer shall be audited by the post-tensioning system supplier, except for standardized components covered by a CE marking or equivalent e.g. steel ducts. The tasks may be transferred to an independent test laboratory. Nevertheless, the post-tensioning system supplier has the full responsibility for all results of the audit. Each audit report shall be made available to the certification body. These audit reports typically include:

- Identification of the component manufacturer
- Check the version of component specifications
- Date of audit of the component manufacturer
- Summary of the results and records of the FPC since last audit
- Summary of the complaint records
- Evaluation of the component manufacturer concerning FPC
- Specific remarks as relevant
- Clear and unique statement whether the requirement of the technical approval are met
- Name and position of signatory
- Date of signature
- Signature

11.5.3 Permanent control of the factory production control (FPC)

The post-tensioning system supplier shall establish and perform a permanent internal control of the production. All the elements, requirements and provisions adopted by the post-tensioning system supplier shall be documented in a systematic manner in the form of written policies and procedures. This control system ensures that the post-tensioning system is in conformity with the technical assessment. The FPC and the prescribed test plan should address the following aspects:

- manufacturing
- distribution and delivery to job site

FPC systems which comply with national standard/specification and which address the requirements of the technical approval are acceptable. Parts of the FPC may be transferred to an independent test laboratory. Nevertheless, the post-tensioning system supplier has the full responsibility for all results of the FPC.

11.5.3.1 Control of the incoming materials

The component manufacturer has to check that the incoming materials comply with its specifications. The characteristics of incoming materials which comply with a harmonized technical specifications are considered satisfactory and no further checking are required, except in case of justified doubts.

11.5.3.2 Inspection and testing

The validity of the type and frequency of checks/tests conducted during production and on the final product is considered as a function of the production process. This will include the checks conducted during manufacture on properties that cannot be inspected at a later stage and for checks on the final product. These will normally include:

- Definition of the number of samples taken by the post-tensioning system supplier
- Material properties e.g. tensile strength, hardness, surface finish, chemical composition
- Determination of the dimensions of components
- Check correct assembly
- Documentation of tests and test results.

All tests are performed according to written procedures with suitable calibrated measuring devices. All test results are recorded in a consequent and systematic way. The post-tensioning system and the approval body issuing the technical assessment agree on a prescribed test plan. This prescribed test plan is necessary to ensure that the product corresponds to the technical assessment and its characteristics remain unchanged.

11.5.3.3 Control of non-conforming products

Products which are considered as not conforming to the technical assessment shall be immediately marked and separated from such products which comply. The prescribed test plan has to address control of non-conforming products.

11.5.3.4 Complaints

The prescribed test plan shall include provisions to keep records of all complaints about the post-tensioning system.

11.5.3.5 Tasks of the certification body

In general, the certification body is requested to perform the following tasks:

- Initial inspection of the factory and FPC
- Continuous surveillance, assessment and approval of the FPC
- Audit testing of samples taken at the factory

11.6 Task of certification body

11.6.1 Initial inspection of the factory and FPC

The certification body shall verify that, in accordance with the prescribed test plan, the manufacturing plant, in particular personnel and equipment, and the factory production control are suitable to ensure a continuous manufacturing of the post-tensioning system according to the given technical specifications. The activities shall be conducted by the certification body or under its responsibility which may include a proportion included by an external inspection body, witnessed by the certification body.

11.6.2 Continuous surveillance, assessment and approval of the FPC

The activities shall be conducted by the certification body or under its responsibility which may include a proportion carried out by an external inspection body and witnessed by the certification body.

The activities include:

- Surveillance inspections: The post-tensioning system supplier is inspected at least once a year. The FPC is checked and verified that the FPC is maintained, and samples are taken for independent single tensile element tests.
- Inspection of components manufacturers: All component manufacturers should be checked once in 5 years except for standardized components covered by a CE marking or equivalent.

11.6.3 Audit testing of samples taken at the factory

During the surveillance inspection the certification body shall take samples of components of the post-tensioning system, for which this technical assessment has been granted, for independent testing. Audit testing is conducted by the certification body or under its responsibility which may include a proportion conducted by an indicated laboratory or by the post-tensioning system supplier, witnessed by the certification body or inspection bodies. The post-tensioning system supplier proposes different sites and prestressing steel from different suppliers actually used. The certification body should choose the site and the prestressing steel supplier. If the post-tensioning system supplier uses several prestressing steel suppliers or several wedge or anchorage device suppliers, then different combinations have to be tested every year. If the post-tensioning system comprises several anchorages or coupling sizes then the tested sizes vary year by year (it is avoided to test always the same size). If the post-tensioning system comprises different types of anchor heads e.g. with different materials, a test series is done for each type.

Audit testing should typically comprise the dimensions and material checks of components and single strand system testing¹¹. Additional tests might be required based on local or project regulations.

11.6.4 Decision of the certification body

The certification body verifies the results of the surveillance inspections, the inspection of components manufacturers and the results of independent testing and ensures conformity with the technical specifications. In case of severe non-conformities which relate to important performance aspects of the post-tensioning system and which cannot be corrected in due time, the certification body shall withdraw the verification document. The certification body shall inform the assessment body about the withdrawal of verification document and report about the reasons. If minor deficiencies are detected, corrective measures shall be taken by the post-tensioning system supplier. These typically include:

- Action against warning from the certification body
- Higher inspection and test frequency
- Implementation of changes



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Acceptance of post-tensioning systems for cryogenic applications

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