STANDARD

DNVGL-ST-F119 Edition August 2018

Thermoplastic composite pipes

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FOREWORD

DNV GL standards contain requirements, principles and acceptance criteria for objects, personnel, organisations and/or operations.

CHANGES – CURRENT

This is a new document.

This document supersedes the December 2017 edition of DNVGL-RP-F119.

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Acknowledgements

<div style="text-align: right">Changes – current</div>

CONTENTS

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SECTION 1 GENERAL

1.1 Introduction

1.1.1 Objectives

This standard describes requirements for flexible thermoplastic composite pipes (TCPs) for offshore applications.

This standard is intended to build trust and confidence in TCPs being safe and reliable for use in offshore service. Further, it has the objective of promoting continued innovation and technology development.

In order to achieve this, the standard describes how TCPs can meet the technical provisions and documentation requirements of DNVGL-ST-C501, and thus achieving the prescribed minimum safety level.

Descriptive technical solutions are not enforced, as that would hinder technology development and limit the opportunities for industry to find and implement cost-effective solutions.

This standard provides the design philosophy and requirements to specifications of loads and global analysis valid for TCPs. The standard applies to all newbuilt TCP systems and may be applied to the modification, operation and upgrading of existing pipelines and risers.

1.1.2 General approach

The approach taken to achieve these objectives is to state high level functional requirements in order for TCPs to be used safely and reliably offshore and to permit alternative ways of achieving compliance with those high level requirements. This is intended to allow for the acceptance of innovative solutions not yet known when the standard was written.

Technical provisions and recommendations are formulated based on current best industry practice among the contributing organizations at the time of writing.

1.1.3 Use

This standard is intended to provide recommendations to users, owners, system integrators, and manufacturers of pipes, load-bearing fibres, thermoplastic polymer materials, tapes and termination hardware.

This standard is structured according to design principles rather than application areas. It has only been attempted to link technical provisions and acceptance criteria to specific uses where necessary, as this will increase the versatility of the document for readers who are involved in several application areas and those who are unfamiliar with the topics.

This standard may be used as a contractual reference between suppliers and purchaser of TCP.

1.1.4 Key principles of application

This standard emphasizes the following key aspects:

— Technical provisions and acceptance criteria are provided to prevent the TCP from failing of the TCP in response to combinations of cross-sectional forces and moments, and internal and external pressures.
— When the TCP is part of a larger system, case-specific issues related to its use and integration shall be accounted for, such as handling, impacts, local abrasive loads and the integration of ancillary equipment.
— This standard requires that a system risk assessment to be performed, the identified risks to be assessed and suitable mitigating actions to be documented.
— Unless a relevant standard or specification for the system is applied, the system risk assessment should be performed in accordance with the technology qualification principles of DNVGL-RP-A203.

1.1.5 Alternative solutions

Alternative solutions found to represent an overall safety level equivalent to that stated in DNVGL-ST-C501 may be accepted, if adequately documented. The principles of DNVGL-RP-A203 can be used for that purpose.

1.2 Scope

1.2.1 General

This standard provides the design philosophy and requirements to specifications of loads and global analysis valid for TCPs. The standard applies to all newbuilt TCP systems and may be applied to the modification, operation and upgrading of existing pipelines and risers.

1.2.2 Description of thermoplastic composite pipe

TCP are flexible bonded structures and the composites are fibre reinforced laminates with a thermoplastic matrix. The pipes are similar to composite pipes made of fibre reinforced thermoset composites. However, the thermoplastic material is more flexible allowing the thermoplastic pipes to be used in applications where higher bending strains are needed. This standard will therefore be largely based on technology and knowledge related to composite thermoset pipes or risers and unbonded metal reinforced flexible pipes or risers. The novelties will be the combination of requirements, and some aspects being unique for bonded flexible thermoplastic pipes and thermoplastic materials in general.

1.2.3 Qualification of thermoplastic composite pipes for offshore use

The standard provides recommendations and information including technical provisions and acceptance criteria pertaining to TCPs in offshore use. The standard addresses three main areas:

— design of TCPs for designated offshore use
— testing of performance characteristics for TCP´s materials and pipes
— analysis of TCP as part of an integrated system.

In addition, at a high level:

— production and delivery of TCPs.

The standard provides recommendations for the design, testing and analysis of TCPs for use in:

— dynamic riser systems in accordance with DNVGL-ST-F201
— subsea pipelines in accordance with DNVGL-ST-F101.

In both cases this standard describes methods to meet the acceptance criteria for:

— Composite materials in accordance with DNVGL-ST-C501.
— Dedicated partial load and resistance factors are specified herein for limit states relevant to TCPs.

The standard provides extensive acceptance criteria versus requirements for basic material properties. The need for extensive material testing is due to the nature of components made from composite materials.

1.2.4 Transfer of responsibility at delivery

On delivery, the responsibility for the pipe is transferred from the supplier to the recipient. Safe and reliable service depends on the proper use and maintenance of the TCP as well as timely decommissioning should its condition deteriorate unacceptably. In support of this, the standard includes production and operational (inspection and repair) requirements, evolving from the design, and assumptions made for the design, that should be observed in service.

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However, this standard does not specify complete operational requirements and manuals for users and operators to ensure that the TCPs remain fit for service when in use. Such specifications depend on the system that the TCP is part of and would need to be developed on a case-by-case basis. Any such specifications shall ensure that the TCP is used within its design envelope.

1.2.5 Range of applications for thermoplastic composite pipe

The applications addressed in this standard are static and dynamic pipes used, for example, as:

— flow lines
— risers
— jumpers
— choke and kill lines
— expansion spools
— well access lines
— chemical injection lines
— downlines for pipeline pre-commissioning
— intervention lines.

No restrictions are put on fluids or environments, as long as the component's compatibility with the fluids and environment can be demonstrated. The fluids inside the TCPs addressed in this standard are typically liquids and gases such as hydrocarbons, water, air, nitrogen or injection chemicals.

The global loads acting on the TCP will be different for each application and are not covered in this standard. They need to be assessed based on system analysis. Some guidance and requirements are given in [3.6].

1.2.6 General build up - components

The TCP assembly comprises a pipe body and end fittings, see Table 1-1.

The pipe body is made up of three main components: an inner thermoplastic liner, a thermoplastic laminate (TCP laminate), and an outer thermoplastic cover. The inner thermoplastic liner serves mainly as a barrier towards the inner fluid. The TCP laminate is the load bearing component. The outer thermoplastic cover is a protective layer. The inner liner, laminate and cover are all bonded or fused to the TCP laminate. A schematic of a typical cross section is shown in Figure 1-1. The interface between the liner and TCP laminate, and interface between the TCP laminate and cover are also defined as pipe components. This is because their properties and behaviour are important to the function of the TCP. Additional outer layers may be added as special-purpose layers, e.g. as local wear and tear protection or fire protection.

Typically the inner liner is an extruded thermoplastic pipe. The TCP laminate is a thermoplastic matrix reinforced by fibres, typically made by tape winding or filament winding. The cover is usually extruded over the laminate.

Sometimes the TCP does not have a liner or cover. In these cases the TCP laminate shall additionally fulfil all the requirements of the omitted liner or cover.

The end fittings (or end terminations) are attached to the ends of the TCP. A generic end fitting is shown in Figure 1-2. This standard addresses the composite-to-metal interface and aspects of the end fitting that relate to TCP performance, such as load transfer and tightness, see also [1.2.9].

Upper and lower end fittings may be designed differently due to different loading conditions.

All the components are summarized in Table 1-1.
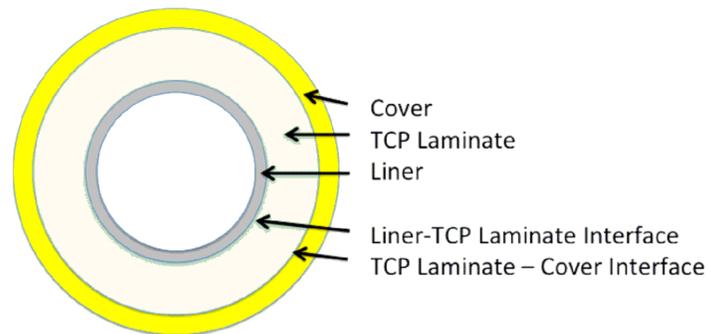
Figure 1-1 Simple schematic cross section of the body of a bonded thermoplastic composite pipe
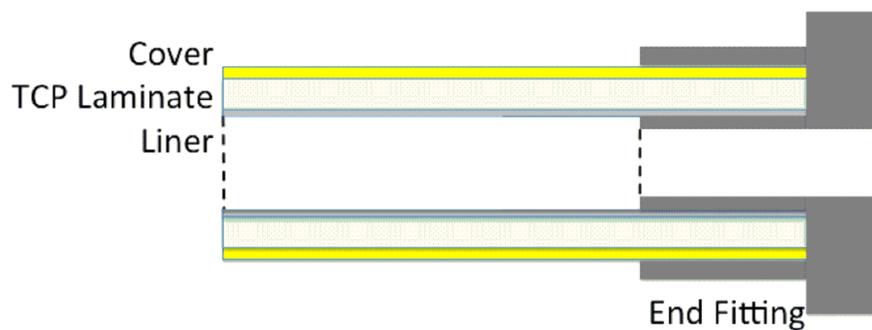
Figure 1-2 Schematic example of a TCP with end fittings (TCP assembly)

Table 1-1 TCP components covered in this standard

Component	Explanation
Liner	See Figure 1-1 and Figure 1-2
Liner-TCP laminate interface	See Figure 1-1
TCP laminate	See Figure 1-1 and Figure 1-2
TCP laminate-cover interface	See Figure 1-1
Cover	See Figure 1-1 and Figure 1-2
End fittings	see Figure 1-2
TCP*	Pipe section without end fitting
TCP assembly	TCP with end fitting
* The term TCP is used for the pipe of the TCP assembly. In some cases TCP may also just refer to the general product described in this standard.	

Ancillary equipment may be added to the TCP, such as an outer special purpose layer, bend stiffeners/restrictors or anchoring points. Ancillary equipment is not covered by this standard and may be developed in accordance with ISO 13628-16/17 or API 17L1/L2.

Interactions between such equipment and the TCP shall be considered.

1.2.7 Matrix materials

This standard is applicable to all thermoplastic matrix materials.

Thermoset and ceramic matrix systems are not covered by this standard. These materials may still be used in the end fittings. Their performance shall be documented according to DNVGL-ST-C501.

1.2.8 Thermoplastic composite pipe fibres

The main load-bearing fibres shall form a continuous reinforcement. Short fibres may be used as fillers.

The fibre material shall not undergo a phase change while the TCP is in use.

The fibres shall always be kept below their melting temperature T_m during the full life cycle of the TCP, such as during production and operational phases.

Some splicing of fibres is acceptable, as described in [7.8.14] and [13.2].

Temperatures during any phase shall never cross the glass transition temperature. Exceptions may be made if TCP properties are measured above and below T_g of the fibres, see [A.2].

This standard covers the following fibre types:

— glass
— carbon
— basalt
— aramid
— polyester
— polyethylene.

Laminates with a mixture of different fibres (hybrids) may be used. Other fibres may be considered if the requirements of [1.2.8] are fulfilled. This standard does not cover steel and metal fibres.

1.2.9 End fitting – composite metal interface

End fittings are generally made of metals. This standard covers the composite metal interface and interactions of the metal end fitting with the pipe section. It covers aspects of the metal that relate to TCP performance, such as load transfer and tightness.

The design of the metal parts of the end fittings themselves and of flanges, etc. is not covered by this standard. Metal components shall be designed in accordance with relevant standards, see [8.3].

Any taper in the metal end fitting to ensure smooth transition of forces into the pipe shall be considered in the design.

If the TCP has extra layers or additional thickness at or near the end fitting, the component shall be designed and analysed as a new section of the TCP. Any tapers in the TCP laminate shall also be considered in the design.

Any sealing mechanisms (O rings etc.) shall be described in the design. Their particular function is not covered by this standard.

Possible metal corrosion shall be addressed in the design. Metal corrosion is not addressed in this standard.

1.2.10 Applicable requirements

This standard refers extensively to:

— DNVGL-ST-C501 *Composite components*
— DNVGL-ST-F201 *Dynamic risers*
— DNVGL-ST-F101 *Subsea pipelines*.

The requirements of these standards shall be fulfilled for the aspects they are referred to.

1.2.11 Relationship of this standard to other standards

This standards scope relative to other flexible pipe standards is shown in Figure 1-3.


```
                    Flexible pipe for offshore use
                    ┌──────────────┴──────────────┐
              Metal based                    Composite based

        Unbonded      Bonded             Unbonded      Bonded


        API 17J       API 17K                       DNVGL-ST-F119

        Specification Specification                 Thermoplastic
        for Unbonded  for Bonded                    composite pipes
        Flexible Pipe Flexible Pipe
```
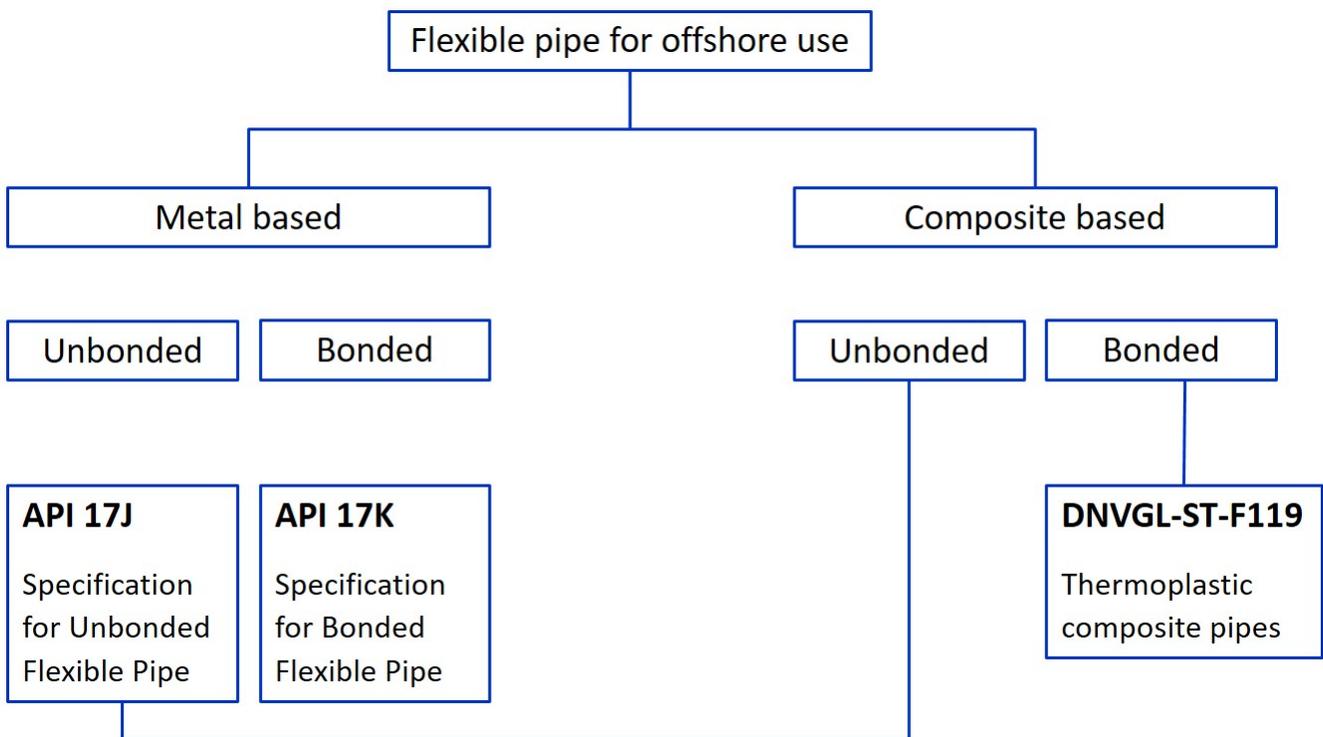
Figure 1-3 Relationship of this standard to other flexible pipe standards.

No standard exists for unbonded composite pipes, but API17J partially covers this subject by referring to DNVGL-ST-C501 (dotted line).

The standard is linked to other DNV GL standards, as shown in Figure 1-4.
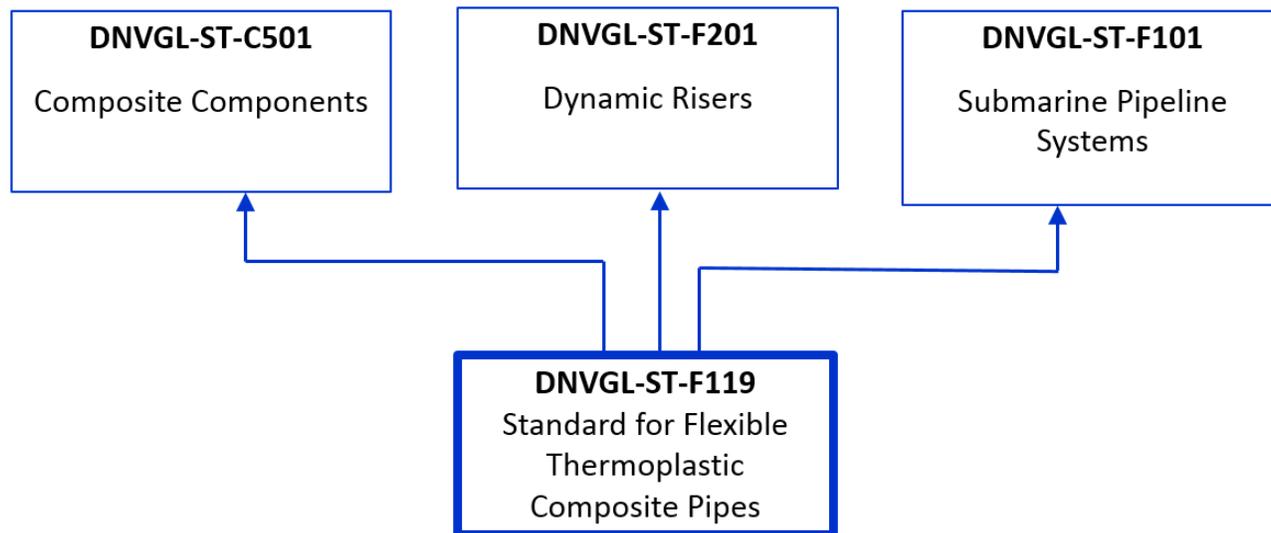
Figure 1-4 Relationship of this standard to other DNV GL standards (ST) concerning composite materials, pipes and risers. The lines show how the standards refers to STs

If requirements in the above documents also apply to TCPs, they are referred to or replicated in this document for convenience. References are not given for each individual case.

API 15 S is a specification for spoolable reinforced plastic line pipe which has some similarities with TCPs. However, API 15 S is not shown in Figure 1-3 and Figure 1-4, because it is only applicable to flow-lines and does not cover offshore applications. Internal pressure and reeling are the only load cases considered.

1.2.12 Structure of this standard

This standard is divided into five main parts:

— The first part describes the standard itself, its introduction, philosophy and scope.
— The second part specifies the design input.
— The third part describes the required material properties and failure criteria.
— The fourth part describes the design process, covering analysis, design criteria, prototype tests and safety factors.
— The fifth part covers activities after the design is finished, such as inspection, quality assurance and documentation.

A link between the main parts and the actual sections of the standard is given in Table 1-2.

Table 1-2 Structure of the standard

Part	Section	Title
Introduction to the standard, philosophy, scope	This section	General
	This section	Introduction
	This section	Scope
	This section	Referenced standards and codes
	This section	Terms, symbols, abbreviations and definitions
	Sec.2	Design philosophy
	[2.1]	Safety philosophy
	[2.2]	Design format
	[2.3]	Design approach
	[2.4]	Risk and FMEA
	[2.5]	Liner and cover damage
Design input	Sec.3	Design
Materials and failure	Sec.4	Materials
	Sec.5	Failure mechanisms
Analysis and testing	Sec.6	Analysis
	Sec.7	Design criteria pipe body
	Sec.8	Design criteria end fittings
	Sec.9	Performance based qualification - full scale testing only
	Sec.10	Prototype test requirements - full scale samples
	Sec.11	Safety factors
Production, service, documentation	Sec.12	Operational phase: inspection, maintenance, repair
	Sec.13	Production QA test requirements
	Sec.14	Marking and packaging
	Sec.15	Documentation

1.3 Application

This standard is intended for:

1) Suppliers of TCPs for offshore service and suppliers of raw materials for such pipes that are seeking market access for their products.
2) Operators, contractors and others seeking acceptance for using TCP in offshore operations.
3) Suppliers and purchasers of TCPs who need a common technical basis for contractual reference.

This standard is applicable to all thermoplastic matrix materials.

Thermoset and ceramic matrix systems are not covered by this standard.

1.4 Referenced standards

1.4.1 Relationship to other standards

The following standards and codes include requirements which, by being refferred to in the text, constitute requirements of this document.

References are defined as either normative or informative. Normative references in this document are mandatory for the document's application. Informative references provide additional information intended to assist the understanding or use of the document.

> **Guidance note:**
>
> Normative references are typically referred to as "testing shall be performed in accordance with ISO xxx", while informative references are typically referred to as "testing may be performed in accordance with ISO xxx or ISO yyyy", or "for testing, reference is given to DNVGL-RP-Fxxx".
>
> ---e-n-d---o-f---g-u-i-d-a-n-c-e---n-o-t-e---

In case of conflict between this standard and referenced DNV GL standards or recommended practices, the standard or recommended practice with the latest edition date shall prevail.

The latest valid edition of each of the DNV GL reference documents applies.

Where reference is made to standards and codes other than DNV GL service documents, the referenced version should be understood to be the version which was current at the date of issue of this standard.

1.4.2 DNV GL standards

Table 1-3 DNV GL standards

Document code	Title
DNVGL-ST-C501	Composite components
DNVGL-ST-F101	Submarine pipeline systems
DNVGL-ST-F201	Dynamic risers

1.4.3 DNV GL recommended practices

Table 1-4 DNV GL recommended practices

Document code	Title
DNVGL-RP-C211	Structural reliability analysis (replacing DNV CN 30.6)
DNVGL-RP-F203	Riser interference
DNVGL-RP-F109	On-bottom stability design of submarine pipelines

1.4.4 Other standards and codes

Table 1-5 Other standards and codes

Document code	Title
API 15S	Qualification of Spoolable Reinforced Plastic Line Pipe, 1st edition, March 2006
API 17 B/ISO 13628-11	Recommended Practice for Flexible Pipe
API 17 J/ISO 13628-2	Specification for Unbonded Flexible Pipe, 3rd edition, July 2008
API 17 K	Specification for Bonded Flexible Pipe
API 17 L1	Specification for Flexible Pipe Ancillary Equipment
API 17 L2	Recommended Practice for Flexible Pipe Ancillary Equipment
API 17 TR2	The Aging of PA 11 in Flexible Pipes, API Technical Report 17TR2,
API RP 2RD (R2006)	Design of Risers for Floating Production Systems (FPS) and Tension-Leg Platforms (TLPs)
ASTM C177	Standard Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Guarded-Hot-Plate Apparatus
ASTM C518	Standard Test Method for Steady-State Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus
ASTM D1044	Standard Test Method for Resistance of Transparent Plastics to Surface Abrasion
ASTM D1505	Standard Test Method for Density of Plastics by the Density-gradient Technique
ASTM D2412 - 11	Standard Test Method for Determination of External Loading Characteristics of Plastic Pipe by Parallel-Plate Loading
ASTM D256	Standard Test Methods for Determining the Izod Pendulum Impact Resistance of Plastics
ASTM D4060	Standard Test Method for Abrasion Resistance of Organic Coatings by the Taber Abraser
ASTM D5229	Standard Test Method for Moisture Absorption Properties and Equilibrium Conditioning of Polymer Matrix Composite Materials
ASTM D5886 - 95(2011)	Standard Guide for Selection of Test Methods to Determine Rate of Fluid Permeation Through Geomembranes for Specific Applications
ASTM D638	Standard Test Method for Tensile Properties of Plastics
ASTM D664	Standard Test Method for Acid Number of Petroleum Products by Potentiometric Titration
ASTM D695	Standard Test Method for Compressive Properties of Rigid Plastics
ASTM D792	Standard Test Methods for Density and Specific Gravity (Relative Density) of Plastics by Displacement
ASTM D974	Standard Test Method for Acid and Base Number by Color-Indicator Titration
ASTM E1269	Standard Test Method for Determining Specific Heat Capacity by Differential Scanning Calorimetry
ASTM E831	Standard Test Method for Linear Thermal Expansion of Solid Materials by Thermomechanical Analysis

Document code	Title
DIN 55303-2	Statistische Auswertung von Daten; Testverfahren und Vertrauensbereiche für Erwartungswerte und Varianzen, 1984
ISO 11357-1	Plastics – Differential scanning calorimetry (DSC) – Part 1: General principles
ISO 11357-4	Plastics – Differential scanning calorimetry (DSC) – Part 4: Determination of specific heat capacity
ISO 11359-2	Plastics – Thermo mechanical analysis (TMA) – Part 2: Determination of coefficient of linear thermal expansion and glass transition temperature
ISO 1183	Plastics: Methods for determining the density of non-cellular plastics
ISO 175	Methods of test for the determination of the effects of immersion in liquid chemicals
ISO 179	Plastics- Determination of Charpy impact properties
ISO 291	Plastics - Standard atmospheres for conditioning and testing
ISO 23936-1	Petroleum, petrochemical and natural gas industries -- Non-metallic materials in contact with media related to oil and gas production -- Part 1: Thermoplastics, Tg, Tm
ISO 2394	General principles on reliability for structures
ISO 527-1	Plastics- Determination of tensile properties - Part 1: General principles
ISO 527-2	Plastics- Determination of tensile properties - Part 2: Test conditions for molding and extrusion plastics
ISO 604	Plastics – Determination of compressive properties
ISO 6179	Rubber, vulcanized or thermoplastic -- Rubber sheets and rubber-coated fabrics -- Determination of transmission rate of volatile liquids (gravimetric technique
ISO 62:2008	Plastics – Determination of water absorption
ISO 868	Plastics and ebonite – Determination of indention hardness by means of a durometer (Shore hardness)
ISO 9352	Plastics – Determination of resistance to wear by abrasive wheels
ISO 23936-1	Petroleum. Petrochemical and natural gas industries- Non-metallic materials in contact with media related to oil and gas production – part 1. Thermoplastics
NORSOK M710	Qualification of non-metallic sealing materials and manufacturers

1.4.5 Literature

Table 1-6 Literature

Author(s)	Title
Echtermeyer, A. T.	Laminate Theory Manual. DNV Research, Report No. 91-2052 Rev. 02, available on request.
K. Lasn, A. Klauson, A.T. Echtermeyer, A. T.	Back-calculation of Elastic Moduli of a ply from the Moduli of cross-ply laminates, Mechanics of Composite Materials 51.1 (2015): 55-68

Author(s)	Title
Neter, J., Wasserman, W. and Kutner, M.H.	Applied Linear Statistical Models, 3rd Ed., R.D. Irwin Inc. Homewood, IL, 1990

1.5 Terms, symbols, abbreviations and definitions

1.5.1 General terms

The general abbreviations and symbols are identical to those found in DNVGL-ST-F201.

1.5.2 Definitions used in this standard

Definitions used specifically in this standard are given in Table 1-3 and Table 1-4.

Table 1-7 Definitions of terms

Term	Definition
component	part of a larger structure The structure is typically the TCP, but it can also be a specific part of the TCP or an external structure. The meaning should be clear from the context.
connector	special end fitting, requirements for end fitting will apply to connector
cover	outer protection of the TCP
dry specimen, dry material	a specimen that has not absorbed any fluid except for air, see also [A.1.3]
dry testing	testing a dry specimen in air (in the laboratory)
end fitting	unit between the pipe and remaining structure
environment	conditions outside the TCP
extreme temperature	the minimum operating temperature and maximum operating temperature
fluid	a liquid, gas or both
liner	inner fluid barrier of the TCP
liner-TCP laminate interface	interface between the liner and laminate
lower end fitting	end fitting of the TCP used on the bottom
representative media	representative compositions of service fluids and/or environments
service fluid	fluid inside the TCP
TCP*	Pipe section without end fitting
TCP assembly	TCP with end fitting
UD laminate	a laminate with unidirectional fibres, all fibres are parallel
UD pipe	pipe made of unidirectional laminate
upper end fitting	end fitting of the TCP used on the top side (if used as a riser)

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Term	Definition
* The term TCP is used for the pipe of the TCP assembly. In some cases TCP may also just refer to the general product described in this standard.	

Table 1-8 Definitions of verbal forms

Term	Definition
shall	verbal form used to indicate requirements strictly to be followed in order to conform to the document
should	verbal form used to indicate that among several possibilities one is recommended as being particularly suitable, without mentioning or excluding others, or that a certain course of action is preferred but not necessarily required
may	verbal form used to indicate a course of action permissible within the limits of the document

1.5.3 Abbreviations used in this standard

Abbreviations used specifically in the standard are given in Table 1-5.

Table 1-9 Abbreviations

Term	Definition
ALS	accidental limit state
API	American Petroleum Institute
ASTM	American Society for Testing and Materials
CMI	composite metal interface
COV	coefficient of variation
DMA	differential mechanical analysis
DMTA	differential mechanical thermal analysis
DSC	differential scanning calorimetry
FAT	factory acceptance test
FE method	finite element method
FLS	fatigue limit state
FMEA	failure mode evaluation analysis
FMECA	failure mode evaluation and criticality analysis
FRP	fibre reinforced plastic
HAZOP	hazard and operability analysis
HDT	heat distortion temperature
ID	inner diameter
ISO	International Organization for Standardization

Term	Definition
LS	limit state
MAIP	maximum allowable incidental pressure
MAOP	maximum allowable operating pressure
MBR	minimum bending radius
NDE	non destructive evaluation
NDT	non destructive testing (as NDE in this document)
OD	outer diameter
R-ratio	loading ratio under fatigue
SLS	serviceability limit state
S-N curve	fatigue lifetime curve of a material
Stdv	standard deviation
TAN	titrated acid number
TCP	thermoplastic composite pipe
TFL	through flow line
TGA	thermo gravimetric analysis
UD	unidirectional
ULS	ultimate limit state

1.5.4 Symbols

Table 1-10 Symbols

Property	Description
$\hat{\sigma}_{fat}$	standard deviation of *log N* of the fatigue S-N curve
$\hat{\sigma}_{stressrupt}$	standard deviation of *log t* of the stress rupture curve
$\Delta\varepsilon_{char}$	fatigue strain amplitude – characteristic value
$\Delta\varepsilon_{mean}$	fatigue strain amplitude – mean
$N_{expected}$	expected number of cycles (lifetime)
N_{test}^{max}	maximum number of cycles
N_{test}^{min}	minimum number of cycles
$t_{expected}$	expected time (lifetime)

Property	Description
T_g^{max}	maximum glass transition temperature
T_g^{min}	minimum glass transition temperature
T_g	glass transition temperature
T_m^{min}	minimum melting temperature
T_m	melting temperature
T_{op}	operating temperature
T_{op}^{max}	maximum operating temperature
T_{op}^{min}	minimum operating temperature
t_{test}^{max}	maximum test time
t_{test}^{min}	minimum test time
$\hat{\sigma}$	standard deviation of static data
$\Delta\varepsilon_0$	origin of S-N curve (strain amplitude at 1 cycle or 0 = log N)
N	number of fatigue cycles
$P_{hydro-test}$	hydrostatic test pressure
R	loading ratio under fatigue
t	time
$X_{laminate}$	strength of the TCP laminate in the axial direction.
α	slope of fatigue S-N curve
β	slope of stress rupture curve
γ_F	general partial load factor
γ_{FF}	partial load factor for functional loads
γ_E	partial load factor for environmental loads
γ_P	partial load factor for pressure loads
γ_{fat}	partial factor for fatigue analysis
γ_M	partial resistance factor
γ_{Rd}	resistance model factor
γ_S	system factor

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Property	Description
γ_{Sd}	load model factor
κ	shift factor for characteristic S-N curve
σ_{ave}	average stress applied to the laminate, calculated as the applied force divided by the entire cross-sectional area of the laminate.

1.5.5 Composite ply and laminate properties

Table 1-7 and Table 1-8 list symbols used to describe laminate and ply properties. For the coordinate system used see also Figure A-2 laminate and ply coordinates.

Table 1-11 Symbols describing composite ply properties

Property	Unit	Description
E_{1C}	GPa	compression Young's modulus in longitudinal direction
E_{1T}	GPa	tensile Young's modulus in longitudinal direction
E_{2C}	GPa	compression Young's modulus in transverse direction
E_{2T}	GPa	tensile Young's modulus in transverse direction
E_{3C}	GPa	compression Young's modulus in out-of-plane direction
E_{3T}	GPa	tensile Young's modulus in out-of-plane direction
G_{12}	GPa	in-plane shear modulus
G_{13}	GPa	through-thickness shear modulus
G_{23}	GPa	out-of-plane shear modulus
G_{Ic}	J/m^2	mode I critical energy release rate
G_{IIc}	J/m^2	mode II critical energy release rate
G_{IIIc}	J/m^2	mode III critical energy release rate
S_{12}	MPa	in-plane shear strength
S_{13}	MPa	through-thickness shear strength in fibre direction
S_{23}	MPa	through-thickness shear strength transverse to fibre direct.
T_g	°C	glass transition temperature
T_m	°C	melting temperature
v_f	%	fibre volume fraction
X_C	MPa	ultimate compression strength in longitudinal direction
X_T	MPa	ultimate tensile strength in longitudinal direction
Y_C	MPa	ultimate compression strength in transverse direction
Y_T	MPa	ultimate tensile strength in transverse direction

Property	Unit	Description
Z_C	MPa	ultimate compression strength in out-of-plane direction
Z_T	MPa	ultimate tensile strength in out-of-plane direction
$\hat{\sigma}_{nk}^{matrix}$	MPa	characteristic value of the strength components to matrix cracking in direction n
σ_{nk}	MPa	characteristic value of the local load effect of the structure (stress) in the direction n
α_1	10^{-6}/°C	longitudinal thermal expansion coefficient
α_2	10^{-6}/°C	transverse thermal expansion coefficient – in plane
α_3	10^{-6}/°C	transverse thermal expansion coefficient – through thickness
β_1		longitudinal swelling coefficient
β_2		transverse swelling coefficient – in plane
β_3		transverse swelling coefficient – through thickness
ζ_{1C}	%	longitudinal compression failure strain
ζ_{1T}	%	longitudinal tensile failure strain
ζ_{2C}	%	transverse compression failure strain
ζ_{2T}	%	transverse tensile failure strain
ζ_{3C}	%	out-of-plane compression failure strain
ζ_{3T}	%	out-of-plane tensile failure strain
ν_{13}	—	through-thickness Poisson's ratio
ν_{23}	—	out-of-plane Poisson's ratio
ν_{12}	—	longitudinal Poisson's ratio
ξ_{12}	%	in-plane failure shear strain
ξ_{13}	%	through-thickness failure shear strain
ξ_{23}	%	out-of-plane failure shear strain

Table 1-12 Symbols describing composite laminate properties

Property	Unit	Description
$E_{Axial-C}$	GPa	compression Young's moduli in longitudinal direction
$E_{Axial-T}$	GPa	tensile Young's moduli in axial direction
E_{Hoop-C}	GPa	compression Young's moduli in transverse direction
E_{Hoop-T}	GPa	tensile Young's moduli in radial direction
$G_{Hoop-Axial}$	GPa	in-plane shear moduli

Property	Unit	Description
$S_{Axial-Radial}$	MPa	through-thickness shear strength in axial direction
$S_{Hoop-Axial}$	MPa	in-plane shear strength
$S_{Hoop-Radial}$	MPa	through-thickness shear strength in hoop direction
$v_{f-laminate}$	%	fibre volume fraction
$X_{Axial-C}$	MPa	ultimate compression strength in axial direction
$X_{Axial-T}$	MPa	ultimate tensile strength in axial direction
Y_{Hoop-C}	MPa	ultimate compression strength in hoop direction
Y_{Hoop-T}	MPa	ultimate tensile strength in hoop direction
$\zeta_{Axial-C}$	%	axial compressive failure strain
$\zeta_{Axial-T}$	%	axial tensile failure strain
ζ_{Hoop-C}	%	hoop compressive failure strain
ζ_{Hoop-T}	%	hoop tensile failure strain
v_{xy}	—	longitudinal Poisson's ratio

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SECTION 2 DESIGN PHILOSOPHY

2.1 Safety philosophy

2.1.1 General

The general safety philosophy as described in:

— DNVGL-ST-F201 for risers
— DNVGL-ST-F101 for submarine pipeline systems
— DNVGL-ST-C501 for general applications

is also applicable for TCP.

The following issues are addressed:

— safety objective
— systematic review
— fundamental requirements
— operational considerations
— design principles
— quality assurance and the quality system.

An overall safety objective shall be established, planned and implemented covering all phases from conceptual development until the decommissioning of the structure.

The standard allows TCPs to be designed with different structural safety requirements, depending on the safety class to which the structure or part of the structure belongs. Safety classes are based on the consequence of failures related to the ultimate limit state (ULS).

The structure's structural reliability is ensured by the use of partial safety factors specified in this standard. Partial safety factors are calibrated to meet given target structural reliability levels.

2.1.2 Quality assurance

This standard's safety philosophy requires gross errors (e.g. human errors) to be controlled by requirements relating to the organization of the work, competence of persons performing the work, verification of the design, and quality assurance during all relevant phases.

Production control shall as a minimum meet the requirements of DNVGL-ST-C501 Sec.11.

2.2 Design format

2.2.1 General principles

The basic approach of the limit state design method consists of recognizing the different failure modes related to each functional requirement and associating each failure mode with a specific limit state beyond which the structure no longer satisfies the functional requirement. Limit states are defined, each limit state being related to a relevant failure mode and anticipated consequence of failure.

The design analysis consists of associating each failure mode with all the possible failure mechanisms (i.e. the mechanisms at the material level). A design equation or design criterion is defined for each failure mechanism, and failure becomes synonymous with the design equation no longer being satisfied.

The design equations are formulated in the so-called partial safety factor method format, according to which partial safety factors (load factors and resistance factors) are applied to the load effects (characteristic load values) and resistance variables (characteristic resistance values) that enter the design equations.

The partial safety factors, which are listed in this standard, have been established such that acceptable and consistent reliability levels are achieved over a wide range of structural configurations and applications.

This section discusses the limit states that have been considered relevant for the design of TCPs, presents the underlying safety considerations for the safety factors and finally introduces the adopted partial safety factor format.

2.2.2 Limit states

The following limit state categories shall always be considered when designing the structure:

— ultimate limit state (ULS)
— serviceability limit state (SLS)
— fatigue limit state (FLS)
— accidental limit state (ALS).

The ULS describes the total collapse or failure of the structure or component. Failures that threaten human life or the environment shall be categorized as ultimate limit state. For example, the ULS may correspond to the maximum load carrying capacity and may be related to structural failure modes. Safety classes are defined in accordance with the safety, environmental and financial consequences of failure . The ULS is irreversible, i.e., if the ULS is exceeded the component may be permanently damaged and may no longer be fit for service.

The serviceability limit state should be related to failure modes for which human or environmental risks are not an issue. The SLS is usually related to failure modes leading to service interruptions or restrictions. Service classes high, medium and low are defined in accordance with the frequency of service interruptions due to these failure modes and the consequence of the failure to the operator.

The fatigue limit state is a ULS accounting for accumulated cyclic or static load effects.

The accidental limit state is a ULS due to accidental (in-frequent) loads.

2.2.3 Safety classes and service classes

Safety classes are based on the consequences of failure when the failure mode is related to the ultimate limit state. Different safety classes may be defined for different parts of the TCP, see [3.4].

The safety classes are defined as (from DNVGL-ST-F201):

— Safety class low:

Where failure implies a low risk of human injury and minor environmental and economic consequences.
— Safety class medium:

For conditions where failure implies a risk of human injury, significant environmental pollution or very high economic or political consequences.
— Safety class high:

For operating conditions where failure implies a high risk of human injury, significant environmental pollution or very high economic or political consequences.

For risers the safety class shall be determined according to DNVGL-ST-F201 Sec.2 , where details about user conditions are given.

Service classes are based on the frequency of service interruptions or restrictions caused by failure modes related to the serviceability limit state. These failure modes imply no risk of human injury and risk of only minor environmental consequences. The operator shall specify the service class to which the structure shall be designed.

Service classes are defined according to the annual number of service failures. Service failure is any interruption or restriction of the normal service of the installation. The medium and high service classes are defined by the nominal reliability levels indicated in Table 2-2.

2.2.4 Failure types

Failure types are based on the degree of reserve capacity intrinsic to a given failure mechanism. A distinction shall be made between catastrophic and progressive failures, and between failures with and without reserve capacity during failure. The failure types for each failure mechanism described in this standard are specified according to the following definitions:

— ductile, corresponds to ductile failure mechanisms with reserve strength capacity. In a wider sense, it corresponds to progressive nonlinear failure mechanisms with reserve capacity during failure.
— brittle, corresponds to all failure mechanisms that are not ductile

The different failure types should be used under the following conditions for materials that show a yield point:

— failure type ductile may be used if: $\sigma_{ult} > 1.3\ \sigma_{yield}$ and $\varepsilon_{ult} > 2\ \varepsilon_{yield}$
— in all other cases failure type brittle shall be used

where σ_{ult} is the ultimate strength at a strain ε_{ult} and σ_{yield} is the yield strength at a strain ε_{yield}.

2.2.5 Selection of partial safety factors

Partial safety factors depend on the safety class and failure type . The partial factors are listed in Sec.11.

2.2.6 Design by the partial safety factor methodology

The partial safety factor method separates the influence of uncertainties and variability originating from different causes. Partial safety factors are assigned to variables such as load effect and resistance variables. They are applied as factors on specified characteristic values of these load and resistance variables, thereby defining design values of these variables for use in design calculations, and thereby accounting for possible unfavourable deviations of the basic variables from their characteristic values.

The variables' characteristic values are selected representative values of the variables, usually specified as specific quantiles in their respective probability distributions, e.g. an upper-tail quantile for load and a lower-tail quantile for resistance. The values of the partial safety factors are calibrated, e.g. by means of a probabilistic analysis, such that the specified nominal reliability is achieved whenever the partial safety factors are used for design. Note that characteristic values and their associated partial safety factors are closely linked. If the characteristic values change, relative to the ones determined according to procedures described in this document, then the partial safety factor requirements will also change in order to maintain the intended nominal reliability level. More details can be found in DNVGL-ST-C501.

2.2.7 Structural reliability analysis

As an alternative to design according to the partial safety factor format specified and used in this standard, a design method based on recognised structural reliability analysis (SRA) in compliance with DNVGL-RP-C211 *Structural reliability analysis* (replacing DNV CN 30.6) or ISO 2394 may be applied provided it can be documented that the approach provides adequate safety for familiar cases as indicated in this standard.

The structural reliability analysis shall be performed by suitably qualified personnel.

Nominal target reliability levels shall be calibrated against identical or similar designs that are known to have adequate safety levels. If this is not feasible, the nominal target reliability shall be based on the limit state category, the failure type and the safety or service class given in the probabilities shown in Table 2-1 and Table 2-2.

Table 2-1 Nominal annual target probabilities of failure P_F

Failure type as defined in [2.2.4]	Failure consequence		
	Low safety class	Medium safety class	High safety class
Ductile failure type (e.g. as for steel or many polymers)	$P_F = 10^{-3}$	$P_F = 10^{-4}$	$P_F = 10^{-5}$
Brittle failure type (basis case for composite)	$P_F = 10^{-4}$	$P_F = 10^{-5}$	$P_F = 10^{-6}$

Table 2-2 Nominal reliability levels in the SLS expressed in terms of the annual target probabilities of failure

Service class	Service failures
Medium	10^{-3}
High	10^{-4}

2.3 Design approach

This standard is performance-based. It does not prescribe any particular design solutions, but it does stipulate design requirements. The designer shall show by calculations and testing that the requirements are met.

Typically, a combination of calculations and testing is used. The calculations are based on structural analysis, e.g. finite element analysis. Extensive testing is needed to obtain all the material parameters required for the analysis. The material testing is also used to obtain statistical information about the material parameters - mainly the characteristic values and standard deviation. Agreement between calculations based on fundamental material parameters is subsequently checked on medium-scale components, such as small pipes. Full-scale or large-scale testing will be used as a final check of the performance against predictions on a very limited number of test specimens. The hierarchy of this approach is shown in Figure 2-1.
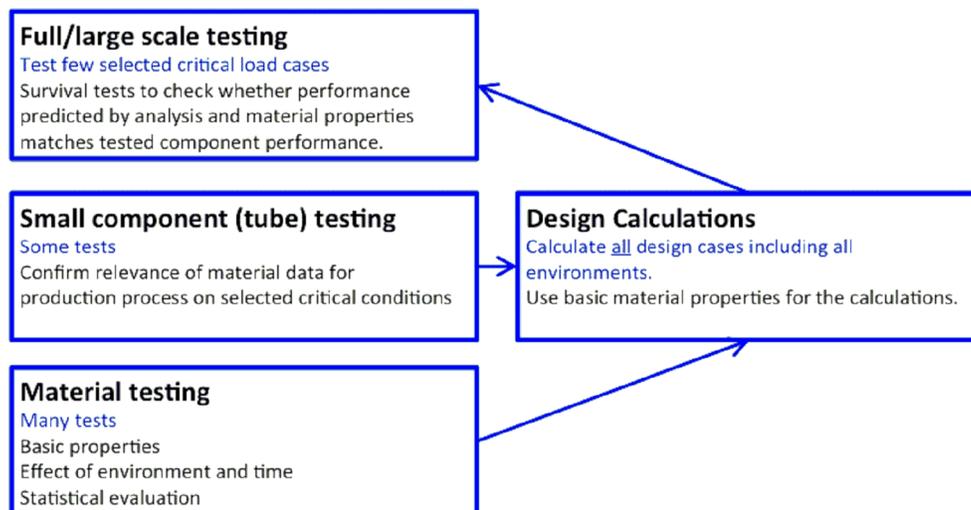
Figure 2-1 Hierarchy of design, based on calculations and testing

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The design calculations covered in this standard are based on macroscopic engineering properties. These are ply properties or laminate properties for composites. Measurements on the level of constituent properties or on the micro-scale may be used to obtain macroscopic properties if sufficient experimental evidence of the validity of the approach can be given.

It is always possible to test at a higher level, e.g. obtain material data and statistical information from pipe testing instead of from basic material testing.

In some cases the combination of calculations and testing may be inconvenient. If so, it is possible to perform the testing directly on the full-scale component, see Figure 2-2. Test results are in this case only valid for the conditions tested.

A combination of both approaches may be used.

Performance based Design
Many tests and load cases
Effect of environment and time
Statistical evaluation
Only valid for the conditions tested
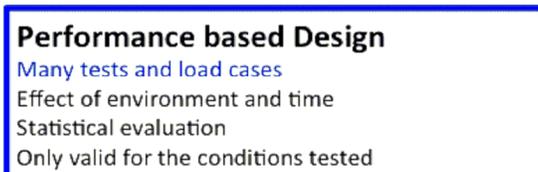
Figure 2-2 Principle of performance based design

2.4 Risk assessment analysis

A risk assessment or HAZOP of the system that the TCP is part of shall be performed, identifying the threats that the TCP can be exposed to. The risk assessment shall address the intended use of the TCP and all the phases described in the design basis (see Sec.3). The risk assessment shall address the TCP interfaces with to the total system, including the integration of any ancillary equipment.

This standard addresses the pipe and its end fittings, as described in [1.2]. The design criteria for the pipe body are given in Sec.7. The TCP design criteria are seen to fully cover failure mechanisms caused by pipe cross-sectional forces, moments and internal and external pressure provided the pipe section is designed and built as described in this standard.

The design criteria for the end fittings are given in Sec.8. Since the detailed design of an end fitting can vary widely and no standard end fitting has been developed by the industry, this standard requires a failure mode evaluation analysis FMEA to be done to identify all possible failure modes and failure mechanisms in the end fitting. Most possible failure modes and mechanisms are expected to be already described in this standard, but an FMEA is needed to ensure a full evaluation for each specific end fitting design. The design report shall subsequently show that none of the identified failure modes and failure mechanisms may become critical. The consequence of the FMEA may be that some additional critical failure modes and mechanisms need to be investigated. Additional design work and testing may be required to be able to predict that these failure mechanisms will not happen within the predicted lifetime and safety margins.

2.5 Liner and cover damage

The TCP shall be designed to tolerate some damage to the liner or cover. The design philosophy shall consider some or all of the following aspects:

— Design for damage by ensuring that the cover or liner does not enhance the TCP laminate performance.
— Ensure that damage to the cover cannot extend to the TCP laminate from the outside.
— Ensure that damage to the liner cannot extend to the TCP laminate from the inside.
— The effect of the liner-laminate bonding strength on the consequences of damage to the liner.
— Ensure that the TCP laminate will not be damaged by short-term exposure to inner fluids or the outer environment.

— The use of any available NDT methods that can detect damage to the liner or cover before it becomes critical.
— Define operational restrictions ensuring that no or only minor damage to the liner and cover can occur. Minor damage and its effect on the liner's performance needs to be specified in detail in the design report.

The selected approach may influence the test requirements described in [4.2.6].

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SECTION 3 DESIGN BASIS

3.1 Introduction

A design basis shall be established and agreed upon in a document. The aspects in the subsections below should be included in such a document

The design basis is defined here as the agreed performance envelope for the TCP.

A purchaser specifying the TCP application requirements shall provide the input to the design basis. The purchaser may decide that some items listed here are irrelevant to the application. Items not specified by the purchaser are assumed to be not relevant for the application.

The manufacturer may state properties describing the TCP's performance envelope (which may be a result of the design calculations).

Tolerances or upper and lower limits shall be given for all specifications.

3.2 Application

The intended service shall be specified and it shall be within the scope defined in [1.2].

The application may be static or dynamic.

3.3 Phases

The TCP will experience various phases during its life. The following phases shall as a minimum be considered:

— manufacturing
— factory acceptance test (FAT)
— assembly
— transport
— storage
— installation
— pre-commissioning/testing
— commissioning
— operation (normal)
— abnormal operation
— maintenance
— retrieval
— repair
— accidental conditions
— decommissioning.

A list of the TCP's relevant phases shall be established.

The manufacturer and purchaser shall evaluate whether other phases may be relevant.

Conditions as described throughout this section shall be specified for all relevant phases by the manufacturer or purchaser.

3.4 Safety classes

Safety class reflecting the consequence of failure, as defined in [2.2.3], shall be specified for each component and phase.

The safety class may be different from one phase to another and may differ depending on the position on the TCP. Changing the product's application may also change the safety class.

If a phase with a lower safety class is followed by a phase with higher safety class it shall be shown that no critical damage, defect or degradation will happen in the first phase, which could be detrimental to the performance in the next phase with higher safety class. If this cannot be documented the higher safety class shall be chosen for the design in both phases.

Service classes should be defined if economic consequences are significant, see [2.2.3].

3.5 Functional and system requirements

3.5.1 General

The purchaser shall define the TCP's functional requirements.

The manufacturer shall specify other requirements that may affect the design, storage, installation, operation or any other phase not specified by the purchaser.

The purchaser and manufacturer shall agree on the combined requirements.

The TCP shall be designed to resist all relevant failure modes for all relevant phases and loads in accordance with Sec.2.

TCP material properties may change with temperature and time. These changes may influence the global behaviour over time. The TCP specification should relate to this by specifying minimum or maximum values or permissible ranges instead of fixed values, if changes are not negligible.

3.5.2 Specific requirements

Some performance specifications may change over time, e.g. the bending stiffness. Such changes may be specified. If no time dependence is specified the TCP shall meet the specifications over its entire lifetime.

Specific functional requirements are listed in Table 3-1 and the following sections.

Table 3-1 Specific functional requirements for TCP

Requirements	Description
Lifetime	The purchaser shall as a minimum specify the operational lifetime (service life). Lifetimes should also be defined for all other relevant phases ([3.3]).
Dimensions	As a minimum the following dimensions shall be specified: — total length including end fittings — nominal inner diameter (unpressurized) — outer diameter (unpressurized) — outer diameter (pressurized) — required torsional rotation balance under load. All dimensions shall be given with tolerances. The maximum allowable ovalization shall be specified or taken into account when defining the inner diameter.

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Requirements	Description
Maximum deformations	The maximum deformations shall be specified. As a minimum the following extreme values shall be specified: — increase of outer diameter — reduction of inner diameter — ovalization — torsional deformation — axial elongation — maximum bending (see MBR above). Note: Providing no limitation is also acceptable if this can be justified.
Mass	The mass of the TCP shall be specified with and without end fittings. The mass can be given as mass per length or total mass. The mass in air and in water shall be specified. The mass shall be given with tolerances of the total mass and mass variations along the length of the TCP. If the TCP has local reinforcements, e.g. near an end fitting, bending stiffener or support point, the local weight change shall be specified. Possible absorption of water over time shall be considered in the weight specifications or weight calculations.
Global stiffness	The global stiffness range shall be specified for: — axial stiffness — bending stiffness — torsional stiffness.
Minimum bending radius	The minimum bending radius (MBR) shall be specified for all phases, as a minimum for transport, storage and operation. The MBR may depend on pressure and axial loads. If the MBR is specified without any related loading conditions it shall be valid for the worst combination of all maximum loads.
TCP configuration	The general configuration requirements shall be specified. For risers this would for example be lazy S, steep wave etc. The topography, seabed/soil conditions, obstacles, installed equipment and pipelines shall be stated in the flow line route drawings. The layout of all components and interfaces shall be described. For risers, the interference between risers shall be considered according to DNVGL-RP-F203 Riser interference.
Maximum permeation rate	A maximum permeation rate shall be defined for each internal fluid given in [3.7.2]. The maximum permeation rate shall be specified over the entire length of the TCP, per length or for a certain section. Special areas requiring low gas permeation shall be specified. The need for a gas monitoring system shall be specified. Usually the permeation over the entire length and permeation close to human activity, e.g. near the platform are critical for the system.
Corrosion protection	Any required corrosion protection for the TCP or system around the TCP shall be specified. This mainly applies for the end fittings. The corrosion protection and electrical conductivity shall be consistent with the entire system that the TCP is part of.

Requirements	Description
Thermal insulation	The purchaser should specify any heat-loss or retention performance requirements for the TCP. If thermal insulation requirements change along the length of the TCP, this should be described.
Gas venting	The TCP is a bonded construction and does not generally require a gas venting system.
Pigging and TFL requirements	Any performance requirements to allow pigging tools, a through flow line, workover, or other operations going through the pipe shall be specified. As a minimum the following shall be specified: — required ID of the pipe and end fittings, see also maximum deformations above — minimum bend radius of the pipe and end fittings — end fitting transition towards the pipe and support structure. The surface properties and geometry of the pigs or any other equipment going through the pipe shall be specified. The operation of pigs shall not cause damage to the liner. Since the liner is softer than metal, pigs used for metal pipes may not be suitable for TCPs. It is recommended not to use scraper pigs.
Fire resistance	Any fire resistance requirements shall be specified. This applies to all phases. It shall be specified whether the fire resistance requirements apply to an empty or filled TCP. A fire resistance requirement would be typically limited to the topside above the splash zone.
End fittings	The upper and lower end fitting system shall be specified, including quick disconnection systems and buoy disconnection systems, connection angles and location tolerances. The end fitting requirements for the TCP's upper and lower end fittings shall be specified. This shall include as a minimum: — end fitting type — connection system, including quick disconnection systems and buoy disconnection systems — connection angles and location tolerances — welding specifications for connection to other structures — seal type and sizes — inner bore (may be different from the TCP body). Any hot work, such as welding, shall be specified in a way that it does not affect the properties of the TCP, see [8.6]. End fittings are typically made of metal. The metal parts shall be designed according to [8.3]. If end fittings made of composites shall be used, they shall be designed according to DNVGL-ST-C501.
Pipe attachments	Pipe attachments such as bending stiffeners, buoys, and piggy back lines and various clamps and their attachment methods shall be specified. The geometry and mechanical properties of the pipe attachments shall be given with sufficient accuracy to calculate the local loads acting on the TCP and the effect of the pipe attachments on the global behaviour of the TCP, see also [3.6.8]. The design of the pipe attachments themselves is outside the scope of this standard.

Requirements	Description
Interface definitions	Possible interfaces causing interference shall be specified, such as: — other pipes/crossing pipes (new or old) — mooring lines — platform columns — vessel pontoons — tanker keel — other vessel — etc. Allowable interference conditions (loads) shall be defined (interference/clashing).
Sharp points	If the TCP touches, crosses or rests on any other structures, components or supports, the sharpness of the contact points and the contact forces shall be specified. Temporary contact with sharp points, especially during installation shall be considered. The manufacturer shall clearly specify the point-loading limitation/limitation with sharp points in the OMM or installation limitation report. In general, point loads should be avoided, see also [5.13], [7.8.9] and [7.8.11].
Vessel conditions	If a vessel is attached to the TCP the following shall be documented, unless load specifications take vessel motions into account.: — data for the attached floating vessel, including the following: — vessel data, dimensions, drafts, etc. — static offsets — first (RAOs) and second order motions — vessel motion phase data — vessel motion reference point — mooring system interface data — position tolerances.
Guides and supports	Any guides and supports, such as I tubes or J tubes, rollers from chutes and bellmouths shall be specified. In terms of the effects of these components on the TCP the same requirements as for pipe attachments apply, see pipe attachments above The design of the guides or supports themselves is outside the scope of this standard.
Protection requirements	Impact protection structures, trenching, rock dumping, mattresses, etc. shall be described. Design impact loads ([3.6.6]) may consider the presence of protection structures.
On bottom stability	If required, allowable displacements shall be specified to ensure on bottom stability. The values shall be compared with the limits given in the maximum deformations section above. The requirements stted in DNVGL-RP-F109 On-bottom stability design for submarine pipelines shall be followed.
Upheaval buckling	Specifications of design cases to prevent upheaval buckling shall be considered by the manufacturer.
Inspection and condition monitoring	Any requirements for the manufacturer to design and implement pipe inspection, monitoring and condition assessment systems and procedures should be specified.

Requirements	Description
Installation requirements	The purchaser should specify performance requirements for installation services. If installation is carried out by the purchaser the following information should be provided: — load restrictions requirements — clamping/tensioner loads — overboarding chute requirements — installation tolerances and port facility limitations. If installation is carried out by the manufacturer the following information should be provided by the purchaser: — seasonal requirements — environmental requirements — vessel limitations — installation tolerances and port facility limitations — restrictions due to conflicting activities and the installation scope (including trenching, burial, testing, inspection, surveying and documentation). In addition, the following requirements should be considered by the manufacturer: — Whether to store the spooled TCP with an internal pressure, if the bending radius is close to the MBR in order to to avoid creep consumption. — During the installation phase, the bottom end of the TCP shall be sufficiently tensioned so far as possible any bouncing on the overboarding chute. — The use of a bellmouth-shaped chute is recommended during the installation phase. — Installations aids (deflectors, tensioners, overboarding chutes) shall be perfectly aligned to avoid overstressing the pipe.
Recoverability and reusability	The purchaser should specify any recoverability or reusability requirements applicable during the service life of the pipe.
Decommissioning	Any decommissioning requirements shall be agreed on between the manufacturer and purchaser.
Exothermal chemical reaction cleaning	If exothermal chemical reaction cleaning shall be used, the purchaser should specify the relevant parameters for the pipe cleaning operations, considering the following as a minimum: — flow rate — pressure variation — maximum heat output — chemical composition. The maximum internal temperature due to exothermal cleaning shall be obtained and compared with the specifications in [3.7.5].

3.6 Loads

3.6.1 General

This section describes general load requirements. Specific aspects are described in [3.7].

This standard uses local loads acting on TCP sections. Load effects are calculated from these loads. The local loads are mainly:

— pressure
— axial loads
— bending loads
— torsion.

Note: The local axial, bending and torsion loads could also be seen as load effects, since they are the result of other loads. In this standard they are called local loads to distinguish them from the load effects on the composite laminate level, i.e. stresses and strains. The definition used here is consistently applied to the use of safety factors in the design criteria.

Other specific loads, such as impact are also addressed.

The local loads shall be obtained from a global system analysis. For risers and pipes/pipelines the applicable standards are:

— DNVGL-ST-F101 Submarine pipeline systems
— DNVGL-ST-F201 Dynamic risers.

A full load matrix shall be defined, including global loads.

Loads and deformations shall be categorized into four groups:

— pressure (P) loads
— functional (F) loads
— environmental (E) loads
— accidental (A) loads.

Loads shall be defined according to the procedures given in DNVGL-ST-F201 Dynamic risers for risers and in DNVGL-ST-F101 Submarine pipeline systems for flow lines.

Loads shall be specified for all phases, see [3.3].

These load definitions are needed to obtain proper load effects in [6.2.2]. The loads can be used with the partial safety factors given in Sec.11.

All the load cases shall be described separately for each phase of the structure's design life.

Loads shall be defined with sufficient statistical information so that extreme values can be calculated. This is typically achieved by defining the yearly probability.

A full probabilistic approach describing the loads may be used as an alternative.

3.6.2 Maximum short-term loads during the lifetime

The 99% quantile in the distribution of the annual maximum environmental load effect is used as the characteristic value of the environmental load effect throughout this document. The 99% quantile may be interpreted as the 100-year load effect, i.e., the load effect value that has a return period of 100 years. This is the load effect value, that, on average, will be exceeded once every 100 years.

The characteristic value of the functional load is the expected maximum value of the functional load over the design lifetime.

3.6.3 Long-term sustained loads

Long-term sustained loads, like top tension, shall be defined over an observation period, which may correspond to the TCP's entire design life or to a part of that design life. For more details see [6.2.4].

Preferably load sequences should be specified in a table with the format given in Table 6-1.

3.6.4 Long-term cyclic loads

Long-term cyclic loads shall be specified as load sequences in terms of minimum loads and maximum loads, together with the number of cycles for each load combination. This information is needed to provide the load effects described in [6.2.5] and [5.22.2].

3.6.5 Pressure

The internal and external pressure acting on the TCP shall be specified.

All pressures shall be specified as absolute values and not differentials between internal and external pressure.

The following pressures shall be specified as a minimum:

— minimum internal and external pressure
— maximum external pressure
— maximum allowable operating pressure (MAOP)
— design pressure
— maximum allowable incidental pressure (MAIP)
— incidental pressure
— factory and field-pressure requirements of governing and/or certifying authorities and overall system requirements (system pressure tests, mill pressure tests)
— number of pressure cycles and sequence of pressure cycles. The pressures shall be described in the same way as cyclic loads ([3.6.4])
— long-term sustained pressure. The pressures shall be described in the same way as sustained loads ([3.6.3])
— accidental pressures.

All specified pressures shall be given together with a temperature. If the pressures are not quoted for the system's extreme temperatures, the pressures at extreme temperatures should be obtained by calculations (see [6.15]).

Pressures shall be defined as described in DNVGL-ST-F101 *Submarine pipeline systems*. Figure 3-1 shows the internal pressures graphically.

For TCP systems conveying liquids particular attention shall be paid to dynamic effects and pump characteristics when determining the incidental pressure.

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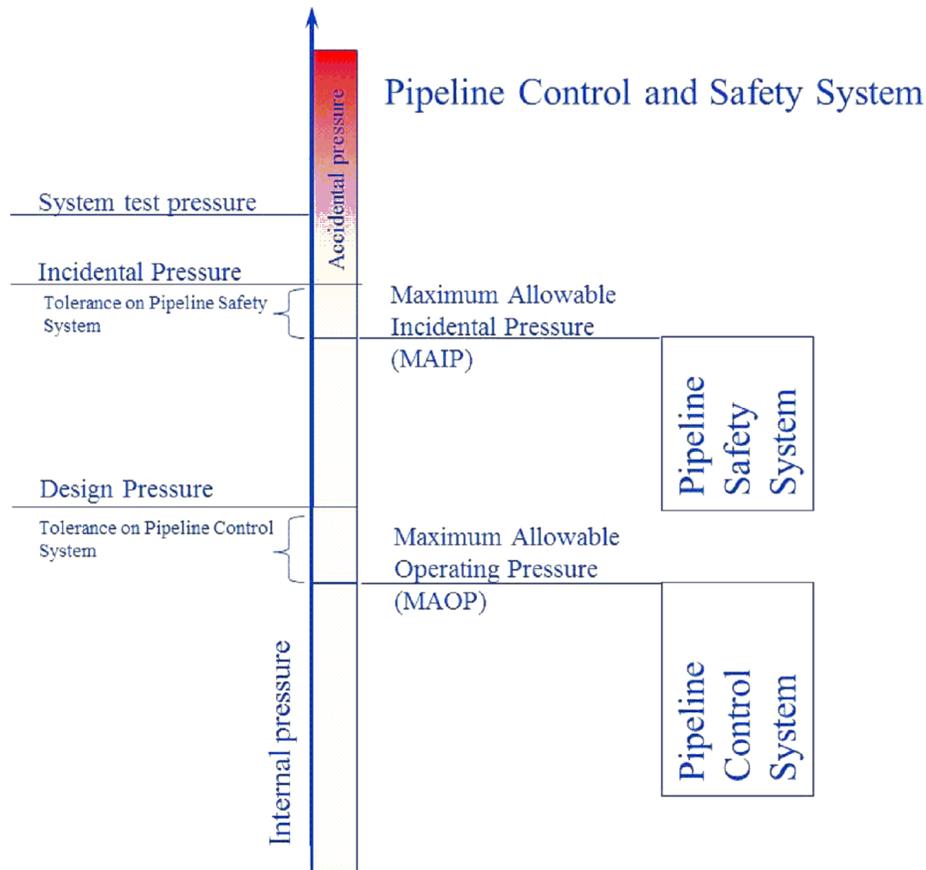
Figure 3-1 Pressure definitions

This standard uses incidental pressure in all limit states.

The incidental pressure is defined as having an annual probability of exceedance that is less than 10^{-2} (a probability of being exceeded within a year). If the pressure probability density function does not have a monotonic decay beyond 10^{-2} the pressure exceeding the incidental pressure shall be checked as an accidental load in compliance with [7.1] and Sec.11.

A design pressure may be defined for each incidental pressure. The incidental to design pressure ratio shall be selected such that the pipeline control and safety system ensures the minimum incidental to design ratios as given in Table 3-2. When the design pressure is used for structural design purpose, this ratio shall be minimum 91% of the incidental pressure.

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Table 3-2 Incidental to design pressure ratios

Condition or pipeline system	γ_{inc}
Typical pipeline system	1.10
Minimum, except for that stated below	1.05
When the design pressure is equal to the full shut-in pressure including dynamic effects	1.00

Other referenced standards and codes (e.g. for components) may use the design pressure instead of incidental pressure. For such applications, the design pressure shall be the higher of p_{li}/γ_{inc} and $0.91 \cdot p_{li}$, where p_{li} is the local incidental pressure.

3.6.6 Impact loads

Resistance to certain impact loads may be relevant for some applications.

The impact requirement should as a minimum define the impact energy and shape. Ideally, the impact speed should also be defined.

Impact loads caused by dropped objects or anchors should be specified.

3.6.7 Trawling and other fishing loads

Trawling or fishing in general can cause impact and pullover forces. The impact of trawl boards or suchlike shall be defined in the same way as general impact in [3.6.6]. The pullover force shall be defined in terms of magnitude and direction.

3.6.8 Pipe attachments

The loads acting on the TCP due to interaction with pipe attachments shall be specified.

Alternatively, the geometry and mechanical characteristics of pipe attachments shall be specified allowing such loads to be calculated, see [3.5.2].

3.6.9 General interfaces

The loads acting from interfaces connected to the TCP shall be defined, see also [3.5.2].

3.7 Service conditions

3.7.1 General

Service conditions shall be specified for each phase ([3.3]).

TCPs service conditions shall be specified as described in this subsection.

Service conditions for the operational phase shall always be specified. However, other phases may see cleaning fluids, solvents, gases for drying the inside, etc. that may influence the properties of the TCP.

The service conditions for metal parts, such as the end fittings, shall be specified according to:

— DNVGL-ST-F101
— DNVGL-ST-F201.

Note: It is generally beneficial to base long-term performance evaluations on realistic sequences and concentration profiles instead of on extreme conditions.

3.7.2 Fluid composition

The internal fluids' chemical composition and physical phases shall be specified.

The length of use of fluids during a phase should also be specified.

Any solids, such as sand etc., carried along in the fluid shall be specified.

Any chemicals injected during the design life shall be specified.

3.7.3 Flow characteristics

The flow rate and nature of the flow (multiphase etc.) shall be specified.

Any requirements regarding turbulences, etc., shall also be described here.

3.7.4 Thermal requirements

Any thermal insulation or thermal conductivity requirements shall be specified.

Any flow assurance requirements related to the fluid's thermal conditions shall be specified.

The fluid's heat capacity shall be specified if relevant for thermal calculations.

The following fluid properties shall as a minimum be specified for thermal performance calculations:

— density (kg/m^3)
— heat capacity (J/kg.K)
— heat transfer coefficient (W/(m^{2}K)
— thermal conductivity (W/m.K).

3.7.5 Internal temperature

The design minimum and maximum fluid or internal temperature shall be specified.

The temperature profiles or sequences throughout the service life should be specified.

It shall be clearly defined whether the specified temperature is the temperature of the material on the inside of the TCP or the temperature of the fluid inside the TCP.

The following conditions shall be considered as a minimum for obtaining temperatures and extreme values:

— operating temperatures
— extreme accidental temperatures (number and range of cycles)
— gas cooling or heating effects (temperature curve, pressure changes).

If nothing else is specified the design temperature shall be the maximum operating temperature.

See also [6.14] for calculating the overall design temperature.

Note: during some phases the pipe may be empty and the external environment will determine the internal temperature.

3.7.6 External temperature

The design minimum and maximum temperature shall be specified.

The same requirements as for internal temperature characterization shall be applied ([3.7.5])

It shall be clearly defined whether the specified external temperature is the temperature of the material on the outside of the TCP or the temperature of the medium on the outside of the TCP.

See also [6.14] for calculating the overall design temperature.

Note: in some cases, the temperature of the outside of the pipe material may be higher than the temperature of the outside environment. The sun may heat the pipe to above the external temperature

of the air. Continuous movement with friction against other components may warm up the pipes. This temperature increase shall be either specified as external temperature or calculated.

3.7.7 External environment - water

The purchaser shall specify the project´s external environmental parameters:

— The maximum design water depth to which the TCP may be exposed. Note, this depth should be specified independently of the TCP's internal pressure.
— The time during which the TCP may be exposed to relative external pressure from the water, i.e. the time during which the external pressure exceeds the internal pressure.
— Geographical variations and tidal variations shall be considered.
— The minimum and maximum water temperature should be specified (see also [3.7.6]).

Note: the maximum external pressure in [3.6.5] cannot be less than the external pressure related to the water depth.

If relevant:

— Current: as a function of the water depth, direction, and return period. Known local current effects should be included.
— Wave data: Significant and maximum waves, associated periods, wave spectra, spreading functions and scatter diagrams, as a function of the direction and return period.
— Density of the seawater.
— pH of the seawater.
— Marine growth: maximum allowable values and variations along the length.

3.7.8 External environment - air

The purchaser shall specify the project´s external environmental parameters (according to API 17J). The following information should be given if relevant:

— Sunlight-UV exposure: length of TCP exposed during operation and/or storage.
— Wind data: as a function of the direction, height above water and return period.
— The minimum and maximum air temperatures should be specified (see also [3.7.6]).
— The possibility of ice growth shall be specified or analysed (see also [7.8.16]).

3.7.9 External environment - soil

If the TCP is in contact with soil, the following soil data shall be stated:

— general description of the type of soil
— shear strength or angle of internal friction
— friction coefficients for seabed scour
— sand waves and variations along the TCP route.

3.7.10 External environment - ice

If the TCP may be in contact with ice, the following ice conditions shall be described:

— maximum ice accumulation
— drifting icebergs
— ice floes.

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SECTION 4 MATERIALS

4.1 Introduction

4.1.1 General

Material properties are needed to perform a design analysis (Sec.6) and to check whether the design criteria are fulfilled (Sec.5, Sec.7 and Sec.8). This section specifies which material properties shall be obtained as a minimum and it describes how the properties shall be obtained. If the design analysis requires more properties than are described here, then additional testing may be needed. The link between material data and design is described in [2.3].

Two main groups of materials are used in a TCP: thermoplastic polymers and thermoplastic composites. The polymers are used in the liner and cover. The thermoplastic composites are used in the TCP laminate. Since the two materials behave quite differently, they are addressed in different subsections of this standard. A subsection addressing the specific properties of interfaces has also been added.

Testing is done using the pyramid principle, as shown in Figure 4-1. Most properties are tested on small specimens. Tests are done on a fairly large number of specimens to obtain statistically relevant data. Larger scale representative pipe specimens are used to confirm that the small-scale specimens are relevant for the application. Full- or large-scale testing is done for final confirmation of the design analysis, as described in Sec.10.

Representative pipe specimens are defined in detail in [4.5.1].

It is always possible to perform testing on a higher level in the pyramid.
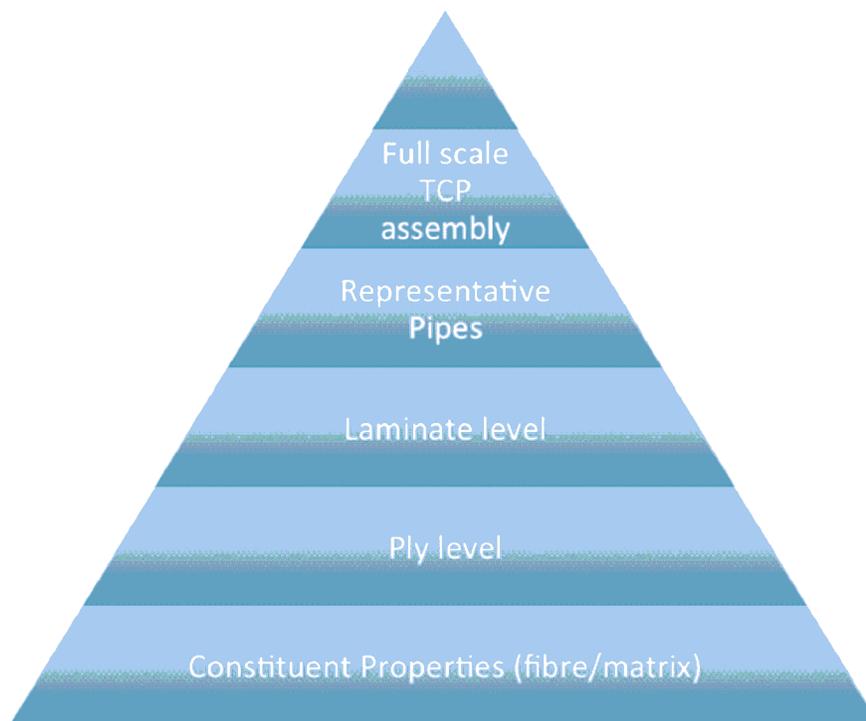
Figure 4-1 Test pyramid

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The test options as described in this standard are also summarized in Table 4-1 for covers and liners and in Table 4-2 for TCP laminates.

Table 4-1 Summary of test program and test materials for cover and liner

	Test program description	*Liner*	*Cover*	*TCP assembly*
Short term testing	Table 4-4 Short-term tests for polymers used in liners and cover, with or without welds	x	x	
Long term testing	Table 4-5 Long-term tests for load-bearing isotropic liners and covers	x	x	
Prototype testing	Sec.10 Prototype test requirements - full-scale samples			x

Table 4-2 Summary of test program and test materials for TCP laminates

	Test program description	*UD flat laminate*	*UD ring or pipe*	*Multiaxial flat laminate*	*Multiaxial pipe*	*TCP samples*	*TCP assembly*
Short term testing	Table 4-6 Short-term tests to obtain ply properties	x	x	x	x		
	Table 4-7 Short-term tests to obtain laminate properties from laminates or pipes			x	x		
	Table 4-9 Confirmation testing – static testing					x	
Long term testing	Table 4-8 Long-term tests for TCP laminates	x	x	x	x		
	Table 4-10 Confirmation testing on TCP – long-term properties					x	
Interface testing	Table 4-11 Short-term test requirements for interfaces					x	

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	Test program description	UD flat laminate	UD ring or pipe	Multiaxial flat laminate	Multiaxial pipe	TCP samples	TCP assembly
	Table 4-12 Long-term test requirements for interfaces					x	
Prototype testing	Sec.10 Prototype test requirements - full-scale samples (not just the laminate)						x

4.1.2 Test requirements and safety class

The safety class determines the level of accuracy needed for testing. Safety classes are described in [2.2.3].

For safety classes medium and high all properties shall be measured. For safety class low, material properties from the literature may be used, provided it can be justified that they are applicable for thematerial in question and their environmental exposures.

All strength and strain to failure parameters shall be determined as characteristic values given by the 2.5% quantile with 95% confidence, as required by this standard. If characteristic strengths and strains to failure cannot be found, a coefficient of variation (COV) of 10% for fibre-dominated properties and 15% for matrix-dominated properties may be used.

Elastic constants shall be taken as the mean value.

For safety class low, direct measurements according to safety class medium or high may always be done.

4.1.3 Obtaining ply properties from constituent properties

Ply properties can be predicted by measuring the properties of the constituent materials and combining the properties with multiscale models. This approach may be used provided the predicted ply data fulfil all confirmation test requirements given in this standard and can reproduce the relevant ply properties measured according to [4.3], [4.4] and [A.4].

Measurements of constituent materials shall not be used to obtain the standard deviation of ply or laminate properties. The standard deviation shall be tested directly on the ply or laminate level.

4.1.4 Non-critical properties

A static material property can be seen as non-critical:

— If design calculations show that a material property could have a twice as unfavourable value (typically lower) and still fulfil the design criteria (when all safety factors are applied).
— If the material property is a strength or strain to failure, the above requirement shall be applied to both the strength and strain to failure.

A time-dependent material property can be seen as non-critical if the TCP'ss component still fulfils the design criteria (when all safety factors are applied) even if both the following conditions apply:

— The design calculations show that the design time or number of cycles can be multiplied by a factor of 20.

— The cyclic amplitude of the load effect can be increased by one standard deviation of the respective static strength or the maximum load effect of permanent sustained loads can be increased by two standard deviations of the respective static strength.

Non-critical properties can be determined according to safety class low, as described in [4.1.2].

4.2 Obtaining test specimens

4.2.1 Selecting and producing test specimens

It shall be ensured that all test specimens are made of the same materials and come from the same material suppliers as the materials used in the final product.

Polymer test samples should be taken from sections of a TCP. They may also be taken from pipes produced in the same way as The TCP's liner or cover. If test samples are made using a different process than that used for the real TCP, it is important that their morphology is comparable to that of the real materials. They should have the same amount of amorphous and crystalline phases, the same spatial distribution characteristics of the phases and the same additives as the real application. Similarity shall be demonstrated by a small test programme according to [4.7].

If similarity cannot be shown, the specially made test samples cannot be used.

If the TCP laminate is made from fibre reinforced thermoplastic tapes the tapes are a good basis for making representative laminates. Joining the tapes together to make a laminate should be done in a process as closely resembling the real case as possible. This is especially important for laminates where the through-thickness properties are measured.

TCP laminates made by filament winding often have different properties from samples made of flat specimens. Full scale or small scale component testing shall be done to obtain relevant properties, unless it can be demonstrated that flat specimens properties are applicable, see [4.5] and [4.5.3].

4.2.2 Material identification of polymers for cover and liner

A description of a polymer should contain at least the following information to identify the product:

— generic description of the polymer
— composition of the polymer parts, if it is a copolymer
— trade name of the polymer
— manufacturing methods
— description of additives
— presence of welds and the welding technique (if a component).

Manufacturer's product data sheets or the equivalent may be used as an alternative to the full material information; provided the company's quality system will ensure that any change in the materials resin, composition or manufacturing method will also create a change in the product data sheets, i.e. any change in the six points listed above is reported.

A change in the technical content of materials or the manufacturer's product data sheets shall require requalification of the product, unless similarity according to [4.7] can be shown.

4.2.3 Material identification of the thermoplastic composite pipe laminate

A description of a TCP laminate should contain at least the following information to identify the product:

— generic fibre type
— fibre bundle type and "tex"
— fibre trade name
— fibre manufacturer
— type of sizing

— type of weave
— weaver
— fabric trade name
— generic matrix type
— trade name of matrix
— manufacturing methods of tapes (if applicable) and laminate
— description of additives.

The manufacturer's product data sheets or codes may be used as an alternative to the full material information; provided the company´s quality system will ensure that any change in the materials' resin, composition or manufacturing method will also create a change in the product data sheets, i.e. any change in the 12 points listed above is reported.

For example, the sizing should at least be specified by a coded name. A change in sizing should change the coded name.

A change in the technical content of materials or the manufacturer's product data sheets shall require requalification of the product, unless similarity according to [4.7] can be shown.

4.2.4 Conditioning of specimens

Some test specimens and components shall be conditioned before testing, as specified for the individual tests described in the standard. If conditioning is required, specimens shall be tested under conditions that are relevant for the application. They shall be tested saturated with the fluids that the TCP is exposed to during service. For thermoplastic materials, the depletion of low molecular additives also needs to be considered.

The TCP material shall be characterized for the extreme (best and worst) conditions during its lifetime that may change its mechanical properties. Typically this would be the initial condition after production and the condition after years of service. Table 4-3 summarizes the principal conditions for characterizing TCP polymers.

Room temperature dry properties are needed for reference purposes and for predicting the performance of full scale testing.

If the extreme conditions cannot be identified, the polymer shall be tested for all service conditions.

Details of how the conditioning shall be done are given in [A.1.1].

Table 4-3 Conditions for characterizing polymers

| Fluid around the polymer | Plasticizer inside the polymer specimen | | | |
	No additives	Additives evaporating in air	Water soluble additives	Hydro-carbon soluble additives
Dry (testing in air in the laboratory)	dry	dry with additives	dry with additives	dry with additives
		dry without additives		
Water	dry	dry with additives	dry with additives	dry with additives
	saturated with water	saturated with water without additives	saturated with water without additives	saturated with water with additives
Hydro-carbon	dry	dry with additives	dry with additives	dry with additives
	saturated with hydrocarbon	saturated with hydrocarbon without additives	saturated with hydrocarbon with additives	saturated with hydrocarbon without additives
Water and hydro-carbon	dry	test dry with additives	test dry with additives	test dry with additives

Fluid around the polymer	Plasticizer inside the polymer specimen			
	No additives	Additives evaporating in air	Water soluble additives	Hydro-carbon soluble additives
	saturated with water and hydrocarbon	saturated with water and hydrocarbon without additives	saturated with water and hydrocarbon without additives	saturated with water and hydrocarbon without additives

4.2.5 Reporting of mechanical test data

A brief description of the experimental set-up shall be given. The following shall be a minimum for all tests:

— The test environment shall be described.
— Loading conditions, such as loading rate, shall be described.
— The type of specimens shall be identified.
— The average and characteristic strength, failure strain and modulus shall be reported. Obtaining characteristic values is described in [A.3].
— The full stress versus strain curve shall be shown in test reports.
— Load displacement curves and any nonlinearities shall be recorded.

Nonlinear behaviour shall be analysed and reported according to [A.5].

Additional test data reporting requirements are given in the sections describing specific tests.

4.2.6 Effect of slow diffusion

This standard characterizes the material properties of dry specimens, dry specimens filled with additives and specimens saturated with the surrounding fluids while depleted of additives. This approach should be conservative, since it describes the extreme cases.

In some cases, diffusion may be so slow that additives will never leach out and/or saturation will never happen during the design life. Possibly only surface layers will be affected by the surrounding fluid. In this case, obtaining the properties of fully depleted materials and fully saturated materials may not be representative of real conditions.

A more thorough analysis could consider the kinetics involved, especially if diffusion happens slowly. In that case it may be that only the surface layers become depleted of additives and filled with components of the external fluid, while the inner part stays in its original condition. Considering these effects may allow for a more optimized design. However, this approach will require more testing than described in this document. The assumptions made in the analysis should be well established or confirmed by experimental evidence.

If it can be shown that the liner or cover keeps the TCP laminate separated from the fluids, the laminate may be analysed as always being dry. In that case the testing of saturated laminates is not required. This approach shall only be used if it can be shown that the liner or cover will never be damaged or that damage will be short-lived and can be detected by non-destructive evaluation.

4.2.7 Thermal fatigue

The resistance to thermal fatigue shall be evaluated:

— If a polymer experiences temperature variations across its T_g^{min} (see [A.1.10] and [5.21])
— If a polymer experiences more than 100 temperature cycles with a temperature difference of $\Delta T > 30$ °C.
— The polymer should never be exposed to temperatures above T_m.

Experience may be used as an evaluation method, if a material has a well-known track record showing no thermal degradation for the expected exposure conditions. The experience will only be valid for a specific

material type, not for the generic class of materials. Whether or not experience can be used shall be agreed on between the manufacturer, purchaser and possibly verifying agent.

If the requirements are not met, degradation due to thermal cycling shall be included in all testing:

— Static strength measurements shall be taken after the polymer has been exposed to the maximum expected number of temperature cycles ([4.3] and [4.4]).
— Fatigue and stress rupture testing ([4.3], [4.4], [4.5] and [4.6]) shall be combined with exposing the polymer to the maximum expected number of temperature cycles.

4.2.8 Conditions under testing

Test temperatures and loading rates for mechanical testing are described in [A.2]. Conditions will depend on the polymers' glass transition and melting temperature. Obtaining these properties is described in [A.1.10].

It shall be ensured that the conditions in terms of fluid concentrations obtained during conditioning remain constant or as severe during the test process.

Long-term testing shall be performed with the specimen in an environment (typical an environmental chamber) that maintains the specified environmental conditions

Short-term testing, e.g. a tensile test finished a few minutes after removing the test specimen from the conditioning bath, may be carried out in air, provided it can be substantiated that fluids will remain inside the specimen during the short transport and test period. Fluids typically stay inside the specimens for short periods if the diffusion constants are high.

Thermogravimetric analysis (TGA) may be used to identify whether additives or fluids remain in the specimens.

During intermediate test periods (a few hours or days), it may be sufficient to wrap test specimens in plastic foil or similar, to keep fluids inside the specimen. If this approach is chosen, justification for the validity of the test method shall be provided addressing the materials and fluids used in the particular case.

Temperatures shall always be as specified for testing. Temperatures should be kept constant within ±2 °C.

4.3 Basic material properties of the liner and the cover

4.3.1 General

The materials shall be as described [4.2.2].

The extent of the testing required depends on the safety class ([4.1.2]) and whether or not properties are non-critical ([4.1.4]).

If the liner or cover has welds, properties with and without welds shall be obtained. It may be that both properties can be tested using the same test samples.

4.3.2 Static short term properties of liner and cover

Table 4-4 lists the tests that shall be done on the polymers used in the liner and cover.

Characteristic and mean values shall be obtained for each test, as described in [A.3].

At least three parallel tests shall be performed for each type of test. It is recommended to test at least five parallel specimens.

Table 4-4 Short-term tests for polymers used in the liner and the cover, with or without welds

	Property	Liner	Cover	Temperature	Fluid-Additive	Sections with more details in this standard or suggested test standard
Physical/ chemical properties	Density and swelling [8]	y	y	R	A	ISO 62, ISO 175, ISO 1183, ASTM D792, D1505
	Hardness [8]	y	y	H	D	Shore , ISO 868, only for reference
	Water absorption	y	y	H	-	ISO 62, ISO 175
	Fluid absorption	y	y	H	-	ISO 175
	Fluid permeability	y	y	H	-	See [A.9]
	Blistering resistance	y	n	R	-	See [A.10]
	Abrasion/wear resistance	n[2]	y	E	D,W	ISO 9352, ASTM D4060 or D 1044 [4]
	Impact strength	n	n	R	D	Tested full scale [10.9]
	UV resistance	n	y	-	-	[A.8]
Thermal properties	Glass transition temp. T_g	y	y	-	A	[A.1.10]
	Softening point (HDT)	n	n	-	-	Not to be tested, Covered by T_g
	Melting temperature	y	y	-	A	[A.1.10]
	Heat capacity	y	y	-	A[1]	ISO 11357-1 or 4, ASTM E1269, Test only if needed for design calculations
	Coefficient of thermal expansion	y	y	E[3]	D[1]	ISO 11359-2, ASTM E831 Test only if needed for design calculations
	Coefficient of thermal conductivity	y	y	R	A[1]	ASTM C177, C518 Test only if needed for design calculations
Mechanical properties	Modulus of elasticity	y	y	E	A	ISO 527-1 or 527-2 ASTM D638 [5]
	Poisson's ratio	y	y	E	A	ISO 527-1 or 527-2 ASTM D 638 [5]
	Yield strength	y	y	E	A	ISO 527-1 or 527-2 ASTM D638 [5, 6]
	Ultimate tensile strength and strain	y	y	E	A	ISO 527-1 or 527-2 ASTM D638 [5]
	Compressive strength and strain	y	y	E	A	ISO 604, ASTM D695 [5]

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Property	Liner	Cover	Temperature	Fluid-Additive	Sections with more details in this standard or suggested test standard
Notch sensitivity Charpy impact test	n[7]	n[7]	E	A	ISO 179, ASTM D256 if needed in [A.2.2] or [4.7.3]

y: yes, shall be tested

n: no, does not need to be tested unless, see note

R: room temperature

H: highest operational temperature

E: extreme temperatures, see [4.2.4] and [A.2]

D: testing dry

A: all conditions, as described in [A.1.1]

W: testing saturated with water [A.1.6]

[1]: The absorbed fluid influences this property, if the property needs to be measured with high accuracy to determine the effect of the fluid. Otherwise measuring dry may be sufficient.

[2]: Should be tested if the internal fluid contains sand or solids that can be abrasive to the inner liner.

[3]: Coefficients of thermal expansion typically show little dependence on the temperature. If this property is critical for the design, it should be measured at the extreme conditions. If the material is used below and above T_g, thermal expansion coefficients shall be measured below and above T_g.

[4]: Specialized non-standardized equipment is typically best for testing. The validity of the test methods should be evaluated for each special case.

[5]: Any suitable ISO or ASTM standard for mechanical properties of polymers.

[6]: The yield strength shall be determined as described in [A.5].

[7]: If needed in [A.2.2] or [4.7.3]

[8]: The test can be carried out dry at room temperature, immediately after conditioning.

4.3.3 Long-term basic properties for liner and cover materials

Long-term mechanical testing of the liners and the covers should mainly be performed to demonstrate that their in-plane properties are good enough to allow the components to follow the movements of the load bearing TCP laminate.

Liners and covers shall also have sufficient through-thickness strength if they may be part of the load path in the end fittings.

Liners and covers shall also be tested for through-thickness properties, if they are part of the load path of other components interacting with the TCP, such as bend stiffeners, caterpillars, etc.

Details about obtaining and analysing long term data are given in [A.6] and [A.7].

The required tests for isotropic liners and covers are given in Table 4-5.

Table 4-5 Long-term tests for load-bearing isotropic liner and cover

	Property	Liner	Cover	Temperature	Fluid-additive	Sections with more details in this standard or suggested test standard
Mechanical properties	Inplane fatigue	y	y	E	A	
Mechanical properties	Through-thickness shear stress rupture/creep*)	y_a	y_a	H	A	Through-thickness testing may be combined with the tests in [4.6].

y: yes, for dynamic TCPs

y_a: if needed for the analysis

E: extreme temperatures, see [4.2.4] and [A.2]

H: highest operational temperature

A: all conditions, as described in [A.1.1]

*):   Through thickness shear testing can be replaced by in-plane shear testing if the polymer created by the relevant actual production process is isotropic.

Test duration requirements are given in [A.6.3] and [A.7.3] for cyclic fatigue and stress rupture respectively.

4.4 Basic material properties of the thermoplastic composite pipe laminate

4.4.1 General

The materials shall be described as stated in [4.2.3].

The extent of the testing required depends on the safety class ([4.1.2]) and whether or not properties are non-critical ([4.1.4]).

Ply properties provide the basic input for analysis of the TCP. Obtaining ply properties is described in detail in [A.4]. Ply properties may be obtained from different sample geometries and test geometries; examples are given in Table A-2.

This standard gives a large variety of test methods and test materials allowing a characterization approach that is tailored to a specific TCP product.

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From a testing point of view it tends to be easiest to measure properties on flat panels. In terms of relevance for the product it may be preferred to test material properties on samples that more closely represent the real product, see also Table 4-1 and Table 4-2. Whether results taken from simple samples are relevant for the real application shall be checked in [4.5]. It is recommended to perform the relevance check early in a test programme and possibly adjust the testing of ply properties accordingly.

The validity of simple laminate testing shall be checked against pipe properties according to [4.5].

For materials showing nonlinear plastic behaviour the yield point (yield strength and yield strain) shall also be measured as described in [A.5].

All properties shall be reported together with the fibre volume fraction v_f.

Characteristic and mean values shall be obtained for each test, as described in [A.3].

At least three parallel tests shall be done for each type of test.

It is recommended to test at least five parallel specimens.

Test methods shall be chosen to characterize the ply properties of the TCP laminate depending on the input requirements of the design analysis, as described in Sec.6, Sec.7 and Sec.8.

Ply properties shall be obtained as described in [4.4.2]. In some cases laminate properties may or shall be obtained as specified in [4.4.3].

4.4.2 Static short term ply properties of the thermoplastic composite pipe laminate

Ply properties shall be tested according to Table 4-6.

Ply properties can be measured on specially made samples using the same fibres and matrix as the TCP in question. Samples may be flat panels or pipes. Guidance on selecting samples is given in [A.4.1], Table A-2.

Table 4-6 Short-term tests to obtain ply properties

	Property	Required property	Temperature	Fluid-additive	Sections with more details in this standard or a suggested test standard
Physical/ chemical properties	Fibre volume fraction	y	R		
	Density and swelling [8] $\beta_1, \beta_2, \beta_3$ [6]	y	R	A	ISO 62, ISO 175
	Hardness [8]	y	R	A	Shore, ISO 868, only for reference
	Water absorption	y	H	-	ISO 62, ISO 175, ASTM D5229
	Fluid absorption	y	H	-	ISO 175
	Fluid permeability	y	H	D	See [A.9]
	Blistering resistance	y	R	D	See [A.10]

	Property	Required property	Temperature	Fluid-additive	Sections with more details in this standard or a suggested test standard
	Abrasion resistance	n			Not needed, unless the TCP has no liner or cover
	Impact strength	n	E	D	Tested full scale [10.9]
Thermal properties	Glass transition temp.	y	-	A	[A.1.10]
	Softening point (HDT)	n	-	A	Covered by T_g
	Melting temperature	y	-	A	[A.1.10]
	Heat capacity	y	-	A[1]	Test only if needed for design calculations
	Coefficient of thermal expansion α_1, α_2, α_3	y	E[3]	D[1]	Test only if needed for design calculations
	Coefficient of thermal conductivity in through-thickness direction	y	R	A[1]	Test only if needed for design calculations
Mechanical properties	Modulus of elasticity E_{1T}, E_{2T} and E_{3T} E_{1C}, E_{2C} and E_{3C}	y	E	A	5, 6
	Shear modulus G_{12}, G_{13} and G_{23}	y	E	A	5, 6
	Poisson´s ratio ν_{12}, ν_{13} and ν_{23}	y	E	A	5, 6
	Yield strength		E	A	If the material deforms plastically 5, 6, 7
	Ultimate tensile strength X_T, Y_T and Z_T and strain If relevant also yield point	y	E	A	5, 6
	Compressive strength X_C, Y_C and Z_C and strain If relevant also yield point	y	E	A	X_C may be influenced by matrix cracking. If matrix cracking can occur, X_C shall be measured in the presence of matrix cracks. 5

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Property	Required property	Temperature	Fluid-additive	Sections with more details in this standard or a suggested test standard
Shear strength S_{12}, S_{13} and S_{23} and strain If relevant also yield point	y	E	A	5, 6 Through-thickness testing may be combined with tests in [4.6].
Critical energy release rate G_{IC}, G_{IIC}	y	E	A	Only if needed for design analysis. 5
Charpy impact test		E	A	Only if needed, as specified in [A.2.2] [4.7.3]

y: yes, shall be tested

n: no, does not need to be tested unless, see note

R: room temperature

H: highest operational temperature

E: extreme temperatures, see [4.2.4] and [A.2]

D: testing dry

A: all conditions, as described in [A.1.1]. See also [4.2.6]

W: testing saturated with water [A.1.6]

[1]: The absorbed fluid influences this property, if the property needs to be measured with high accuracy to determine the effect of the fluid. Otherwise measuring dry may be sufficient.

[3]: Coefficients of thermal expansion typically show little dependence on the temperature. If this property is critical for the design, it should be measured at the extreme conditions.

[4]: Specialized non-standardized equipment is typically best for testing.

[5]: Any suitable ISO or ASTM standard for mechanical properties of composites. For test materials, see Table A-2. Obtaining fibre dominated strength and stiffness usually requires that some fibres are oriented in the direction of the test load.

[6]: If a ply property is not needed for analysis or can be obtained by the methods described in [A.4.2], it does not need to be measured.

[7]: The yield strength shall be determined as described in [A.5].

[8]: The test can be carried out dry at room temperature, immediately after conditioning.

If pipes or rings are used for testing, the properties listed in Table 4-6 shall be obtained. Test methods should be adopted to suit the special specimen geometry.

4.4.3 Static short term laminate properties of the thermoplastic composite pipe

Laminate testing is required if fibres in the laminate have an angle of more than 70°, see below. In addition, in some cases it may be preferred to analyse the TCP laminates on the laminate/pipe level in addition to or instead of on the ply level as described in [4.4.2].

Testing should be done on the real pipes with the actual laminate as described in this section and stated in Table 4-7 or properties of representative subsections of the laminate may instead be measured.

A section can only be a representative subsection if it is possible to build the complete laminate from the representative subsections or a combination of subsections and plies. If the entire TCP laminate can be described by subsections without using ply properties, some testing according to [4.4.2] may not be needed.

If the TCP laminate is built up of layers with different fibres, subsections need to be tested for each fibre type.

Laminate testing should be linked to the laminate design criterion in [5.5] or be used for back-calculations of ply properties [A.4.1]. Tests described here are for:

— axial tension and compression
— hoop tension and compression
— axial bending
— torsion
— internal and external pressure.

The test methods chosen depend on the input requirements of the design analysis and failure criteria, as described in Sec.6, Sec.7 and Sec.8, see also [4.4.2].

If the laminates' fibers have an angle of more than 70° between them, the laminate properties shall be measured in that direction , see [4.4.4], [5.5] and Figure 4-2. This is the case for many TCPs in the axial direction.

A laminate typically develops failure mechanisms such as matrix cracking, yielding and delamination before ultimate failure caused by fibre fracture. The design analysis (Sec.6, Sec.7 and Sec.8) shall determine the failure mechanisms that are critical for the TCP laminate. Testing shall be carried out in such a way that the onset of the critical failure mechanisms can be recorded.

Table 4-7 Short-term tests to obtain laminate properties from laminates or pipes

	Property	Required property	Temperature	Fluid-additive	Comments and suggested test approaches
Mechanical properties	Axial tension	y_a	E	A	Test on laminate or pipe (Table A-2, no. C,D)
	Axial compression	y_a	E	A	Test on laminate or pipe (Table A-2, no. C,D)

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Property	Required property	Temperature	Fluid-additive	Comments and suggested test approaches
Axial bending	y$_a$	E	A	Test on long pipe section, if needed
Hoop tension	y$_a$	E	A	Test on pipe (Table A-2, no. D). Use split disk test or pressurized pipe with supported ends.
Hoop compression	y$_a$	E	A	Test on pipe (Table A-2, no. D). The compressive strength X_c may be influenced by matrix cracking. If matrix cracking can occur X_c shall be measured in the presence of matrix cracks.
Inplane shear	y$_a$	E	A	Test pipe in torsion
Internal pressure	y$_a$	E	A	Test on pipe (Table A-2, no. D) with end fittings Free or supported ends
External pressure	y$_a$	E	A	Test on pipe (Table A-2, no. D) with end fittings Free or supported ends
Obtaining fibre dominated strength and stiffness usually requires some fibres to be oriented in the direction of the test load. Maximum ± 15 degree pipes in axial tension can be tested to obtain ply fibre strength properties.				

y$_a$: yes, if needed for the analysis. It can be an alternative to testing ply properties as described in [4.4.2]

E: extreme temperatures, see [4.2.4] and [A.2]

A: all conditions, as described in [A.1.1]. See also [4.2.6].

The results of tests in this section shall be used in combination with the failure mechanisms described in [5.5].

Test results may also be used to back calculate ply properties ([A.4.1]).

Whether or not results from simple samples are relevant for the real application shall be checked in [4.5]. It is recommended to perform the relevance check early in a test programme and possibly adjust the testing of ply properties accordingly.

4.4.4 Long-term basic properties of thermoplastic composite pipe laminates

The test materials shall be chosen based on the same criteria as for static testing described in [4.4.2] and [4.4.3]. Details about obtaining and analysing long term data are given in [A.6] and [A.7].

Fatigue in the fibre direction shall be documented. Unidirectional plies tested in the fibre direction may be used to establish the S-N curve. In some cases unidirectional specimens are extremely difficult to test and failure always happens in the grip area. In that case, 0/90 specimens may be used. The initial fatigue strain shall be measured in the load-controlled test. The fatigue strength would then be the initial strain times the Young's modulus of the 0 plies. The 90 plies will be ignored.

Laminate testing shall be used if the gap between fibres is larger than 70°, see also [4.4.3] and Figure 4-2. Note that the purpose of this laminate testing is different from back calculating ply properties as described in [4.4.3]

Fatigue testing of a [$\pm\alpha$] laminate shall be done. For convenience, a [±45] laminate may be tested. Alternatively, the full laminate layup may be tested in the gap direction.

If the TCP laminate shall not have matrix cracks (see [7.2.2]) fatigue resistance to matrix cracking shall be tested.

The long-term test requirements for TCP laminates are given in Table 4-8.

Table 4-8 Long-term tests for TCP laminates

	Property	Temperature	Fluid-additive	Sections with more details in this standard
Mechanical properties	Fatigue in fibre direction	E	A	See special conditions described below the table
	Fatigue [$\pm\alpha$] laminate	E	A	Only if 2α >70 ^{o}, see Figure 4-2
	Fatigue transverse to fibre direction	E	A	Only if the TCP laminate cannot have matrix cracks, see [7.2.2]
	Through-thickness shear fatigue	E	A	Through-thickness testing may be combined with testing in [4.6].
	Tensile stress rupture in fibre direction	H	A	See special conditions below the table
	Compressive stress rupture in fibre direction	H	A	
	Stress rupture [$\pm\alpha$] laminate	H	A	Only if 2α > 70 ^{o}, see Figure 4-2.
	Through-thickness shear stress rupture	H	A	Through-thickness testing may be combined with testing in [4.6]

H: highest operational temperature

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E: extreme temperatures, see [4.2.4] and [A.2]

A: all conditions, as described in [A.1.1]. See also [4.2.6]

W: in water.

Testing shall be done to obtain characteristic long-term curves as described in [A.6.2] for fatigue and [A.7.2] for stress rupture.

For the choice of R-ratio for the fatigue tests, see [A.6.4].

Stress rupture testing shall be done in tension and compression, unless one direction can be shown to be non critical for the application [4.1.4]

Special conditions for tensile fatigue and tensile stress rupture testing in fibre direction:

— Tests can be waived if data exist for similar fibres [4.7.4], saturated in the same medium at the same temperature, but embedded in a different matrix.
— Cyclic fatigue data are obtained at a similar fibre volume fraction.
— The results of carbon-fibre-reinforced plies are temperature independent provided the extreme temperatures are 20°C below the melting temperature of the matrix and the operational or extreme conditions do not cross the martix's glass transition temperature within ±20°C. Further evidence shall be provided that the carbon fibres themselves are stable within the range of the extreme temperatures.
— It can be assumed that carbon fibres are inert to hydrocarbons and water, i.e. test results obtained in air can also be used for saturated conditions for these fluids.
— It can be assumed that glass fibres are inert to hydrocarbons, i.e. test results obtained in air can also be used for saturated conditions in hydrocarbons (but not in water).
— If the hydrocarbons or water are mixed with other components, e.g. H_2S, the performance in these fluids needs to be shown and the inertness of the fibres cannot be assumed.
— If any compressive stresses are involved, the special conditions described here do not apply.

If the TCP laminate has a lay-up where the fibre directions are not evenly distributed, the maximum gap between fibre directions shall be identified. If the gap is larger than $2\alpha = 70^o$ the laminate´s fatigue properties shall also be tested in the direction of the gap, as listed in Table 4-7.

Figure 4-2 shows an example of a pipe laminate with a gap larger than 70°.

If fibre directions have a gap 2α of more than 70° degrees in a laminate, matrix cracking and reorientation of the fibres may become critical for the load-bearing properties. This requires extra testing.
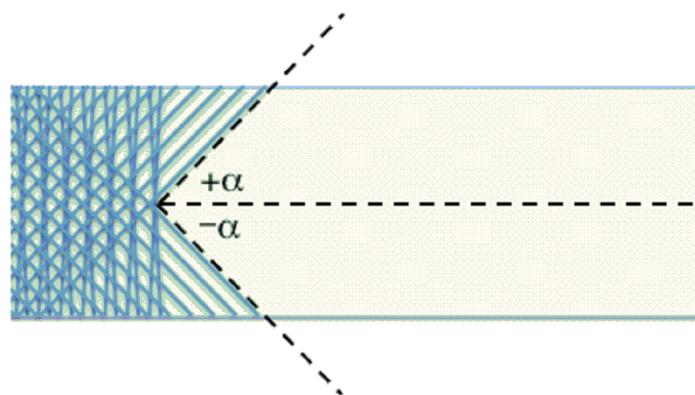
Figure 4-2 TCP laminate with a fibre-direction gap in of 2α

Examples:

— The pipe has a layup [±85, ±60]. In this case the gap angle 2α is: $2\alpha = 2 \times 60^o = 120^o$.

— [90/±60] laminate needs testing in the axial direction, as described in this section.
— A [0/90/±45] laminate needs only unidirectional testing in a fibre direction as described in [4.4.2].

4.5 Confirmation testing on representative thermoplastic composite pipes

4.5.1 General

Some tests on representative TCPs shall be done to demonstrate that the material tests performed on a coupon level or on simple pipes in [4.3] and [4.4] are relevant for the actual product. The tests are shown in Table 4-9.

TCP samples are representative if all the following points are fulfilled:

— They contain all major fibre angles of the TCP laminate.
— $0.6 \dfrac{t_{TCP\ laminate}}{D_{TCP\ tube}} \leq \dfrac{t_{test\ tube}}{D_{test\ tube}} \leq \dfrac{t_{TCP\ laminate}}{D_{TCP\ tube}}$, where t is the thickness of the pipe's laminate and D is the diameter of the pipe. *
— The diameter of the test pipe is within ±50% of the actual TCP**.
— If the spread of angles around a major direction is more than 5 degrees, the minimum and maximum angle should be included in the test laminate, not just the mean angle.

* The thickness range may be extended if experimental evidence can be provided.

** The diameter range may be extended if experimental evidence can be provided.

Major fibre angles are the main orientations of the fibres in the TCP laminate, e.g. a [±83, ±58, ± 28, ±85, ±60, ±30, ±87, ±62, ±32] would have the major orientations ±85, ±60 and ±30. If different types of fibres are used in a laminate, the major angles of each fibre type shall be represented.

Testing may be performed on samples with or without a liner and cover because the main purpose is to verify the ability to predict laminate properties.

The actual TCP always qualifies as a representative pipe.

If the material testing of a property was performed on TCPs that meet all the requirements of this section, confirmation testing for this property is not needed.

The pipes' production process shall be identical to that of the real TCP.

The behaviour of the pipes shall be predicted from the material data.

4.5.2 Static testing

At least three axial compression tests shall be performed.

At least three tests shall be performed, making the pipe fail in the hoop direction. The testing may be done using a split disk test or internal pressure. Internal pressure testing can only be used if it produces a failure of the fibres in the hoop direction.

All tests shall be instrumented with strain gauges and the predicted mean stress versus strain curve shall be compared with the actual stress versus strain curve. The stresses and strains to failure should be within one standard deviation of the predicted mean stresses and strains. All tests are summarized in Table 4-9. Since strain gauges tend to fail before the component, strains to failure may be measured by other means or extrapolated.

All experimental failure loads and failure strains should be the calculated loads based on the mean material strength plus or minus one standard deviation. The standard deviation shall be taken from the material data, not the pipe measurements. A more detailed probabilistic analysis as given in [4.7.5] may be conducted to confirm that the data belong to the same population.

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The calculation model used to predict failure based on the material data shall use the same modelling approach as that used for the design calculations of the full-scale TCP. If any scaling factors are used in the model, the factors shall be the same for all analysis.

If these tests are passed it can be assumed that the material properly tests represent the behaviour of the TCP laminate . Results based on other conditioning and temperatures may then be transferred to the pipes' properties.

If these tests are not passed, the coupon testing described in [4.3] or in [4.4] should be replaced by full scale pipe testing or other tests giving results that fulfil this section's requirements.

Table 4-9 Confirmation testing – static testing

	Property	TCP sample	Temperature	Fluid-additive	Sections with more details in this standard or suggested test standard
Mechanical properties	3 Axial compression tests	y	H	D	
	3 Pressure tests	y	H or R	D/W*	
	3 Hoop strength tests	y	H	D	Use a split disk test or pressurized pipe if it creates hoop failur
	3 Crushing ring tests	y	R	D	See [A.10.5]

y: yes, shall be tested

R: room temperature

H: highest operational temperature

D: testing dry

W*:   testing with water to obtain pressure, but no saturation of the laminate is needed.

The pressure tests shall be performed without supported ends. If the ends are supported in the actual application testing may be performed with supported ends.

The crushing ring test typically shows delamination between layers. The location and onset of delamination shall be predicted based on the ply data from [4.4.2].

4.5.3 Confirmation testing on thermoplastic composite pipe – long-term properties

Some tests using real TCP shall be undertaken to demonstrate that the material tests performed on a coupon level or on simple pipes in [4.3] and [4.4] are relevant for the actual product. The tests are shown in Table 4-10.

If the material testing of a property was performed on a TCP that fulfilled all the section's requirements, confirmation testing for this property is not needed.

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Pressure fatigue or axial fatigue should be tested.

Further testing for long-term properties is specified in Sec.10.

Table 4-10 Confirmation testing on TCPs – long-term properties

	Property	Temperature	Fluid-Additive	Comments
Cyclic properties (10^5 cycles)	3 pressure tests*)	H	D	
	3 axial compression tests	H	D	
	3 axial tensile tests	H	D	
Stress rupture properties (1000 hours)	3 pressure tests*	H	D	
	3 axial compression tests	H	D	

H: Hhighest operational temperature

D: testing dry

*) Pressure tests shall be performed without supported ends. If the ends are supported in the actual application then testing may be performed with supported ends.

Note: Through-thickness interlaminar shear fatigue is addressed in [4.6].

Axial fatigue testing is recommended to check at an early stage whether or not ply data can be applied to pipes.

The test time should be the application's maximum number of cycles but not more than about 10^5 cycles for fatigue testing and not more than 1000 hours for stress rupture.

All experimental failure times (or number of cycles) for tests in Table 4-10 should be the calculated mean times (or mean number of cycles) based on the material's long-term properties plus or minus one standard deviation. For the confirmation testing, the standard deviation shall be based on the long term curves measured for the material (S-N curve or stress rupture curve), and not on the TCP test data o.

4.5.4 Model factor

It may be possible to measure long term properties on simple laminates, even if static test results of simple laminate testing ([4.3] and [4.4]) did not agree well with results obtained from TCP laminates ([4.5]). In this case the ratio ϑ in properties φ between simple laminate tests and tests on the TCP should be obtained as:

$$\vartheta = \frac{\varphi_{simple\ test}^{static}}{\varphi_{TCP\ laminate}^{static}}$$

Predictions of long term properties of tests as described in Table 4-10 may then be calculated from mean times (or the mean number of cycles) to failure obtained from simple testing multiplied by ϑ. The factor ϑ shall be applied to stress or strain, not to the number of cycles or time.

A more detailed probabilistic analysis as given in [4.7.6] may be conducted to confirm that the data from small scale testing belongs to the same population as data from the testing of TCP laminates (Table 4-10).

4.6 Interface properties of full scale thermoplastic composite pipes – short and long term

4.6.1 General

Interface properties describe the strength and robustness of the joint between the TCP laminate and the liner or cover.

Testing shall be done on full scale TCPs.

The liner and cover shall be part of the pipe, if they are used for the TCP design.

4.6.2 Short term testing

The short-term tests specified in Table 4-11 shall be performed.

Table 4-11 Short term test requirements for interfaces

	Property	Liner –TCP laminate	TCP Laminate - cover	TCP laminate	Temperature	Fluid-additive	Sections with more details in this standard or suggested test standard
Physical/ chemical proper-ties	Blistering resistance	y	y				See [A.10].
Mechanical properties	Through-thickness strength Z_T or Z_C	n*	n*	n*	E	A	
	Through-thickness shear strength $S_{Axial\text{-}Radial}$ or $S_{Hoop\text{-}Radial}$	y	y	y	E	A	Lap shear test of part from the TCP laminate or torsional shear on the pipes. For simplification see [4.6.3].
	Critical energy release rate G_{IC} and G_{IIC}	n*	n*	n*	E	A	

y: yes, shall be tested.

n*:   Only if needed in the design analysis.

E: Extreme temperatures, see [A.2].

A: All conditions, as described in [A.1.1]. See also [4.2.6].

4.6.3 Simplified interlaminar shear testing

Instead of testing all materials and interfaces the minimum interlaminar shear strength of the TCP may be tested first by a short beam shear test combined with a lap shear test. The short beam shear test can only identify the TCP's weakest section. Subsequently, the interlaminar shear strength of the weakest section shall be tested using the lap shear test or torsional shear test.

The minimum shear strength can also be measured by a torsional test of the entire TCP.

Other test methods following the same test philosophy may be used provided they give realistic interlaminar shear strength values for the TCP design calculations.

If the weakest part of the TCP is an interface, blistering tests of that interface need to be performed, see [5.18].

4.6.4 Long-term testing

Long term testing of the interfaces shall be performed according to Table 4-12.

Table 4-12 Long-term testing requirements for interfaces

	Property	Liner –TCP laminate	TCP laminate - cover	TCP (liner, laminate and cover)	Temperature	Fluid-additive	Sections with more details in this standard or suggested test standard
Mechanical properties	Through-thickness shear strength $S_{Axial-Radial}$ or $S_{Hoop-Radial}$, cyclic fatigue	b	c	a	E	A	Could use the same test methods as in [4.6.2] and [4.6.3].
	Through-thickness shear strength $S_{Axial-Radial}$ or $S_{Hoop-Radial}$, stress rupture	b	c	a	E	A	Could use the same test methods as in [4.6.2] and [4.6.3].

E: Extreme temperatures, see [4.2.4] and [A.2].

A: All conditions, as described in [A.1.1]. See also [4.2.6].

a: Through thickness shear properties shall be measured for all TCP laminates.

   If the polymers of the liner and cover are the same as in the TCP laminate and if the through thickness punch tests from Table 4-11 show that the interface strengths are as strong (within 5%) or stronger than the interlaminar strength of the laminate, the complete TCP with liner and cover or just the laminate may be used for testing. No testing under b or c is necessary.

b: If the liner is part of the axial load path in the end fitting design, the fatigue properties shall be tested (unless waived by point "a").

c: If the cover is part of the axial load path in the end fitting design, the fatigue properties shall be tested (unless waived by point "a").

Test duration requirements are given in [A.6.3] for cyclic fatigue and in [A.7.3] for stress rupture.

The simplified minimum strength approach from [4.6.3] may also be used for long-term testing.

4.7 Using representative data and similar materials for characterization

4.7.1 General

It is often desirable to evaluate and qualify more than one specific material for use in a TCP. If the new material is similar to the originally tested material, it may be possible to characterize and qualify the new material using a reduced test programme.

The similarity shall be demonstrated based on the requirements given in this section.

The comparison shall only be made against well-characterized representative data, see [4.7.2].

In addition to the similarity evaluations given in this section, a general evaluation shall be conducted to justify similarity. This evaluation shall concentrate on whether the similar materials would behave similarly for the actual use of the material in the TCP.

If a material is qualified as similar to a representative material, the full-scale test effort for this material may be reduced, see [4.7.5] and [4.7.6].

4.7.2 Representative data

Representative static data shall be based on at least 10 measurements. The standard deviation and number of tests should be reported, allowing the calculation of characteristic values according to [A.3],

Long-term representative data (a property versus number of cycles or time) shall be based on at least 15 measurements. The data points should be fairly evenly distributed over the time scale or number of cycles. Characteristic values shall be obtained according to [A.6.2] and [A.7.2]. It should be possible to extrapolate the data to the expected lifetime of the TCP based on the requirements given in [A.6.3] and [A.7.3].

The generic material type as well as the manufacturer, trade name and batch number should be available as described in [4.2.2] and [4.2.3].

4.7.3 Physical similarity requirements for polymers

A polymer should only be considered to be similar to the representative material, if:

— It is made of the same basic polymer material.
— It can be substantiated that additives and fillers are of a similar nature as the representative material.
— The glass transition temperature and melting temperature are the same within ±5 °C.
— The Charpy impact strength is within ±15% at minimum and maximum use temperature.
— The tensile stress strain curves are identical within ±5%.
— Differential scanning calorimetry (DSC) tests give the same curve within ±5%.
— Water and Xylene (or similar solvent) absorption at saturation is the same within ±5%.
— The static strength at minimum and maximum operating temperatures is similar according to [4.7.5]
— The creep resistance is similar: the creep curves are similar within 10% in strain and time.

All deviation limits are relative %.

4.7.4 Physical similarity requirements for composite laminates

A thermoplastic composite should only be considered similar to the representative material if:

— The thermoplastic composite´s matrix fulfils the same similarity requirements as given for polymers in [4.7.3].
— The reinforcing fibres are of the same generic type as the ones in the representative material. Note: not all carbon fibres are the same type, but for example all fibers with the same properties as TM 7000 can be seen as generically the same.
— The sizing on the fibres is similar, based on the basic chemical composition, compatibility with fibre, matrix and expected environmental exposures.
— The fibre arrangement (layup, weave) are the same as the one in the representative material.

4.7.5 Requirements for similarity of static data

At least three measurements shall be made for each property to be compared.

Not more than 50% of the data should be below the mean of the representative data.

Not more than 16% of the data should be below the mean – 1 stdv of the representative data.

Not more than 2.5% of the data should be below the mean – 2 stdv of the representative data.

If the testing shows that the above requirements are not fulfilled, the data is not similar to the representative material, and an independent test series needs to be carried out.

Alternatively hypothesis testing may be used to determine similarity, see DNVGL-ST-C501 [4.8.7].

4.7.6 Requirements for similarity of long-term data

At least six measurements shall be made for each property to be compared.

The data points should be fairly evenly distributed over the time scale or number of cycles scale.

At least two of the six specimens should be tested for so long that they fail within one standard deviation of the TCP's anticipated lifetime or anticipated number of cycles.

If the anticipated lifetime exceeds 1000 hours testing up to 1000 hours is sufficient.

If the anticipated number of cycles exceeds 10^5 cycles, testing up to 10^5 cycles is sufficient.

Not more than 2.5% of the data should be below mean – 2 stdv of the reference curve.

Not more than 16% of the data should be below mean – 1 stdv of the reference curve.

Not more than 50% of the data should be below mean of the reference curve.

In addition the slope fitted to the test data shall not deviate more than 10% from the reference curve.

If the testing shows that the above requirements are not fulfilled, the data is not similar to the representative material and an independent test series needs to be carried out.

Alternatively, hypothesis testing may be used to determine similarity, as described in DNVGL-ST-C501 [4.8.8] or DNVGL-ST-C501 [3.8.9].

4.7.7 Similarity requirements exposure condition

If exposure of a polymer or composite to two different environments is expected to give the same mechanical properties, the similarity evaluation in [4.7.5] and [4.7.6] shall be applied to the exposure conditions.

4.8 Solubility approach

It may be possible to predict the influence of chemicals on mechanicals using the solubility approach. The effect of chemicals is similar if they have the same solubility. It may also be possible to relate solubility levels to temperature. If sufficient experimental evidence can be provided, this approach may be considered for characterizing material properties.

SECTION 5 FAILURE MECHANISMS AND DESIGN CRITERIA

5.1 Introduction

This section describes design criteria for individual failure mechanisms.

Safety factors shall be taken from Sec.11. The detailed use of the safety factors in the individual design criteria is described in DNVGL-ST-C501.

5.2 Fibre-dominated ply failure

5.2.1 General

Fibre failure is seen here as the fibre-dominated failure of a ply. It is not the failure of an individual fibre. Fibre failure should be checked at the ply level, not at the laminate level.

5.2.2 Maximum strain and stress design criteria

The maximum strain criterion and maximum stress criterion shall be satisfied.

In displacement-controlled conditions, ply strains in the fibre direction shall satisfy the maximum strain criterion.

In load-controlled conditions, ply stresses in the fibre direction shall satisfy the maximum stress criterion.

In mixed or unclear loading conditions, both criteria shall be satisfied.

For single loads the maximum strain design criterion is given as:

$$\varepsilon_{nk} < \frac{\hat{\varepsilon}_k^{fibre}}{\gamma_M \cdot \gamma_{Rd}}$$

and the maximum stress design criterion is given as:

$$\sigma_{nk} < \frac{\hat{X}_k^{fibre}}{\gamma_M \cdot \gamma_{Rd}}$$

The load effect (stresses σ_{nk} or strains ε_{nk}) shall be obtained from the local loads multiplied by the partial load factor γ_F [11.2], the load model factor γ_{Sd} [11.4.1] and the system factor γ_S [11.5]

where:

ε_{nk}	characteristic value of the local response of the structure (strain) in the fibre direction n
$\hat{\varepsilon}_k^{fibre}$	characteristic value of the time dependent axial strain to fibre failure
σ_{nk}	characteristic value of the local response of the structure (stress) in the fibre direction n
$\hat{X}_k^{fibre}$	characteristic value of the time dependent axial strength in the fibre direction
k	index describing the plies in the laminates
γ_M	partial resistance factor
γ_{Rd}	partial resistance-model factor, $\gamma_{Rd} = 1.0$.

The maximum strain and stress criteria shall be checked in all n directions parallel to the fibres as well as for tensile and compressive strains.

5.2.3 Obtaining strength data

The strength and strain to failure shall be measured according to [4.4], Table 4-6 or Table 4-7. Fibres shall always be oriented in the load direction to obtain fibre properties. If laminates with fibres oriented in different directions are tested, the test will obtain the properties of the fibres in the load direction.

If the presence of matrix cracks is acceptable to the design and matrix cracks will develop, the compressive strength shall be determined in the presence of matrix cracks, see [4.4.2]. Compressive strength may also be loading-rate-dependent due to the viscoelastic matrix surrounding and supporting the fibres.

The fibre strength and strain to failure may also be obtained from laminate testing as described in [5.5]. This approach only works for laminates and test set-ups where fibre dominated ply properties can be calculated from the test results without ambiguity, e.g. analytically for a cross plied laminate or by using FE analysis of the test set-up.

5.2.4 Alternative approaches

Other design criteria may be used if it can be shown that they are equal or conservative compared to the criterion given here. Alternatively, the other criteria can be evaluated according to [5.25]. Note that the nonlinear character of the TCP requires a stress-based and strain-based evaluation as described in the criteria given here.

5.3 Matrix cracking

5.3.1 General

If matrix cracking is critical for the design (see Sec.7 and Sec.8, matrix cracking shall be analysed according to DNVGL-ST-C501 [6.4]).

Matrix design criteria apply to matrix in a ply where the deformation of the matrix is restrained by the fibres of the ply or the surrounding laminate. Matrix cracking is defined here as the onset of matrix cracking. The matrix cracking criteria presented in this section do not cover the increase of the number of matrix cracks at higher stresses or strains.

Matrix cracking shall be checked at ply level.

Two alternative design criteria are given here, the simple stress criterion (see [5.3.2]) and the Puck criterion (see [5.3.4]).

If the TCP may fail due to wedge-shaped matrix cracks in compression, the Puck criterion shall be used to obtain the direction of the failure surface.

5.3.2 Maximum stress design criterion for matrix cracking

The following design criterion should be used when the stress in one direction is dominating compared to the stresses in the other directions.

$$\sigma_{nk} < \frac{\hat{\sigma}_{nk}^{matrix}}{\gamma_M \cdot \gamma_{Rd}}$$

The load effects (stresses σ_{nk}) shall be obtained from the local loads multiplied by the partial load factor γ_F [11.2], the load model factor γ_{Sd} [11.4.1] and the system factor γ_S [11.5]

where:

n   direction of the dominating stress

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σ_{nk} characteristic value of the local load effect of the structure (stress) in the direction n

$\hat{\sigma}_{nk}^{matrix}$ characteristic value of the strength components to matrix cracking in direction n

γ_M partial resistance factor

γ_{Rd} partial resistance-model factor, $\gamma_{Rd} = 1.0$.

The ply co-ordinate system.

The strength of the matrix (stress to matrix cracking) is in general direction-dependent. This is due to the presence of fibres that concentrate the stresses, such that the matrix stress to failure in the direction parallel to the fibres is generally larger than in the perpendicular direction.

The stress in one direction is said to be dominating when the following condition is satisfied:.

$$max_i\left[\frac{\sigma_{ik}}{\hat{\sigma}_{ik}^{matrix}}\right] / \sum_{n \neq i}\left[\frac{\sigma_{nk}}{\hat{\sigma}_{nk}^{matrix}}\right] \geq 10$$

The ply co-ordinate system, where i and n refer to the directions 22, 33, 12, 13 and 23. The directions 22 and 33 are identical to the more commonly used directions 2 and 3. They are used here to simplify the matrix-based equation.

When the combination of the stress components in several directions shall be taken into consideration, the design criterion for matrix cracking is given by:

$$\gamma_M \cdot \gamma_{Rd} \cdot \sqrt{\sum_n\left(\frac{\sigma_{nk}}{\hat{\sigma}_{nk}^{matrix}}\right)^2} < 1$$

The load effects (stresses σ_{nk}) shall be obtained from the local loads multiplied by the partial load factor γ_F [11.2], the load model factor γ_{Sd} [11.4.1] and the system factor γ_S

where:

n the ply co-ordinate system, where n refers to the directions 22, 33, 12, 13 and 23, The directions 22 and 33 are identical to the more commonly used directions 2 and 3.

σ_{nk} characteristic value of the local load effect of the structure (stress) in the direction n for ply k

$\hat{\sigma}_{nk}^{matrix}$ characteristic value of the strength components to matrix cracking in direction n for ply k

k index describing the plies in the laminates

γ_M partial resistance factor

γ_{Rd} partial resistance-model factor, $\gamma_{Rd} = 1.15$.

A resistance-model factor $\gamma_{Rd} = 1.15$ should be used with this design rule. The model factor shall ensure a conservative result with respect to the simplifications made regarding the treatment of combined loads.

This design criterion is often unavailable in finite element codes or other commercial software. The Tsai-Wu criterion can be used instead to check for matrix cracking, if the following modifications are made to the strength parameters:

— the ply strengths in the fibre direction may be chosen to be much (1000 times) higher than the actual values.
— the interaction parameter $f_{12} = 0$ shall be set to 0.

However, it is recommended to use the Puck criterion to predict matrix cracking.

5.3.3 Obtaining strength data

The matrix dominated ply strength shall be measured according to [4.4], Table 4-6.

The matrix strength and strain to failure may also be obtained from laminate testing as described in [5.5]. This approach only works for laminates and test set-ups where matrix dominated ply properties can be calculated from the test results without ambiguity, e.g. analytically for a cross plied laminate or by using FE analysis of the test set-up.

Note that matrix cracks will form easily under fatigue.

Unless data indicate otherwise, the COV to be used as the basis for selecting the correct material factor in Sec.11 can be set equal to the maximum COV amongst the COVs for the involved strengths in various directions

$$COV_{comb} = max_n (COV_n)$$

where COV_{comb} is an equivalent representative COV for the implied strength that results from combining the different strength components within a ply as specified in the design criterion.

The partial safety factors γ_F and γ_M shall be chosen as described in Sec.11 with COVs equal to COV_{comb}, as described here.

If the matrix of a ply shows yielding before failure the matrix strength values shall be replaced by the matrix yield point in the failure criteria given above.

If yielding and related permanent plastic deformations can be accepted in the design, the nonlinear behaviour shall be considered in the design calculations. If viscoelastic and related semi-permanent plastic deformations can be accepted in the design, the nonlinear behaviour shall be considered in the design calculations.

5.3.4 Alternative approaches and the Puck criterion

Other design criteria may be used if it can be shown that they are equal or conservative compared to the criterion given here.

The Puck criterion (partially described in DNVGL-ST-C501) may be used.

Alternatively, another criterion can be evaluated according to [5.25].

5.4 Delamination

Delamination shall be analysed based on the three dimensional matrix failure criteria given in [5.3]. The partial resistance-model factor shall be set at $\gamma_{Rd} = 1.3$.

The fracture mechanics based design criteria are to be taken from DNVGL-ST-C501 [6.5]. The resistance model factor shall be chosen according to [11.4.2]

The through-thickness ply strength shall be measured according to [4.4].

5.5 Laminate failure

Laminate failure is due to a combination of matrix cracking, delamination and fibre failure.

As an alternative to analysing laminate failure using the individual failure mechanism laminate failure may be measured directly on the actual laminate. When using this approach the design shall define the laminate's critical failure mechanisms as matrix cracking, yielding, delamination and fibre rotation or fibre failure.

This design criterion shall be used in addition to the other failure criteria if fibres in the axial direction are oriented more than 70° apart. The criterion may also be used for other laminate layups.

The laminate criterion shall only be applied to strains in the axial or hoop direction.

The laminate may be a sub-laminate of the total TCP. The strains used for the design criterion shall in such case be the strains of the sub-laminate.

Other loading conditions shall be covered by the other failure criteria.

The design criterion shall prevent the onset of the critical failure mechanism in the laminate. The design criterion is given as:

$$\varepsilon^{axial} < \frac{\hat{\varepsilon}^{axial}_{laminate}}{\gamma_M \gamma_{Rd}}$$

or

$$\varepsilon^{hoop} < \frac{\hat{\varepsilon}^{hoop}_{laminate}}{\gamma_M \gamma_{Rd}}$$

The load effects (strains $\varepsilon^{axial}_{ave}$ or ε^{hoop}_{ave} shall be obtained from the local loads multiplied by the partial load factor γ_F [11.2], the load model factor γ_{Sd} [11.4.1] and the system factor γ_S [11.5]

with:

$\gamma_{Rd} = 1.05$ if the failure mechanism is fibre failure and

$\gamma_{Rd} = 1.15$ if the failure mechanism is matrix dominated

where:

ε^{axial}	characteristic value of the local response of the structure (strain) in the axial direction.
ε^{hoop}	characteristic value of the local response of the structure (strain) in the hoop direction.
$\hat{\varepsilon}^{axial}_{laminate}$	is the strain to yield or strain to failure of the TCP laminate under axial loading. It shall be measured according to [4.4.3]
$\hat{\varepsilon}^{hoop}_{laminate}$	is the strain to yield or strain to failure of the TCP laminate under axial loading. It shall be measured according to [4.4.3]
γ_M	partial resistance factor.
γ_{Rd}	resistance model factor.

This design criterion shall only be used for the load conditions measured i.e. axial tension and compression, hoop tension and compression.

If $\sigma^{char}_{laminate} < 2\Upsilon^{char}_T$, the yield criterion [5.8] and load-bearing polymer design criterion [5.7] shall be applied in the design. $\sigma^{char}_{laminate}$ is the measured characteristic strength of the $\pm\alpha$ laminate and Υ^{char}_T is the characteristic ply strength transverse to the fibres. In this case the strength of the $\pm\alpha$ laminate is matrix dominated and the polymer design criterion shall be applied even if matrix cracking was seen as not being critical.

If it can be shown that the ply failure criteria in [5.2], [5.3] and [5.4] give the same or conservative results as the laminate failure criterion in this section, only ply failure criteria may be used.

5.6 Fluid tightness – permeability

Fluid tightness shall be demonstrated based on the permeability measurements stated in [4.3.2] Table 4-4 and [4.4] Table 4-6.

If thickness is reduced due to yielding or wear and tear, the permeability calculations shall be based on the reduced thickness.

If the material can have matrix cracks or crazes or is not designed against crazing, permeabilities shall be measured with the presence of matrix cracks or crazes, see also [5.11].

Any cracks or puncturing shall be considered as a local leak (very high permeability).

5.7 Polymer fracture

Polymers of the TCP may be load-bearing (typically in the end fitting) or displacement-controlled (typically liners and covers connected to the laminate).

If the polymer is displacement controlled it shall be shown that the maximum principal strains do not exceed the polymer's capacity:

$$\varepsilon_{\max} < \frac{\widehat{\varepsilon}^{polymer}}{\gamma_M \gamma_{Rd}}$$

The load effects (principal strains $\varepsilon_{\max}$ shall be obtained from the local loads multiplied by the partial load factor γ_F [11.2], the load model factor γ_{Sd} [11.4.1] and the system factor γ_S [11.5],

where:

$\varepsilon_{\max}$	characteristic value of the load effect (strain) in the maximum principal direction
$\widehat{\varepsilon}^{polymer}$	characteristic strain to failure of the polymer
γ_M	partial resistance factor
γ_{Rd}	partial resistance-model factor, $\gamma_{Rd} = 1.0$.

If the polymer is load bearing, polymer fracture shall be analysed using the ultimate strength design criterion for orthotropic materials. In most cases the polymer can be seen as an isotropic material, where the properties are the same in all directions.

$$\gamma_M \cdot \gamma_{Rd} \cdot \sqrt{\sum_n \left(\frac{\sigma_{nk}}{\widehat{\sigma}_{nk}}\right)^2} < 1$$

The load effects (stresses σ_{nk}) shall be obtained from the local loads multiplied by the partial load factor γ_F [11.2], the load model factor γ_{Sd} [11.4.1] and the system factor γ_S [11.5]

where:

n	the ply co-ordinate system, and refers to the directions 11, 22, 33, 12, 13 and 23, The directions 11, 22 and 33 are identical to the more commonly used directions 2 and 3.
σ_{nk}	characteristic value of the local load effect of the structure (stress) in the direction n for ply k
$\widehat{\sigma}_{nk}$	characteristic value of the strength (stress to failure for in direction n) for ply k
k	index describing the plies in the laminates
γ_M	partial resistance factor
γ_{Rd}	partial resistance-model factor, $\gamma_{Rd} = 1.25$.

For orthotropic materials the directions shall be the material axes. For isotropic materials the directions shall be along either the principal normal stresses or the principal shear stresses.

This is a conservative design criterion. It has been chosen due to a lack of data for, and experience with, ultimate failure under multiple stress conditions. Other design criteria may be used if experimental evidence for their validity can be given.

Guidance note:

A resistance-model factor γ_{Rd} = 1.25 should be used with this design rule. The modelling factor should ensure a conservative result with respect to the simplifications made regarding the treatment of combined loads.

---e-n-d---o-f---g-u-i-d-a-n-c-e---n-o-t-e---

Unless data indicates otherwise, the COV to be used as the basis for selecting the correct material factor in Sec.11 can be set at the maximum COV of the COVs for the involved strengths in various directions;

$$COV_{comb} = max_n (COV_n)$$

where COV_{comb} is an equivalent representative COV for the implied strength that results from combining the different strength components within a ply as specified in the design criterion.

The partial safety factors γ_F and γ_M shall be chosen as described in Sec.11 with COVs equal to COV_{comb}, as described here.

The strain to failure used in this design criterion shall not exceed 15%.

Higher strains to failure may be used if experimental multiaxial load testing has shown that the design criterion described here is still valid.

The ultimate strength and ultimate strain shall be measured according to [A.4.1], Table 4-4 for liners and covers.

If the strain limit of 15% is used in the design and the polymer fails at strains of more than three times the limit, the accuracy in determining the strain to failure is not so critical. In such case, the COV can be set at 5%.

The strength shall be taken as the strength at the failure strain.

5.8 Plastic deformation, yielding of isotropic materials

The von Mises yield criterion shall be used to describe materials that yield. This criterion uses the principal stresses.

$$\gamma_M \cdot \gamma_{Rd} \cdot \sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2} < \sigma_y$$

The load effects (stresses σ_n) shall be obtained from the local loads multiplied by the partial load factor γ_F [11.2], the load model factor γ_{Sd} [11.4.1] and the system factor γ_S [11.5]

where:

σ_n	characteristic principal stresses, n=1,2,3
σ_y	characteristic value of the material's yield stress
γ_M	partial resistance factor
γ_{Rd}	resistance-model factor, γ_{Rd} = 1.0.

When two or more loads are combined, each stress component σ_n in direction n may be the result of several combined loads. In such case, each stress component σ_n^j, the local response of the structure in direction n due to load j, shall be considered separately as an individual stress component.

The choice of partial safety factors shall be based on the most conservative partial safety factors obtained when treating each stress component σ_n^j, the local response of the structure in direction n due to load j, as a single load. The material's COV shall always be the COV of the yield strength.

The yield strength shall be measured according to [4.4] Table 4-6 for composite laminates and according to [4.3], Table 4-4 for liners and covers.

Testing of the results' rate dependence shall be considered. The strength used in the calculations shall be representative of the application's actual loading rates .

Note: If yielding is permitted in the design, the ultimate strength requirement stated in [5.7] still needs to be fulfilled.

5.9 Maximum deformation

5.9.1 General

The TCP may have maximum deformation requirements in terms of axial elongation, torsion, ovalization etc. as described in [3.5].

Possible creep and yielding shall be considered in all calculations, especially permanent deformations due to long-term reeling. Yielding shall be addressed using the criteria in [5.8].

The deformation design requirement

$$d_n < \frac{d_{spec}}{\gamma_{Rd}\gamma_M}$$

shall be used.

The load effect (deformation d_n) shall be obtained from the local loads multiplied by the partial load factor γ_F [11.2] and the load model factor γ_{Sd} [11.4.1]

where:

d_n characteristic value of the structure's local response , here displacement

d_{spec} specified maximum displacement requirement

γ_M partial resistance factor

γ_{Rd} partial resistance-model factor, $\gamma_{Rd} = 1.0$.

5.9.2 Axial deformation

The TCP will elongate due to axial forces. Pressure may cause axial elongation, compression or no length change depending on the layup. All these effects shall be considered when calculating axial deformations.

Possible creep and yielding shall be considered in all calculations.

5.9.3 Ovalization

The TCP shall not be subject to excessive ovalization. The residual flattening due to bending and point loads, long-term creep, together with the out-of-roundness tolerance from the pipe's fabrication , is not to exceed 3%, defined as:

$$f_0 = \frac{D_{max} - D_{min}}{D} \le 0.03$$

where:

D is the undeformed diameter of the pipe.

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D_{max} and D_{min} are the maximum and minimum diameters of the ovalized pipe respectively.

The requirement may be relaxed if:

— a corresponding reduction in moment resistance has been included
— geometrical restrictions are met, such as pigging requirements
— additional cyclic stresses caused by the ovalization have been considered
— tolerances in the relevant repair system are met.

Ovalization shall be checked for at any point loads along the TCP. Such point loads may arise at free-span shoulders, artificial supports, support settlements, bend stiffeners and caterpillars.

Any effects of ovalization on buckling shall be considered in [7.4].

5.9.4 Accumulated deformation

Accumulated plastic deformation of the TCP caused by cyclic loads leading to an increased diameter or ovality (ratcheting) shall be considered. If ratcheting causes increased ovality, special consideration shall be given to the effect on buckling resistance.

Accumulated longitudinal displacement of the TCP (could e.g. be caused by pipeline walking) shall be considered. This may occur during start-up/shut-down for:

— pipelines shorter than two anchor lengths, or
— pipeline parts with a virtual anchor,
— pipelines laying on a seabed slope, or
— pipelines connected to a pulling force (e.g. connected to SCR).

5.10 Debonding

Debonding between different components shall be analysed in the same way as delamination in [5.4].

The through-thickness ply strength shall be measured according to [4.6].

5.11 Crazing, cracking

Some polymers develop crazes before failure. Crazes are often an alternative failure mechanism to yielding. The presence of crazes may reduce the polymer's strength and increase permeation rates.

Polymer materials that do not craze should preferably be chosen. If they show crazing investigations shall be systematically conducted after each burst test and material strength tests.

The onset of crazing shall be addressed in the same way as matrix cracking, unless it can be shown that crazes have no influence on the mechanical properties.

5.12 Impact

An impact may cause damage to the laminate, cover and liner and reduce the strength of the TCP material. The acceptable damage shall be determined experimentally according to [10.9].

An impact may also cause a dent in the pipe section, thus reducing the cross-sectional area.

The acceptable dent size shall create a shape change that is less than that which is acceptable for ovalization, as described in [3.5] and [5.9.3].

When allowing for permanent dents, additional failure modes such as fatigue and collapse shall be taken into account. Any beneficial effect of internal over-pressure, i.e. "pop-out" should not be included. (Pop out describes the effect of dents being removed by the internal pressure. Permanent damage such as micro cracks tends to remain after pop-out).

The beneficial effects of protective coatings may be taken into account. The coating's effectiveness against impact damage shall be documented.

Impact is analysed on the full-scale component level in this standard, see [10.9].

5.13 Puncturing, scratches and point loads

Puncturing or scratching are processes that reduce the material's thickness , create stress concentrations and may indirectly reduce the material's strength. If puncturing or scratching can happen, the effects on geometry and strength shall be considered in all failure criteria. The reduction in strength may also be determined experimentally.

Scratching and especially puncturing may also increase permeability.

Generally, point loads shall be avoided. All possible point loads shall be evaluated and it shall be ensured that they will not damage the material. See also [3.5.2] and [7.8.9].

Temporary weakening of the cover or liner may be acceptable if a repair and inspection method can be specified. The maximum duration of the damage shall also be specified and justified. It shall be shown that the temporary damage does not detrimentally affect the remaining TCP.

5.14 Wear and tear

Wear and tear will reduce the material's thickness. The reduced thickness calculated according to DNVGL-ST-C501 [6.13], shall be applied.

The wear or abrasion resistance shall be measured according to [A.4.1], Table 4-4, for liners and covers.

If a TCP has no liner or cover and wear/abrasion is relevant for the application, the wear abrasion tests for liners or covers should be modified to be suitable for the laminate.

Temporary damage may be acceptable as described in [5.13].

5.15 Chemical degradation

The possible chemical reactions between the TCP's materials and the inner and outer fluids shall be evaluated.

As a minimum, hydrolysis and oxidation shall be considered.

Hydrocarbons tend to cause swelling, but no direct degradation. This shall be confirmed from a chemical analysis point of view.

If chemical reactions that break down the polymer chains can occur, a degradation of mechanical properties due to the chemical reactions should be evaluated.

The combination of hot and wet conditions may accelerate degradation more than expected based on the individual effects.

If the chemical reactions are expected to happen during the long-term mechanical testing the degradation due to chemicals shall be addressed.

If chemical reactions are expected to be suppressed initially due to additives, the depletion time of the additives should be estimated.

If possible, viscosity measurements versus time should be carried out in addition to the mechanical tests. API 17TR2 may be used as guidance. Typically, the polymer's viscosity is proportional to the polymer's molecular weight. A viscosity drop indicates a reduction in molecular weight. Mechanical properties tend to be only affected after a substantial drop in molecular weight.

Long diffusion times may lead to degradation that is only close to the surface. Short diffusion times tend to create degradation throughout the bulk of the material.

The same effects apply to composite materials; their polymers, fibres and fibre's sizing. Note that the interface between the fibres and matrix can create a fast diffusion path.

An overall evaluation of the chemical reaction kinetics shall demonstrate that chemical breakdown is not expected to affect the mechanical properties beyond the mechanical degradations determined in the other parts of this section.

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If chemical degradation may occur, all the mechanical properties stated in Sec.4 shall also be obtained for the chemically degraded material.

Documented evidence of a material's resistance may be used as an alternative to the chemical evaluation, if a material has a well-known track record showing no chemical degradation for the expected exposure conditions. The experience will only be valid for a specific material type, not for the generic class of materials. Whether or not experience can be used shall be agreed on between the manufacturer, purchaser and, if relevant verifying agent.

Galvanic corrosion between carbon fibres and metal components shall be considered if carbon fibres are used in the TCP. Galvanic corrosion should be prevented by having an electrical insulation layer between the carbon fibres and steel parts.

5.16 Swelling or shrinkage

The swelling or shrinkage of mechanical properties shall be evaluated by testing as described in Sec.4. The TCP laminate, liner, cover and interfaces shall be considered.

5.17 Leaching of additives

The effects of additives leaching on mechanical properties shall be evaluated by testing as described in Sec.4. The TCP laminate, liner and cover shall be considered.

5.18 Rapid gas decompression - blistering resistance

Fluids can diffuse into the material and may accumulate inside the molecular structure, inside voids or in material interfaces. When the diffusion happens under pressure, the fluids are compressed inside the material. If the pressure is suddenly released, the expansion of the fluids may lead to material damage, blistering or interface debonding.

The resistance to the phenomenon shall be shown by testing as described in [4.4], Table 4-6 for composite laminates and in [4.3], Table 4-4 for liners and covers.

If the strength of the liner-TCP-laminate interface or TCP-laminate-cover interface is less than the strength of the base materials, the respective interface shall be tested for blistering resistance according to [4.6], Table 4-11. The strength of the interfaces can be demonstrated by through-thickness testing, Table 4-11 or by the simplified interlaminar testing [4.6.3]

5.19 Ultraviolet exposure

Resistance to UV exposure shall be determined experimentally according to [A.8].

Long-term experience with the same type of material may also be used to demonstrate UV resistance. The experience should be based on the product's design lifetime .

5.20 Thermal softening or hardening

The effects of swelling or shrinkage on mechanical properties shall be evaluated by testing as described in Sec.4. Possible morphology changes as described in [5.21] shall also be considered.

The effects of thermal cycling shall be evaluated as described in [4.2.7].

5.21 Morphology change

When a polymer is exposed to temperatures close to its glass transition temperature T_g, or even more if the temperature crosses T_g several times, the polymer´s morphology may change. Depending on the type of polymer, this change may significantly influence the mechanical properties. Repeated exposure to solvents may cause similar morphology changes.

If the polymer is exposed to temperatures repeatedly crossing T_g its mechanical properties shall be measured according to Sec.4 before and after the repeated T_g crossings, as described in [4.2.7].

Note that T_g is also influenced by water content, plasticizer and pressure, see [A.1.10].

5.22 Lifetime calculations - cyclic fatigue

5.22.1 General

Every failure mechanism shall be evaluated for fatigue ([5.2], [5.3], [5.4], [5.5], [5.6], [5.7], [5.8], [5.10].)

The fatigue performance of all TCP components shall be calculated using characteristic S-N curves, the Goodman diagram (see [A.6.4]) and Miner sum.

The S-N curves used in the calculations should be relevant for the failure mechanism investigated. They should also be relevant for the environmental conditions experienced by the TCP components.

If the failure criterion requires a strain based evaluation the S-N curve should be converted into an epsN curve.

The load effects (stresses or strains) for the fatigue analysis shall be obtained from the local loads multiplied by the load model factor γ_{Sd}[11.4.1]. Details about this approach can also be found in DNVGL-ST-C501 [6.11.3].

The maximum, minimum and operational temperatures shall be considered in the analysis, using the relevant S-N curves and including thermal stresses in the calculations.

The S-N curves for the fatigue analysis are usually measured at higher frequencies than the TCP experiences in service. An evaluation of the effect of the frequency should be provided. Testing at frequencies below 10 Hz can be seen as relevant for lower loading frequencies of the real application, provided no frequency dependent phase transition occurs in the material between the real and tested loading frequencies.

Polymer fatigue may be combined with large plastic deformations. The accumulation of these deformations (ratcheting) should be considered.

Saturation and plasticizer (environmental exposure) content shall be evaluated.

5.22.2 Calculation principle

A Goodman or Hall diagram (see [A.6.4]) shall be used to predict the fatigue life of different combinations of strain range and mean strain.

A table shall be established listing the local strain sequences, as shown in Table 5-1.

Table 5-1 Example of sequence of fatigue strains and number of cycles used for fatigue calculations

Strain range	Mean strain	Number of cycles	Predicted number of cycles	Life ratio
$\Delta\varepsilon$	ε_{mean}	N_{actual}	$N_{predicted}$	$\dfrac{N_{actual}}{N_{predicted}}$

The Miner sum should be calculated according to:

$$M = \sum \frac{N_{actual}}{N_{predicted}} < \frac{1}{\gamma_{fat}}$$

The Miner sum approach is only valid for high cycle fatigue, typically when loads are below yielding.

Fatigue under high loads giving yielding or other plastic deformations or lifetimes of about 1000 cycles or less (low cycle fatigue) should be avoided. If such conditions cannot be avoided a special test program shall be established.

5.22.3 Fibre-dominated failure - cyclic fatigue

Local strains shall be measured in the fibre direction to analyse the fibre fatigue of TCP laminates. Each fibre direction in the TCP laminate shall be evaluated.

S-N curves for the fatigue analysis shall be measured and analysed according to [4.4] and [A.6].

5.22.4 Through-thickness delamination and debonding - cyclic fatigue

Local through-thickness stresses shall be obtained for analysing delamination and debonding fatigue, especially in the end fitting region.

S-N curves for the fatigue analysis shall be measured and analysed according to [4.4], [4.6] and [A.6].

5.22.5 Matrix cracking - cyclic fatigue

Matrix cracks generally develop in a laminate. If the TCP does not have a liner that ensures fluid tightness in the presence of matrix cracks, fatigue testing shall show that no matrix cracks causing leakage develop in the TCP laminate during the lifetime.

5.22.6 Laminate failure - cyclic fatigue

The laminate failure criterion shall be applied for the axial or hoop direction [5.5]

For most TCPs the laminate failure will be applied in the axial direction.

Load effects (strains) shall be obtained for analysing laminate fatigue.

S-N curves for the fatigue analysis shall be measured and analysed according to [4.4] and [A.6]. The S-N curve shall always be obtained in load control, but shall be presented as initial strains versus number of cycles.

5.22.7 Polymer fracture of liner and cover - cyclic fatigue

Local maximum principal strains shall be identified for use in the fatigue calculations for the liner and cover.

S-N curves for the fatigue analysis shall be measured and analysed according to [4.3] and [A.6].

5.22.8 Thermal fatigue

In this standard, thermal fatigue is evaluated by determining the fatigue damage caused by cyclic thermal loads and including that in the total calculated fatigue damage. This is determined by preconditioning and testing, as described in [4.2.7].

Thermal fatigue should also be analysed considering the cyclic thermal stresses in the fatigue analysis.

5.23 Stress rupture

5.23.1 General

Every failure mechanisms shall be evaluated for stress rupture ([5.2], [5.3], [5.4], [5.5], [5.6], [5.7], [5.8], [5.10].)

The resistance to stress rupture of all TCP components shall be calculated using characteristic stress rupture curves and Miner sum.

The stress rupture curves used in the calculations should be relevant for the failure mechanism investigated. They should also be relevant for the environmental conditions experienced by the components.

The load effects (stresses) for the stress rupture analysis shall be obtained from the local loads multiplied by the load model factor γ_{Sd} [11.4.1]. Details of the approach can also be found in DNVGL-ST-C501 [6.10.4].

The maximum, minimum and operational temperature shall be considered in the analysis, using the relevant stress rupture curves and including thermal stresses in the calculations.

The saturation condition and plasticizer (environmental exposure) content shall be evaluated.

5.23.2 Calculation principle

A table shall be established listing the local strain sequences, as shown in Table 5-2.

Table 5-2 Example of sequence of long-term stresses and exposure time used for stress- rupture calculations

Long-term stress	Exposure time	Predicted survival time	Life ratio
$\sigma_{long-term}$	t_{actual}	$t_{predicted}$	$\dfrac{t_{actual}}{t_{predicted}}$

The Miner sum should be calculated according to:

$$M = \sum \frac{t_{actual}}{t_{predicted}} < \frac{1}{\gamma_{fat}}$$

For stress rupture evaluation of $\pm\alpha$ laminates the initial strain shall be used instead of $\sigma_{long-term}$, using the initial-strain based stress rupture curve [A.7.2], [5.23.2].

5.23.3 Fibre dominated failure – stress rupture

Local stresses shall be measured in the fibre direction to analyse the fibre dominated stress rupture of TCP laminates. Each fibre direction in the TCP laminate shall be evaluated.

Stress rupture curves shall be measured according to [4.4.4].

5.23.4 Through-thickness delamination and debonding - stress rupture

Local through-thickness stresses shall be obtained for analysing delamination and debonding, especially in the end fitting region.

Stress rupture curves shall be measured according to [4.4.4] and [4.6].

5.23.5 Matrix cracking - stress rupture

If the TCP does not have a liner that ensures fluid tightness in the presence of matrix cracks, stress rupture testing shall show that no matrix cracks causing leakage develop in the TCP laminate during the lifetime.

5.23.6 Laminate failure - stress rupture

Axial stresses shall be obtained for analysing stress rupture.

Stress rupture curves shall be measured according to [4.4.4] and [4.6].

5.23.7 Polymer fracture of the liner and cover – in-plane stress rupture

The in-plane stress rupture of liner and cover does not need to be calculated, as long as the TCP laminate is the load bearing part and the liner and cover follow the movements of the laminate.

5.23.8 Liner and cover in-plane stress rupture

The in-plane stress rupture of liners and covers does not need to be calculated, as long as the TCP laminate is the load bearing part and the liner and cover follow the movements of the laminate.

5.24 Combination of cyclic fatigue and stress rupture

Cyclic fatigue and stress rupture should be evaluated independently of each other.

However, the period of stresses related to cyclic fatigue shall also be accounted for in the stress rupture calculations.

5.25 Requirements or other design criteria

If a structure or component shows a failure mechanism not properly described above it may be necessary to describe a design criterion for this failure mechanism.

All design criteria shall be verified against experimental evidence. The model factor assigned to the design criterion shall compensate for the discrepancies between prediction and experiment. The model factor is a deterministic factor.

It shall be confirmed that the design criterion is of general nature and does not just apply to one material or one load case, unless the criterion is only used for that particular condition.

The partial safety factors in the criterion shall be calibrated by probabilistic methods to ensure a consistent level of safety with respect to the rest of the standard.

SECTION 6 ANALYSIS METHODOLOGY

6.1 Introduction

The purpose of this section is to provide an overview of the analysis methodology for TCPs.

Global analysis shall be performed as described in DNVGL-ST-F101 for pipe-related applications and in DNVGL-ST-F201 for riser-related applications.

All the phases specified in [3.3] shall be analysed.

The main purpose of the analysis is to obtain the local load effects for the given global design input in Sec.3. Global loads shall be obtained as described in [3.6].

The load effects are input to the design criteria from Sec.7 and Sec.8. It shall be shown that all requirements are fulfilled based on all load effects, service fluids, environments and other conditions.

This section describes how to obtain load effects in a way that is consistent with the safety factors used in this standard.

At any time during the structure's design life, it should be documented that the structure can fulfil its functional requirements for:

— all characteristic load effect values combined with all sustained environmental values,
— all sustained load effect values combined with all characteristic environmental values.

The structural stress analysis shall be undertaken in a professional and well-documented manner. There are many possible ways to perform such an analysis.

Detailed local analysis shall be applied for end fittings/joints and other critical parts of the TCP system.

As a default, nominal dimensions shall be used for all calculations related to FRP laminates or polymers. Other dimensions may be used if it can be shown that the choice is more correct or conservative.

For metals, the dimensions as described in the related metal standards, such as DNVGL-ST-F201 for dynamic risers, shall be used.

As a default, the characteristic material strength as described in [A.3], [A.6.2] and [A.7.2] shall be used for all calculations. Other strengths may be used if it can be shown that the choice is more correct or conservative.

6.2 Load effects

6.2.1 General

The design criteria in this standard are applied to load effects (local stresses and strains).

Several combinations may have to be checked when load effects from several load categories are included in one design check.

Any non-linearities in the conversion from load to load effect shall be considered in the design calculation and in the estimation of the load model factor, see [11.1] and [6.11].

It is important to note that the relationship between loads and load effects is generally not linear. For this reason it is necessary to always distinguish between global loads, local loads and load effects. The safety factors shall be applied to local loads. Under combined loading conditions, local loads shall be combined to obtain the combined local load effect.

Local loads shall be categorized into four groups, as also described for loads in [3.6.1].

— pressure (P) load
— functional (F) load
— environmental (E) load
— accidental (A) load.

All load effects shall be described separately for each phase of the structure's design life.

The design shall account for short-term load effects (extreme loads) and long-term load effects. Long-term load effects can be sustained or cyclic.

For example, global loads would be wave loads, ship movements etc. Local loads are pressure, axial loads and moments on a pipe segment. Load effects would be stresses at the liner composite interface.

6.2.2 Short-term load effects – characteristic values

Short-term load effects shall be characteristic values.

The characteristic load effect value will only rarely be exceeded. For time-dependent processes, this is generally given in terms of a return value for occurrence, i.e. a load effect which on average is exceeded once in a specified reference time period (denoted return period or recurrence period).

The characteristic load effect shall be determined as the characteristic value of the structure's local response to the applied load. It shall be based on a probabilistic representation of the variability in the local response.

A probabilistic representation should be established for the effect of each load on the structure in every relevant location. The load effect is obtained from the basic loads in Sec.3 using structural analysis as described in this section.

The characteristic load effect can be determined as the characteristic value of the externally applied global load in the following cases:

— when the design rule is expressed in terms of the structure's global response
— when the transfer function is from global to local response and the analysis is linear.

The characteristic load effect is defined as the 99% quantile in the distribution of the annual extreme value of the structure's local response, or of the applied global load when relevant. The 99% quantile in the distribution of the annual maximum load effect is used as the characteristic load value throughout this document. The 99% quantile may be interpreted as the 100-year load, i.e., the load value that has a return period of 100 years. This is the load effect value, which on average will be exceeded once every 100 years.

Extreme values driving the design may be maximum as well as minimum values. Should the minimum load effect values be driving the design, the characteristic load effect shall be defined as the 1% quantile in the distribution of the annual minimum load.

6.2.3 Short-term load effects – pressure

Short-term pressure loads shall always be taken as the incidental pressure defined in [3.6.5].

6.2.4 The sustained load effect

All sustained loads as given in [3.6.3] and all phases shall be considered when calculating sustained load effects.

The sustained value of the stress or strain fluctuations (load effect fluctuations) shall be specified as the maximum within each observation period for each time interval. Data should be reported as shown in Table 6-1.

Table 6-1 Presentation of sustained load effect data

Exposure time (duration)	Sustained value
t_{s1}	S_{s1}
t_{s2}	S_{s2}
t_{s3}	S_{s3}
…..	…..

For rapid fatigue loading conditions the sustained value may be taken as the mean value of the fatigue cycles for the total duration of the cycling around that mean value.

6.2.5 The fatigue load effects

All load effect fluctuations, e.g. stress or strain fluctuations, imposed during the entire design life shall be taken into account when determining the long-term distribution of stress or strain ranges. All loads as given in [3.6.4] and all phases shall be considered when obtaining fatigue load effects.

Both low-cycle fatigue and high-cycle fatigue shall be considered.

It shall be determined whether fatigue occurs in load or displacement control, since this may influence the way the S-N curve is measured, see [A.6.2]. Fatigue occurring in load control may be assumed to be the default.

The characteristic distribution of load effect amplitudes should be taken as the expected distribution of amplitudes determined from available data that is representative of all relevant loads. This is a long-term distribution with a total number of stress/strain cycles equal to the expected number of stress/strain cycles over a reference period such as the structure's design life.

For fatigue analysis, the mean and amplitude of the stress or strain fluctuations shall be specified. The sequence of load effects shall be analysed using the Rainflow method. Table 6-2 gives an example of how the data can be presented.

Table 6-2 Matrix representation of the Rainflow counted amplitude distribution of cyclic fatigue load effect data

Number of cycles	Mean load effect	Amplitude of load effect
N	S	A

The minimum resolution of the discrete stresses should be defined before the stress history is established. The maximum value of the resolution interval shall be inserted into Table 6-2.

Note that for the fatigue analysis the history of mean stress/strain and amplitude is needed. In a nonlinear analysis, the mean may shift relative to the amplitude during the transfer from applied load to load effect.

The load effect data in Table 6-2 may be simplified, provide it can be shown that the simplification is conservative (leading to a higher Miner sum) compared to the complete data.

Based on the material properties, in particular the characteristic *S-N curve* and the magnitude of its slope parameter, it shall be assessed whether the bulk of the fatigue damage will be caused by several thousand or more stress cycles from the characteristic stress distribution, or by only one or a very few extreme stress amplitudes from this distribution.

In the former case, the natural variability in the individual stress amplitudes can be disregarded as its effect on the cumulative damage will average out, and the partial load factor can be set to 1.0. In the latter case, the natural variability in the few governing extreme stress amplitudes cannot be disregarded and needs to be accounted for by a partial load factor given for static loads. If no detailed analysis of the load factor can be made, the same factors as those given for static loads shall be used.

6.2.6 Combination of load effects and environment

The fundamental approach to combining load effects is described in DNVGL-ST-F201.

For TCPs it is important to combine pressure loads, functional loads, environmental loads and environmental conditions in the proper way, because material properties depend on the environmental conditions.

Procedures for combining load effects for nonlinear systems are given in DNVGL-ST-F201 App.C.

For linear systems (local load effects are linearly proportional to the actual loads) either load effects or loads may simply be combined directly.

The combination and severity of load effects and/or environmental conditions should be determined taking into account the probability of their simultaneous occurrence.

The combination of characteristic load effects and the environment should be determined such that the combined characteristic effect has a return-period of 100 years. A method to determine the 100-year combined effect of several load effects and environments is described in this chapter. It is based on the so-called Turkstra's rule, see e.g. DNVGL-ST-C501 [3.11.2] *Load effect and environmental conditions for ultimate state*.

When several stochastic load effects and/or environmental conditions occur simultaneously, the extreme combined effects of the associated stochastic processes are required for designs based on the ultimate limit state. Each process is given a characteristic value. The characteristic values are to be factored and combined to produce a design effect. For this purpose, a (limited) number of possible load effect and/or environmental condition combinations are considered. The most unfavourable combination among these shall be found and will govern the design.

The most unfavourable relevant combinations shall be defined for every point in time during the design life. In most cases, the most unfavourable relevant combinations are the same over the entire design life. However, in some cases conditions may change with time, which may in turn cause changes in the relevant combinations.

The fatigue load effects should be combined with the sustained environmental values for the fatigue analysis specified in [A.6].

The combination of load effects and environments as described above should be used to obtain the load effects, i.e., local stresses and strains.

6.2.7 Interface loads

Various interfaces and pipe attachments may create additional loads and load effects not given in the specifications described in Sec.3. These load effects shall be calculated and added to the already existing load effects.

Load effects due to geometrical constraints that restrict the natural elongations of the TCP shall be considered in the design analysis.

6.3 Analysis procedure for thermoplastic composite pipes

6.3.1 General

The global analysis of the TCP system shall be performed in the way described in DNVGL-ST-F101 for submarine pipelines or DNVGL-ST-F201 for dynamic risers. Detailed local analysis shall be conducted for connectors/joints and other critical parts of the TCP system. An equivalent approach should be used for other applications.

TCPs behave in a complex manner because the development of failure in composite materials usually involves a sequence of failure mechanisms (e.g. matrix cracking or yielding, delamination and fibre failure), each of which leads to a local change in the material properties. It is usually difficult to establish analytical acceptance criteria on a global level for all failure modes. Therefore, local analysis should be used extensively when evaluating TCP failures. A method for obtaining global acceptance criteria by numerical analysis is given in [6.3.3].

The development of local failure mechanisms, with corresponding local degradation of material properties, may result in decreased values for the global stiffness parameters. This may affect the overall global behaviour (e.g. displacements, bending moments and effective tension) of the TCP. Thus, the parameters that serve as boundary conditions for the local analysis may need to be modified. Accelerated degradation due to a local reduction in stiffness creating hinge effects may have to be considered.

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Below, analysis procedures for TCPs are recommended. The principal difference between the methods is the level on which the failure criteria (or limit states) are evaluated. Another obvious difference, which follows from the previous one, is the order in which the global and local analysis is conducted. Other analysis procedures may be found in DNVGL-ST-C501 Sec.9.

6.3.2 Global - local analysis procedure

The first step in evaluating the limit states is to perform a global analysis of the entire TCP system. The resulting global load effects (e.g. effective tension, bending moment, thermal loads and internal or external overpressure) serve as boundary conditions for the forthcoming local analysis.

Based on the load effects from the global analysis, a local analysis, which leads to local load effects (stresses and strains), is then conducted.

Finally, the local load effects resulting from the local analysis are finally applied in the local acceptance criteria (or failure criteria) in order to detect possible failure mechanisms of the TCP components.

If the local investigations are performed by progressive failure analysis ([6.4.4] and [6.4.5]), it is possible to detect a sequence of (acceptable) failure mechanisms that may arise prior to the final (unacceptable) failure mechanism (often fibre failure). Let us assume that the local analysis predicts the presence of matrix cracking, viscoelastic deformation or yielding somewhere in the TCP (and that matrix cracking viscoelastic deformation or yielding is acceptable), which in turn leads to reduced TCP stiffness or permanent deformation. This local reduction in stiffness may influence the overall behaviour of the TCP system. Therefore, in certain cases it may be necessary to repeat the global analysis (with degraded material properties and plastic or viscoelastic deformation where relevant). Subsequently, the presence of additional failure mechanisms should be investigated through a new local analysis. This iterative procedure (between global analysis (with degraded nonlinear/plastic material properties) and detailed local failure analysis should be performed until no new failure mechanism is observed (acceptable design) or a crucial failure mechanism is predicted (unacceptable design).

Guidance note:

The change of axial stiffness due to local degradation mechanisms is usually small and does not influence the global loads on the TCP system. In such cases, the global (static and dynamic) analysis does not need to be repeated even if the local analysis demonstrates that (acceptable) failure mechanisms occur. A conservative approach should be chosen for the simplified analysis.

---e-n-d---o-f---g-u-i-d-a-n-c-e---n-o-t-e---

6.3.3 Global procedure with response surface

This procedure gives a global performance envelope for the TCP. This performance envelope can be used in a standard global analysis of pipes and risers, as is usually applied to products made of metal.

As an alternative to the global – local procedure presented in [6.3.2], this procedure requires extensive local analysis to be conducted prior to the global failure analysis. The local analysis is used to establish the response surface that can be used in the subsequent global analysis.

A TCP is a relatively simple structure on a global scale. Usually, it contains a small number of identical pieces of composite pipe that are all connected using the same type of connectors or joints. In other applications, continuous TCPs with constant properties along the pipe, may be used. In all these situations, the following failure-evaluation procedure may be advantageous.

Prior to the global analysis of the TCP system, global limit states (on the form $g_{max} = 1$) are established by performing local failure analysis (of the pipes as well as the connectors/joints) for a large number of combinations of global load effects (bending moments, effective tension, torsion and internal or external overpressure). The global limit states are represented as surfaces in a space/co-ordinate system with bending moments, effective tension, torsion and internal/external overpressure along the axes. The surfaces are obtained by interpolating a collection of points (load cases) from the local analysis that satisfies $g_{max} = 1$. Such global limit states may be established for several kinds of (local) failure mechanisms.

After these initial local investigations, the rest of the TCP analysis may be performed on a global level.

If the initial local investigations are conducted using progressive failure analysis ([6.4.4] and [6.4.5]) global limit states may be established for a wide range of (local) failure mechanisms. In this way, an iterative procedure may be adopted. In the first step (after establishing the limit states) global analysis is performed using initial (non-degraded) stiffness properties. Let us assume that a limit state (corresponding to a non-crucial failure mechanism) is exceeded in certain global elements. The stiffness properties in those elements should then be reduced (according to the observed local failure mechanism) and the global analysis should be repeated. This iteration should continue until no new limit state is exceeded (acceptable design) or a crucial limit state is exceeded (unacceptable design).

Guidance note 1:

The change of axial stiffness due to local degradation mechanisms is usually small and does not influence the global loads on the TCP system. In such cases, the global (static and dynamic) analysis does not need to be repeated even if the local analysis demonstrates that (acceptable) failure mechanisms occur.

---e-n-d---o-f---g-u-i-d-a-n-c-e---n-o-t-e---

Guidance note 2:

Example of a global design criterion: for a long continuous TCP a global design criterion would typically only be established for the pipe section. The two joints would be investigated individually.

---e-n-d---o-f---g-u-i-d-a-n-c-e---n-o-t-e---

The loads and TCP section are shown schematically in Figure 6-1. Typically a section is analysed for the following loads:

a) pressure   = P

b) torsion   = T

c) axial load   = - A (compression)

d) moment   = M

e) axial load   = A
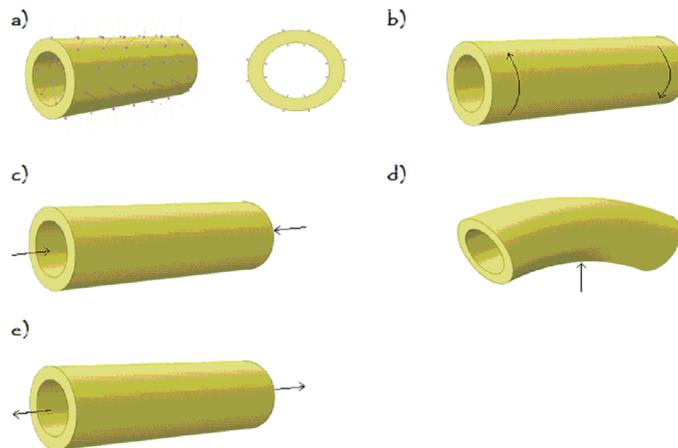
Figure 6-1 General loading conditions for a TCP

The axial load can be defined as the effective axial load, i.e., the axial load without the axial end cap load caused by the pressure, or it can be defined as the absolute axial load. The choice is a matter of convenience, but it is important to use a consistent approach.

Torsion in metal risers is often neglected. However, even small torsional loads may cause damage to a composite TCP or the end fitting, depending on the particular layout and joint geometry.

The chosen section of the TCP should be analysed for all possible combinations of P, A, M and T.

For each combination a stress analysis of the section shall be carried out and all relevant design criteria in Sec.7 and Sec.8 shall be checked.

The most unfavourable combination of functional loads and environmental load effects and their respective safety factors shall be applied.

Once all combinations of P, A, M and T have been analysed, a four-dimensional failure envelope can be defined for that section of the TCP.

An imaginary schematic axial load-moment global failure envelope for three different internal pressures is shown in Figure 6-2. This failure envelope would have to be repeated for various torsional loads if they are critical.
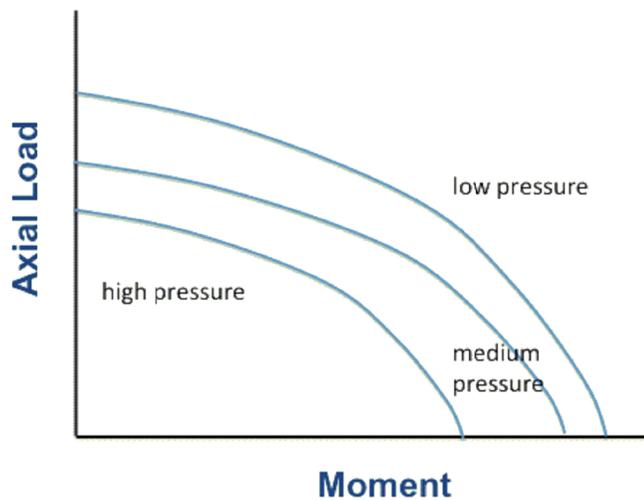
Figure 6-2 Schematic global failure envelope for a TCP

6.3.4 Fatigue and long term analysis of thermoplastic composite pipes

The effect of cyclic loads and permanent static loads on TCPs shall be evaluated.

This long-term analysis is typically done on the local level using the global local approach given in [6.3.2]. Since long-term analysis is done on mean sustained loads ([6.2.4]) and not on characteristic loads, the loads and load effects can be combined more easily than for the extreme load cases.

6.4 Local analysis

6.4.1 General

High pressure TCPs generally have generally thick walls and a 3-D analysis is required. The region at and near the end fittings also requires a 3-D analysis. If a 2-D analysis is used it shall be shown that through-thickness stresses and changes of inplane stresses through the thickness can be ignored.

The boundary conditions should be selected carefully in order to represent the nature of the problem in the best possible way. It should be demonstrated that the chosen boundary conditions lead to a realistic or conservative analysis of the structure, see also [6.11.3].

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6.4.2 Input data

Thermal stresses and residual stresses that result from the production process or in service loading should be considered in all analysis. Note that residual stresses may reduce with time due to stress relaxation.

Stresses due to swelling or shrinkage caused by absorbed fluids or depleted additives should be included if relevant.

The elastic properties of the materials constituting the structure should be obtained as described in Sec.4. In particular, time-dependent stiffness properties based on the expected degradation due to environmental and loading conditions should be considered. Local variations of these conditions should also be considered.

Laminates should be analysed on the ply level. Each ply should be described by four elastic constants (E_1, E_2, G_{12}, ν_{12}) for in-plane 2-D analysis and by nine elastic constants (E_1, E_2, G_{12}, ν_{12}, E_3, G_{13}, G_{23}, ν_{13}, ν_{23}) in 3-D analysis. A nomenclature for the various elastic constants is defined in [1.4.5].

As an alternative to elastic constants, the stiffness matrix for orthotropic plies may be used.

It should be shown that the estimated stiffness gives conservative load-effect results. The choice of stiffness values may be different for strength- and stiffness-limited designs. More details are given in the sections below.

If fibres are not oriented in the principal stress directions they want to rotate into these directions. The matrix usually prevents this rotation. If the matrix cracks or yields, the fibres may be free to rotate slightly. This rotation is usually not modelled. However, it should be checked that ply stresses transverse to the fibres and ply shear stresses are low in a ply with a degraded matrix. Otherwise, a re-analysis using rotated fibre directions may be required.

If fibres are more than 70° apart, see Figure 4-2, the behaviour in the unreinforced direction shall be established by testing representative pipes as described in [5.5], [4.4.3] and [4.5.3]. The test results shall be implemented in the FE analysis.

6.4.3 Analysis types

Analytical and or numerical calculations may be used in the structural analysis. The FE method is presently the most commonly used numerical method for structural analysis, but other methods, such as finite difference or finite series methods may also be applied.

> **Guidance note:**
>
> While the FE-method is applicable for a wide range of problems, analytical solutions and the finite series approach often put too many restrictions on the laminate layup, geometry etc., and are thus insufficient in the design of most real world composite structures.
>
> ---e-n-d---o-f---g-u-i-d-a-n-c-e---n-o-t-e---

Laminate analysis is an additional type of analysis that is applied to layered composites in order to derive the properties of a laminate from the properties of its constituent plies.

The structural analysis should be performed for all phases during the structure's entire lifetime. Initial and degraded material properties should be considered if relevant.

6.4.4 Local linear analysis with degraded properties

In many TCP applications (for example TCPs with liners) several failure mechanisms (e.g. matrix cracking, yielding or viscoelasticity in the TCP laminate) may be accepted, while fibre failure is the mechanism of interest. The local analysis of such TCPs may be performed using a linear procedure with degraded properties. It should be assumed that fibre failure is the only failure mechanism of interest. The TCP may then be analysed based on the assumption that matrix cracking, yielding or viscoelasticity has already occurred throughout the TCP. This means that the TCP may be modelled with reduced stiffness in all TCP elements. In most cases this is a conservative (with respect to local and/or global load effects) simplification. However, in certain displacement-controlled cases (for example in relation to a riser, if the displacement of

the top of the TCP is dictated by prescribed platform movement) the simplification may be non-conservative. This effect should be carefully investigated when relevant.

The method may be applied to both 2-D and 3-D cases.

Due to the assumption of matrix cracking, yielding or viscoelasticity in the component the material properties are degraded in the entire domain by setting certain elasticity parameters at zero (or close to zero for numerical reasons). This means that, for in-plane 2-D analysis the stiffness in the fibre direction (of each ply) remains unaltered, while the rest of the properties are assumed to be changed to zero.

If 3-D analysis is required, the in-plane parameters are dealt with as in the 2-D analysis, while all through-thickness parameters are changed if through-thickness stresses cause matrix cracking or nonlinear deformation of the matrix.

Other more detailed degradation methods for the elasticity parameters may be used if experimental justification can be provided, e.g. keeping higher stiffness in compression or only small reductions in stiffness in the case of minor damage.

This method should be mainly used for statically determined problems, as is the case for a TCP. Otherwise this simplified method, with the degradation of material properties in the entire domain, may offer considerably incorrect stress/strain distributions. If the error cannot be analysed and included in the model factor, a more refined method shall be used.

6.4.5 Local progressive analysis

Local progressive analysis, which is presented herein, provides more accurate results than those obtained using the simplified method presented in [6.4.4]. Instead of degrading almost all the parameters in the entire domain, this method is based on step-wise degradation of a limited number of parameters in bounded regions.

All kinds of local failure mechanisms may be detected by the method.

The method may be applied for both 2-D and 3-D cases.

Initially, non-degraded ply properties shall be used in the progressive failure analysis.

The boundary conditions (load effects from the global analysis) for the component are imposed in a step-wise manner, as a first step a small portion e.g. 10% of the load is applied. Based on this load level, laminate and ply stresses and strains are calculated and analysed using the relevant failure criteria (for each ply). If a failure or degradation (such as yielding or viscoelastic deformation) is detected somewhere in a ply, certain material properties of that ply shall be locally degraded, which means that the parameters shall be reduced in locations (e.g. finite elements) where the failure is detected. Then, the local analysis shall be repeated with locally degraded parameters for the same load level. If no failure is observed, the load is increased to e.g. 0.2 x load, and a similar failure analysis is performed.

If the analysis finds that the matrix is degraded, the properties should be changed according to [6.4.4].

The step-wise increase in loads continues until a critical failure mechanism is observed (unacceptable design) or until the entire load is applied and no critical failure mechanism is detected (acceptable design).

6.5 Analytical methods

Analytical methods can be divided into two classes: analytical solutions of (differential) equations or the use of handbook formulae.

Analytical methods shall not be used outside their assumptions and limitations.

Guidance note:

The main disadvantage of available analytical solutions is that simplifications often put too many restrictions on geometry, laminate build-up etc. and hence the solutions are insufficient for the design of more complex composite structures.

Handbook formulae are usually too simple to cover all the design issues and are also in general insufficient. Simplified isotropic calculation methods should not be used unless it can be demonstrated that they give valid results.

---e-n-d---o-f---g-u-i-d-a-n-c-e---n-o-t-e---

Analytical solutions or handbook formulae used within their assumptions and limitations may be utilized to validate finite element analysis results.

6.6 Local finite element analysis

Finite element calculations shall be done in a professional way using recognized methods. More details on using FE calculations for composites can be found in DNVGL-ST-C501.

Analysis results shall be presented in a clear and concise way using appropriate post-processing options. The use of graphics is recommended, i.e. contour plots, (amplified) displacement plots, time histories, stress and strain distributions etc.

The results shall be documented in a way that helps the designer in to assess the adequacy of the structure, identify weaknesses and ways of correcting them and, where desired, optimize the structure.

FEA results shall be verified by comparing them to relevant analytical results, experimental data and/or results from previous similar analysis.

When changing the FEA software/program the reference calculations shall be repeated to demonstrate that the new software gives acceptable results.

Verification of the correct application of the many different relevant co-ordinate systems shall be considered.

Results shall also be compared against the prototype testing in Sec.10.

6.7 Impact response

Impact should be evaluated by testing as described in [5.12] and [10.9].

6.8 Thermal strains and stresses

Changes in the temperature from the environment resulting in dimensional changes to the pipe body shall be taken in account. The general thermal strains, e_i, can be expressed as: $e_i = \alpha_i \Delta T$, where α_i is the thermal expansion coefficients, and the temperature is denoted by T.

Thermal expansion coefficients may depend on the temperature and environmental conditions. The relevant coefficients for the actual temperatures shall be used.

Residual stresses shall be calculated against the reference temperature for which α_i was determined. For thermoplastic materials, this is initially usually the processing temperature. Due to stress relaxation the references temperature tends to change towards the usual storage or use temperature.

Accordingly, the stress-strain relations shall be modified to account for the stress free environmentally induced expansional strains as follows: $\{\varepsilon\} = [S]\{\sigma\} + \{e\}$.

Changes in temperature from the environment resulting in dimensional changes of the body shall be taken in account. The general thermal strains, e_i, can be expressed as: $e_i = \alpha_i \Delta T$.

α_i is the thermal expansion coefficients, and temperature is denoted by T.

If the TCP or a part of it is constrained, the effect of stresses due to thermal effects shall be considered.

6.9 Swelling or shrinkage effects

Changes in fluid absorption from the environment resulting in dimensional changes to the pipe body shall be taken into account. The general swelling strains, e_i, can be expressed as: $e_i = \beta_i C$.

β_i is the swelling expansion coefficients and C is the swelling agent concentration inside the laminate.

Accordingly, the stress-strain relations shall be modified to account for the stress free environmentally induced expansional strains as follows: $\{\varepsilon\} = [S]\{\sigma\} + \{e\}$.

If the TCP or a part of it is constrained, the effect of stresses due to swelling shall be considered.

Similar to the absorption of fluids, fluids or additives may leach out. This shall be treated in an equivalent way to swelling.

6.10 Buckling

All parts of the TCP, such as the pipe body, liners and fittings shall be evaluated for buckling.

Details about buckling analysis can be found in DNVGL-ST-C501 [9.11].

A buckling analysis of the TCP shall be carried out with the aid of well-established finite-element software or the equivalent.

The following aspects shall be considered in the analysis:

— presence of axial compressive stresses in the pipe section
— presence of circumferential compressive or shear stresses in the TCP
— presence of all compressive stresses in the area of the end fitting.

An assessment shall be made of the shape and size of initial, geometrical imperfections, such as ovality, that may influence the buckling behaviour of the member. Normally the most critical imperfection shape for a given buckling mode has a similar form to the buckling mode itself. However, any geometrical feature (including eccentricity of loading) resulting in compressive forces that are not coincident with the neutral axis of the member may require consideration. The assumed form and amplitude of the imperfection shall be determined on the basis of the production process used with due consideration of the relevant production tolerances, see DNVGL-ST-C501 [6.8].

Possible changes due to the shape of the TCP over the lifetime shall be considered. In particular ovalization due to caterpillar pressure, reeling and the touching of hard spots shall be evaluated. The effects of bending shall also be considered.

In some cases a geometrically nonlinear analysis may be avoided as follows. The elastic critical load (without imperfections) P_e is calculated. In addition an ultimate failure load P_f is estimated at which the entire cross-section would fail by compressive fibre failure, in the absence of bending stresses at the section in question. If $P_e > P_f$ the further assessment may be based on geometrically linear analysis provided geometrical imperfections are included and the partial load effect modelling factor is increased by multiplying it by the factor:

$$\frac{1}{1 - P_f \big/ 4P_e}$$

In cases where it is possible to establish the bending responses (stresses, strains or displacements) associated with in-plane loading separately from the in-plane (axial) responses, a first estimate of the influence of geometrical nonlinearity combined with the imperfection may be obtained by multiplying the relevant bending response parameter obtained from a geometrically linear analysis by the following factor:

$\frac{1}{1 - P \big/ P_e}$, $\frac{1}{1 - \sigma \big/ \sigma_e}$ or $\frac{1}{1 - \varepsilon \big/ \varepsilon_e}$ and combining the modified bending responses with the (unmodified) in-plane responses.

The above procedures may be non-conservative for some cases where the post-buckling behaviour is unstable. Examples include cylindrical shells and cylindrical panels under axial loading. Such cases shall be subject to special analysis and/or tests.

Initially a natural frequency buckling analysis shall be performed assuming initial (non-degraded) elastic properties for the laminates. This shall be repeated with alternative, finer meshes, until the lowest natural frequency and corresponding modes are not significantly affected by further refinement. The main purposes of this analysis are to clarify the relevant buckling mode shapes and to establish the required mesh density for subsequent analysis.

Careful attention shall be paid to the correct modelling of boundary conditions.

If the applied load exceeds, or is close to, the calculated elastic critical load, the design should be modified to improve the buckling strength before proceeding further.

A step-by-step analysis shall be carried out. Geometrical nonlinearity shall be included in the model. The failure criteria shall be checked at each step. If partial failure such as matrix cracking, yielding or delamination is predicted, any analysis for higher loads shall be performed with properties reduced as described in [6.4.5].

Alternatively, a geometrically nonlinear analysis may be performed using entirely degraded properties throughout the structure, see [6.4.4]. This will normally provide conservative estimates of stresses and deformations. However, provided reinforcing fibres are present in sufficient directions, so that the largest range of un-reinforced directions does not exceed 60º, such an estimate will not normally be excessively conservative.

The calculated buckling load will be the load that causes the violation of one of the design criteria given in Sec.5.

6.11 Partial load-model factor

6.11.1 General

A deterministic factor shall be assigned to each structural analysis method. This is designated in this standard as the partial load-model factor γ_{Sd}, see also [11.4.1].

The load-model factor accounts for uncertainties in the structural analysis method being used to accurately describe and quantify the structure's response.

Model factors for the main structural analysis methods are given in the following subsections.

In some cases a structure is only evaluated by testing, and such an approach evaluates only the particular conditions tested. A procedure for this approach is given in [6.17] and Sec.9.

6.11.2 Connection between partial load-model factor and analytical analysis

When analytical methods are used within their assumptions and limitations a model factor of 1.0 should be used.

If analytical methods are used outside their assumptions and limitations, it shall be documented that the magnitude of the model factor ensures that all predicted stresses and strains are higher than in reality. If the choice of model factor cannot be documented, the analytical method shall not be used.

6.11.3 Connection between partial load-model factor and finite element analysis

FE methods are generally very accurate when the structure is properly modelled. The use of these methods with unsatisfactory models is much more uncertain.

When FE methods are used within their assumptions and limitations (and according to [6.6]) a model factor of 1.0 may be used.

If FE methods are used outside their assumptions and limitations, it shall be documented that the magnitude of the model factor ensures that all predicted stresses and strains are higher than in reality. If the model factor cannot be documented, the analysis method shall not be used.

If the boundary conditions do not exactly represent the real conditions or are clearly conservative the effect on the load model factor shall be evaluated. As a minimum, a factor of 1.1 shall be used.

If the load-model factor cannot be determined for calculations in a critical region, e.g. a critical joint or region of stress concentrations, experimental qualification should be carried out.

6.12 Material properties

The origin of all material properties used in the analysis shall be documented and traceable.

The testing and documentation requirements stipulated in Sec.4 shall be applied to all properties listed in that section.

6.13 Geometric parameters

The geometric parameters shall represent the dimensions of the actual TCP and its components.

The geometric parameters used in the analysis shall be consistent with the specifications stated in Sec.3 and the design drawings.

Any geometrical simplifications made in the analysis compared to the real structure shall be explained and justified.

6.14 Design temperatures – thermal conditions

The temperatures of fluids and environments are given according to the design input requirements stated in [3.7.5] and [3.7.6]. The temperatures shall be calculated for each part or component of the TCP. As a minimum, the maximum temperature T_{op}^{max}, minimum temperature T_{op}^{min} and typical operating temperature T_{op} shall be calculated for each phase.

The temperatures may differ from one phase to the other and may change over the lifetime, leading to many more temperatures that may be defined. Certain temperatures may also only be relevant in combination with specific fluids or environments. It may be beneficial to establish temperature sequences over the lifetime in order to optimize the design and prototype testing.

If simplifications in the temperature calculations are made, it shall be documented that the choices are conservative.

Note that in some cases the choice of too high temperatures may be conservative, while in other cases too low temperatures may be the conservative choice. E.g. creep is most severe at high temperatures, while fracture toughness is lowest at low temperatures. Thermal stresses are most severe for high temperature gradients.

6.15 Calculated design pressures

Pressures are specified in [3.6.5].

A system evaluation shall be conducted to ensure that the stated pressures are the absolute maximum and cannot increase due to temperature changes, pump failures, dynamic pulses (water hammer), etc.

6.16 Impact response

Impact should be evaluated by testing as described in [10.9].

6.17 Performance-based approach – testing full-scale components

In some cases, it may be desirable to test a full-scale component instead of producing design calculations. This approach is described in Sec.9.

6.18 Combining design and large-scale test results

It is often practical to combine design calculations from this section with full or large-scale testing as described in [6.17], Sec.9 and Sec.10. The approach is:

— Predict test results based on basic material parameters, as obtained from Sec.4.
— Perform the testing and compare predicted and experimental results.
— Evaluate reasons for possible discrepancies and update some FE model parameters to make results match.

If this approach is used in the design, the updating of the FE analysis shall be documented. It shall be further justified why these updates are reasonable. Guidance can be found in DNVGL-ST-C501 [10.3.4] *Procedure for updating the predicted resistance of a component*.

If the same analysis shall be used for other load cases or conditions, it shall be shown that these updates can also be used for the new conditions.

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SECTION 7 DESIGN CRITERIA PIPE BODY

7.1 Introduction

7.1.1 General

This section provides design criteria for the TCP's pipe section.

The design report shall demonstrate the fulfilment of each requirement either stated in Sec.3 or specified by the purchaser or manufacturer in the purchasing contract.

In some cases it should be sufficient to demonstrate that a certain failure mode can never occur due to the conditions related to the application.

All load conditions stated in Sec.3 shall be considered in relation to all the design criteria. As a minimum, the following load cases shall be evaluated:

— internal/external pressure
— axial tension/compression
— bending
— torsion
— and all possible combinations of these loads.

It shall be noted that, depending on the construction, small loads acting in other directions than the major loads, may cause severe damage to a TCP.

For pipeline and riser applications failure modes stated in DNVGL-ST-F101 and DNVGL-ST-F201 should be considered and applied if found relevant.

7.1.2 Ultimate limit state

All static requirements listed in this section describe the ultimate limit state (ULS).

7.1.3 Fatigue limit state

Long term requirements, such as fatigue and stress rupture, describe the fatigue limit state (FLS).

7.1.4 Accidental limit state

The accidental limit state (ALS) is a limit state due to accidental loads or events. The loads should be infrequent. More details about the definition of ALS conditions are given in DNVGl-ST-F201 Sec.5. The same design criteria for ULS and FLS listed in this section shall be analysed for the ALS, but the load safety factor will be different, see [11.2].

7.2 Rupture, fluid tightness

7.2.1 General

Rupture is the TCP's loss of structural integrity.

A loss of fluid tightness is related to a leaking TCP. Fluid tightness is lost when the TCP ruptures. Small defects may also cause a loss of fluid tightness, even if only a small amount of fluid seeps out. If the maximum permeation requirement stated in [3.5.2] is violated, the TCP is not considered to be fluid tight anymore.

Fluid tightness relating to of the inner fluid and external water shall be demonstrated. It shall be shown which TCP components prevent the TCP from leaking.

A design could be based on the liner providing sufficient internal-fluid tightness, the cover providing sufficient external-water tightness and the laminate not providing any fluid tightness (only structural integrity). The components may also work together to provide the required fluid tightness.

Any mechanical damage to or degradation of the TCP shall not cause a rupture or lead to the fluid tightness requirements being exceeded. This shall be ensured by checking the failure mechanisms for each TCP component as described in the subsections of [7.2].

7.2.2 Thermoplastic composite pipe laminate

The TCP laminate is the main load-bearing component and the design shall ensure that laminate failure does not occur.

The laminate may also be designed to ensure fluid tightness and low fluid permeation.

As a minimum, the failure mechanisms stated in Table 7-1 shall be evaluated in the design. In addition, effects that may influence the mechanical properties used in the failure criteria shall be considered, as described in Table 7-2.

Table 7-1 The laminate's failure mechanisms related to rupture and fluid tightness

Failure mechanism	Description	Reference: section for design criterion
Fibre dominated failure	The design shall ensure against fibre dominated failure. Fibre dominated failure is the onset of rupture. If the TCP has splices in the laminate, the effect of the splices on the strength shall be considered.	[5.2] [5.22.3] [5.23.3] [7.8.14]
Matrix cracking	Matrix cracking of the laminate may be acceptable, if the liner and cover remain intact and provide sufficient fluid barriers, see [7.2.1]. In such case the laminate does not need to be checked for matrix cracks.	None
	If the laminate contributes to low permeability, or does not have a liner or cover two approaches may be used: — a design ensuring that matrix cracking shall not happen. — long-term testing can be undertaken to demonstrate fluid tightness and permeability levels in the presence of some matrix cracks.	[5.3] [5.22.5] [5.23.5]
	If fibres directions have a gap 2α of more than 70° degrees in a laminate (see Figure 4-2), matrix cracking may become critical for the load bearing properties. Matrix cracking may reduce the compressive fibre strength.	[5.5] [5.22.6] [5.23.6] [5.2] [5.22.5] [5.23.5]
Delamination	Delamination reduces bending stiffness and buckling resistance, but does not usually influence burst. If fibres directions have a gap 2α of more than 70° degrees in a laminate (see Figure 4-2), delamination may become critical for the load bearing properties.	[5.4] [5.22.4] [5.23.4] [5.5] [5.22.6] [5.23.6]

Failure mechanism	Description	Reference: section for design criterion
Plastic deformation	The yielding of the laminate (matrix or fibres) or creep may cause large local deformations that can weaken the structure, mainly at joints.	[5.8] [5.6] [5.22.7] [5.23.8]
Permeability change	The possible influence of any thickness changes on permeability shall be evaluated.	[5.6]

Table 7-2 Factors influencing the laminate's mechanical properties

Exposure conditions	Description	Reference: section for design criterion
Impact ([3.6.6])	Damage due to impact may influence the strength of the laminate. Impact damage may also increase permeability.	[5.12] [5.6]
Puncturing and scratches ([3.5])	Wear and tear, scratches and puncturing of the laminate are typically only relevant if no liner or cover is present.	[5.13] [5.6]
Wear and tear	The laminate shall maintain its required load bearing capacity and fluid tightness after degradation due to these effects.	[5.14] [5.6]
Exposure to fluids ([3.7])	The TCP laminate is usually protected by a liner and cover. It shall nevertheless be resistant to service fluids and water.	./.
	Chemical degradation may change elastic properties, strength and permeability. It shall be shown that no significant property changes will happen during the lifetime or the changes should be quantified and addressed in the design.	[5.15]
	The changes in mechanical properties due to swelling or shrinkage shall be evaluated.	[5.16]
	The changes in mechanical properties due to the leaching of additives shall be evaluated.	[5.16]
	Gas accumulation may cause debonding. Once debonding exists, gas can accumulate in the interface and increase the debonding area.	[5.18]
	Blistering resistance/rapid decompression	[5.18]
UV exposure ([3.7.8])	UV exposure shall be evaluated if the laminate does not have a cover.	[5.19]
Thermal exposure ([3.7])	The influence of thermal exposure on mechanical properties shall be considered.	[5.20][5.21]

7.2.3 Liner

The liner and cover shall be designed not to rupture.

The liner shall have sufficiently high strains to failure and yield strains that is can follow the TCP movements without failure or plastic deformation.

The liner should generally be kept in its elastic range. If yielding is accounted for the aspects in Table 7-3 shall be addressed.

If the liner has welds the liner and its welds shall fulfill the requirements of this section.

Any mismatch in thermal properties between the liner and laminate shall be considered in the design.

All failure mechanisms shown in Table 7-3 shall be analysed with respect to the liner and its welds (if welds exist).

In addition, effects that may influence the mechanical properties used in the failure criteria shall be considered, as described in Table 7-4.

Table 7-3 Failure mechanisms related to the rupture and fluid tightness of the liner.

Failure mechanism	Description	Reference: section for design criterion
Polymer fracture	The liner shall be designed to prevent fracture. Through-thickness cracks lead to reduced fluid tightness.	[5.7] [5.22.7] [5.23.7]
Polymer yielding	Generally the liner shall not yield under operation. If the liner is designed to be exposed to yielding occasionally, for example during reeling under transport, the consequences of the plastic deformation shall be considered in the design. When unloading, the plastically deformed liner will go into compression. This may cause buckling of the liner. It shall be evaluated if a reduction in the thickness of the liner due to yielding would increase permeability beyond the required value.	[5.8]
Debonding	The liner and TCP laminate shall not debond.	[5.10] [5.22.4] [5.23.4]
Crazing	Crazing may reduce strength and increase permeability.	[5.11]
Permeability change	The possible effect of permeability of any thickness changes or presence of matrix cracks shall be evaluated.	[5.6]

Table 7-4 Factors influencing the liner's strength

Exposure conditions	Description	Reference: section for design criterion
Impact	Damage due to impact may affect the strength of the liner or liner-laminate interface. Impact damage may also increase permeability.	[5.12] [5.6]
Puncturing, scratches	The liner shall keep its required load bearing capacity and fluid tightness after degradation due to puncturing or scratches. Equipment running through the TCP may cause puncturing or scratching. This reduces the liner's thickness and may cause failure under load control conditions or fatigue.	[5.13] [5.6]

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Exposure conditions	Description	Reference: section for design criterion
Wear and tear	The liner shall keep its required load-bearing capacity and fluid tightness after degradation due to wear and tear from fluids, sand and equipment running through the pipe. Fluids, especially dissolved solids, may cause wear and tear. Wear and tear reduces the liner's thickness and may cause failure under load control conditions or fatigue. Thickness may be added to the liner to compensate for the loss of material due to wear and tear.	[5.14]
Exposure to fluids	Chemical degradation may change elastic properties, strength and permeability. It shall be shown that no significant property changes will happen during the lifetime or the changes should be quantified and addressed in the design.	[5.15]
	The changes in mechanical properties due to swelling or shrinkage shall be evaluated.	[5.16]
	The changes in mechanical properties due to additive leaching shall be evaluated.	[5.17]
	Gas accumulation may cause debonding. Once debonding exists, gas can accumulate in the interface and increase the debonding area.	[5.18]
	Blistering resistance/rapid decompression.	[5.18]
UV exposure ([3.7.8])	Typically the liner is not exposed to UV. Its resistance to UV shall only be evaluated in the case of UV exposure.	[5.19]
Thermal exposure	The effect of thermal exposure on mechanical properties shall be considered.	[5.20] [5.21]

7.2.4 Cover

The cover provides protection against the outer environment.

The cover shall be watertight or at least have low permeation for water.

If the cover is damaged, the TCP laminate needs to provide the water-tightness.

The cover may also be designed not to be water or fluid tight, in which case the TCP laminate needs to assume that function.

The cover shall be designed not to rupture.

The cover shall have sufficiently high strains that it can failure and yield strains to follow the TCP movements without failure or plastic deformation.

The cover should generally be kept in its linear range. If yielding is accounted for, the aspects in Table 7-5 shall be addressed.

If the cover has welds, it and its welds shall fulfil the requirements of this section.

Any mismatch in thermal properties between the cover and laminate shall be considered in the design.

All the failure mechanisms shown in Table 7-5 shall be analysed in relation to the cover.

In addition, any effects that may influence the mechanical properties used in the failure criteria shall be considered, as described in Table 7-6.

Table 7-5 Failure mechanisms related to the rupture and fluid tightness of the cover

Failure mechanism	Description	Reference: section for design criterion
Polymer fracture	The cover shall be designed to prevent fracture. Through-thickness cracks lead to reduced fluid tightness.	[5.7] [5.22.7] [5.23.7]
Polymer yielding	Generally, the cover shall not yield under operation. If the cover is designed to be being exposed to yielding occasionally, for example during reeling under transport, the consequences of the plastic deformation shall be considered in the design. When unloading, the plastically deformed cover may go into compression. This may cause unacceptable debonding of the cover. It shall be evaluated whether a reduction in the thickness of the cover due to yielding would increase permeability beyond the required value.	[5.8]
Debonding	The cover and TCP laminate shall not debond. Debonding reduces the ability to carry shear loads from joints, clamps and caterpillars etc.	[5.10] [5.22.4] [5.23.4]
Crazing	Crazing may reduce strength and increase permeability.	[5.11]
Permeability change	The possible influence of any thickness changes on permeability shall be evaluated.	[5.6]

Table 7-6 Factors influencing the cover's strength

Exposure conditions	Description	Reference: section for design criterion
Impact	Damage due to impact may influence the strength of the cover or cover/laminate interface. Impact damage may also increase permeability.	[5.12] [5.6]
Puncturing, scratches	The cover shall keep its required load bearing capacity and fluid tightness after degradation due to puncturing or scratches. The handling and operation of the TCP may cause puncturing or scratching. This reduces the cover's thickness and may cause failure under load control conditions or fatigue. Temporary damage may be acceptable.	[5.13] [5.6]
Wear and tear	The cover shall keep its required load-bearing capacity and fluid tightness after degradation due to wear and tear caused by handling. Thickness may be added to the cover to compensate for any loss of material due to wear and tear. Temporary damage may be acceptable.	[5.14]
Exposure to fluids	Chemical degradation may change elastic properties, strength and permeability. It shall be shown that no significant property changes will happen during the lifetime or the changes should be quantified and addressed in the design.	[5.15]

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Exposure conditions	Description	Reference: section for design criterion
	The changes in mechanical properties due to swelling or shrinkage shall be evaluated.	[5.16]
	The changes in mechanical properties due to additive leaching shall be evaluated.	[5.17]
	Gas accumulation may cause debonding. Once debonding exists, gas can accumulate in the interface and increase the debonding area.	[5.18]
	Blistering resistance/rapid decompression.	[5.18]
UV exposure	UV exposure shall be evaluated.	[5.19]
Thermal exposure	The influence of thermal exposure on mechanical properties shall be considered.	[5.20] [5.21]

7.3 Resistance to burst, axial loads and bending

As a minimum resistance to burst from internal pressure, axial loads and bending shall be considered by evaluating all the requirements stated in [7.2].

The maximum axial load that can be applied to the TCP shall be calculated.

The minimum bending radius (MBR) shall be calculated for the conditions:

— unpressurized TCP
— pressurized TCP
— unpressurized TCP with axial load
— pressurized TCP with axial load,

unless it can be shown that such loading conditions will never happen in the application.

Calculations shall show that the MBR requirements given in Table 3-1 are met.

7.4 Buckling

The TCP may buckle due to hydrostatic pressure, see [7.5], an internal vacuum or axial compression. Bending and torsional buckling shall also be considered.

The TCP may also buckle due to local compressive loads, such as loads from caterpillars, clamps, storage, compression under reeling etc., see Sec.3.

For most applications, axial compression is not a relevant design case. It shall be confirmed that this applies.

If the liner and cover are less stiff than tolaminate, it is sufficient to only consider the laminate for buckling calculations.

Regarding hydrostatic pressure, it shall be made clear which surfaces this is acting upon. If the design allows cracks in or the puncturing of part of the TCP, the surface may change. For example, hydrostatic pressure usually acts on the outside of the cover. If the cover is damaged, hydrostatic pressure will act directly on the laminate.

New conditions and conditions involving relevant damage to the TCP shall be considered in the buckling calculations.

Geometrical imperfections shall be quantified for the TCP and taken account of in the buckling calculations. Ovalization, especially from reeling, long-term deformations or bending shall be included in the calculations ([5.9.3]).

Buckling shall be calculated according to DNVGL-ST-C501 Sec.6.

The buckling calculations shall consider stiffness reductions due to matrix cracking or softening, matrix yielding, delaminations and debonding, if these failure mechanisms are permitted to happen in the design, see [7.2]. The strength of the bondline shall be measured according to [4.6].

In general, the liner's bond to the laminate shall be as strong as or stronger than the laminate's delamination resistance, if resistance to hydrostatic pressure or an internal vacuum is relevant. Bond strengths shall be measured according to [4.6].

If the bond between the liner and laminate is the weak link it shall be shown that the liner can withstand a vacuum by itself without buckling and that no fluid can accumulate in the weak interface over time. See also [5.18] for rapid gas decompression and blistering resistance.

The cover does not need to be checked for buckling.

7.5 Resistance to external hydrostatic pressure

If the TCP is used under water, the resistance to external hydrostatic pressure shall be evaluated in relation to collapse (strength-based failure), leakage, buckling and excessive deformation.

Details can be found in [7.2], [7.4], [7.7] and [7.8.5] respectively.

Long-term resistance to external pressure shall be based on long-term material properties, especially considering creep and stress rupture. The exposure time is given in [3.7.7].

It shall be shown whether compressive strength or buckling is the critical failure mode.

The accuracy of the buckling calculation methods combining hydrostatic external pressure and bending shall be verified by experiments.

It shall be shown whether non-critical material properties (see [4.1.4]) can be used to calculate resistance to hydrostatic pressure. If non-critical properties can be used resistance to hydrostatic pressure is not critical and the full-scale test requirements in [10.6] can be simplified.

The role of the cover, laminate and liner and possible damage to each component shall be evaluated. If the cover is tight matrix cracks in the laminate may be acceptable. If the cover is damaged, water may seep through the matrix and debond the liner, leading to the outside water leaking into the inside of the TCP.

7.6 Torsional balance

The TCP's torsional balance shall fulfil the dimension requirements stated in [3.5.2].

Torsional balance shall be tested according to [10.7].

The design criterion in [5.9] shall be used for the calculations.

7.7 Excessive deformation

TCP deformations under all load cases shall be calculated. The deformations shall not exceed the limitations given in the design input in [3.5.2].

The design criterion in [5.9] shall be used for the calculations.

7.8 System design criteria

7.8.1 Maximum permeation rate

The TCP shall not leak any fluids, beyond the requirements stated according to [3.5.2].

A maximum permeation rate shall be calculated for each internal fluid given in [3.7.2].

Permeation rates shall be calculated according to [5.6].

7.8.2 Corrosion protection

It shall be demonstrated that corrosion protection requirements for the entire system, as given in [3.5.2] are fulfilled.

If the TCP body does not contain any metal parts, corrosion protection of the TCP body itself is not required. Chemical and mechanical degradation shall be evaluated as described in [5.15] and [5.16].

If the TCP body contains metal parts their corrosion resistance shall be evaluated according to DNVGL-ST-F201 or API 17J.

7.8.3 Thermal insulation

Thermal insulation and heat loss shall be calculated if requirements according to [3.5.2] are stipulated.

Overall heat transfer coefficients shall be based on the pipe's nominal ID and shall differentiate between the pipe itself and any external effects, such as soil cover for buried pipe.

Thermal properties shall be measured according to [4.3.2] and [4.4.2].

7.8.4 Gas venting

The TCP is a bonded construction and does not generally need a gas venting system.

The special purpose layer (see [1.2.6]) may need gas venting if it is not well bonded to the TCP.

7.8.5 Pigging and through flow line requirements

It shall be demonstrated that the performance requirements stated in [3.5.2] are met for all the TCP's relevant loading conditions. ID changes due to ovalization shall be considered in this demonstration.

It shall be shown by calculations or experiments that pigs or any other equipment running through the TCP do not scratch or puncture the TCP or cause wear and tear beyond levels considered in the design ([5.13] and [5.14]).

7.8.6 Fire resistance

The TCP shall generally be considered to be non-fire-resistant. If the TCP is exposed to a fire, it may leak or burst.

If fire resistance is required ([3.5.2]), this shall be evaluated on a case-by-case basis. Fire performance shall be demonstrated by testing or compliance with relevant standards and procedures.

Testing with and without internal fluid may produce give very different fire resistance results.

7.8.7 End fittings

End fittings requirements are given in Sec.8.

7.8.8 Attachments - bending stiffeners, clamps, piggyback lines etc.

If attachments (such as bending stiffeners, clamps or piggyback lines, roller from chutes) are used, their interactions with the TCP shall be defined.

Loads from attachments to the TCP shall be considered in the design calculations throughout Sec.6 and this section. The loads shall either be taken as defined in the design input in [3.6.8] or calculated from the characteristics of the attachments given in [3.5.2]. Consistency between these two approaches shall be ensured.

If sharp points exist between the TCP and attachments, [7.8.9] shall be considered.

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Attachments may alter the TCP's system behaviour.

Clamps may restrain the radial movements of the pressurized TCP and thus create unfavourable local loads.

Attachments to the TCP may create locally higher temperatures due to less water cooling. The temperatures should be evaluated and possible changes in material properties considered.

7.8.9 Sharp points

If the TCP touches, crosses or rests on any supports the sharpness of the contact points shall be specified (see [3.5.2]) and the contact forces shall be calculated and used in the design (Sec.6 and this section).

Temporary contact with sharp points, especially during installation shall be considered.

The design of a TCP requires more attention to sharp points and point loads than a steel pipe would require. See also [7.8.11].

7.8.10 Trawling requirements

It shall be demonstrated that the TCP can withstand possible impact and loads from trawling, as defined in [3.6.7].

The effect of an impact shall be evaluated as described in [5.12].

The trawling loads should not initiate any of the critical failure mechanisms in the TCP ([7.2]) or end fitting ([8.7]).

7.8.11 Installation requirements

The consequences of the installation requirements stated in [3.5.2] shall be evaluated with respect to loads on and interactions with the TCP.

All requirements stated in [3.5.2], [7.8.8] and [7.8.9] apply.

All sharp particles should be removed from the trench floor before TCP installation. A hard uneven trench bottom should be levelled to prevent point loading. If sharp points creating point loads cannot be avoided the effect of the point loads on the TCP's short and long-term performance shall be demonstrated.

The TCP should never be rolled or dragged over rough ground.

Point loads from lifting hooks, etc., should be avoided. Specially designed handling tools should be employed.

7.8.12 Recoverability and reusability

The consequences of the recoverability and reusability requirements stated in [3.5.2] shall be evaluated with respect to loads on and interactions with the TCP.

7.8.13 Exothermal chemical reaction cleaning

It shall be shown that the TCP is designed for the loads and environments caused by exothermal chemical reaction cleaning, as specified in [3.5.2]. The same approach as described in Sec.6 and this section shall be used.

It shall be ensured that the maximum pressure and temperature and the chemical composition due to cleaning is within the limits used for the general design of the TCP.

7.8.14 Splices in the laminate

If the TCP laminate has splices potential changes to the strength and thickness shall be documented.

The local strength reduction in the laminate due to splicing should be obtained by conservative estimates or by testing. Testing may be done according to Sec.4.

Typically splices will be placed far apart within a laminate to reduce the effect of local strength reduction on global strength. The strength reduction shall be calculated and the distance between splices in a TCP laminate shall be specified in the axial, radial and thickness directions. The distance between splices shall be implemented in the production QA, see [13.2].

7.8.15 Marine growth

A procedure shall be provided to ensure that marine growth is kept to the limits specified in [3.7.7].

Marine growth will increase the weight of the TCP and the cross section facing water currents. The effects of these changes on TCP loads shall be considered.

It shall be demonstrated by experience or other means that the TCP's outer surface is not attacked or damaged by the marine growth.

7.8.16 Ice growth

Ice growth shall be considered as described in [3.7.10]. It may increase the weight of the TCP and ice will increase the cross section in the splash zone. The effects of these changes on TCP loads shall be considered.

It shall be demonstrated by experience or other means that the outer surface of the TCP does not get attacked or damaged by the ice growth.

7.8.17 Reeling

Reeling shall be considered in the design.

Long-term loads and buckling shall be included in the calculations.

7.8.18 Static electricity

If the TCP is used above water in a low humidity environment static electricity may build up on the polymeric surfaces.

It may be necessary to make the surface of the TCP conductive to prevent the build-up of static electricity and the related fire/explosion hazard.

7.8.19 Buoyancy and weights

The TCP may need buoyancy or weight elements to give it its desired configuration and behaviour in the water. The need for such elements shall be investigated in the system analysis. Local loads and effects due to the elements shall be considered as described in [7.8.8].
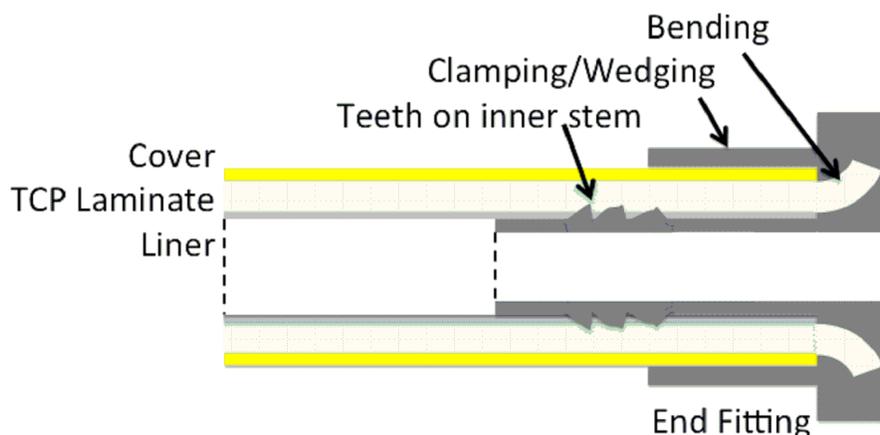
SECTION 8 END FITTING DESIGN CRITERIA

8.1 Introduction

End fittings shall be designed to meet at least the same reliability requirements as the entire TCP and the pipe section.

The end fitting design criteria given in this section are based on analysing the performance of the end fitting. The analysis is then checked by full scale testing in Sec.10 for a few critical cases. Alternatively, joints may be analysed by testing alone as described in Sec.9.

It shall be checked that the end fitting design fulfils all the specifications given in [3.5.2].

There are many possible ways to design an end fitting and various design aspects can be combined in different ways. This standard allows a free choice of design solutions, as long as the solution can be verified and passes the performance requirements. Figure 8-1 shows a schematic illustration of some details of an end fitting that might be used alone or in various combinations (this is not a real existing solution for an end fitting). Many other solutions are possible.

Figure 8-1 Combinations of end fitting solution details

All end fittings and interfaces shall be evaluated against the same design criteria as described for the pipe in Sec.7 and the additional requirements given here. All the limit states as stipulated in [7.1] shall be considered.

The three dimensional stresses shall be addressed when designing the end fittings. Typically a 3-D finite element analysis is needed.

A large conservative bias may be necessary in the analysis to account for the many uncertainties in a joint design. This bias shall nevertheless be estimated in order to obtain a reasonable prediction of the full-scale tests described in Sec.10. The full-scale tests may also be used to update the design analysis, as for example described in DNVGL-ST-C501 [10.3.4] *Procedure for updating the predicted resistance of a component*.

8.2 Failure mode evaluation analysis for end fitting

An FMEA shall be conducted for each end fitting solution. All critical failure mechanisms shall be evaluated for the design.

If the FMEA identifies failure modes or failure mechanisms that are not addressed in Sec.5, Sec.7 and this section of this standard, these failure mechanisms shall be carefully evaluated. Additional testing may be needed to obtain material properties in addition to those is specified in Sec.4 and full or large-scale testing in addition to Sec.10 may be needed to confirm calculations.

8.3 Metal components

Metal parts shall fulfil all the requirements given in DNVGL-ST-F201 *Dynamic risers*, in particular section 6 of that standard.

The inner steel part (stem) may be under high compressive forces. It shall be shown that ovalization remains within the acceptable tolerances of the inner bore and that the system will not collapse.

Possible flow disturbances in the inner fluid due to the geometry of the inner stem shall be checked against the flow requirements specified in [3.7.3].

It shall be checked whether the clamping forces may be reduced due to creep of the liner or laminate and, if so, what the consequences for the end fitting's functionality are.

8.4 Liner, laminate and cover - fluid tightness

The design shall show that fluid tightness is ensured in the end fitting region.

The liner typically provides fluid tightness in the TCP's pipe section. The transition region from the pipe to the end fitting and termination of the liner shall be checked for fluid tightness.

The cover typically provides tightness against external water and the environment in the TCP'c pipe section. The transition region from the pipe to the end fitting and termination of the cover shall be checked for water tightness.

Any sealing system, such as O-rings, clamps etc. shall be clearly described and its performance shall be documented.

The possible loss of pre-tensioning due to creep shall be evaluated for the fluid tightness of all sealing systems, such as the liner and O-rings.

If a combination of laminate, liner and cover is a structural part of the end fitting system, the transfer of loads from the end fitting to the laminate shall be described. The following aspects shall be considered as a minimum in addition to the requirements given for the pipe section in Sec.5 and Sec.7.

— The characteristics of the metal-laminate, metal-liner and metal-cover interfaces. The materials may be bonded, in which case the bond strength is required for the design. The interfaces may be unconnected, in which case, friction coefficients need to be known. The interfaces may have mechanical interlocking so that interface properties may not be important.
— A description of the adhesive system used between the metal and the laminate, liner or cover (if present). The long-term performance of an adhesive should be established with great care. The long-term performance is influenced not only by properties of the substrate, adhesive and interface, but also by the surface preparation and application method.
— The transfer of shear stresses from the metal part through the laminate, liner or cover into the laminate.
— Possible effects of clamping forces on the laminate, liner or cover and their interfaces.
— Excessive penetration of steel teeth into the liner, cover or laminate (see Figure 8-1).
— The effect of swelling or shrinkage of the polymeric materials.
— The effect of thermal stresses.
— The effect of loss of clamping forces between the end fitting and TCP due to stress relaxation, creep, slippage etc.

8.5 Ballooning of the thermoplastic composite pipe

The end fitting adds local ring stiffness to the TCP system. The pipe section will expand more than the end fitting under internal pressure and contract more under external pressure. This creates a ballooning effect at the transition between the end fitting and pipe. The end fitting shall be designed such that the ballooning does not create stress concentrations that are too high for the pipe or end fitting.

8.6 Welding of metallic components

If the end fitting's metallic components need to be welded, it shall be ensured that the heat transfer during the welding process does not increase the polymer's local maximum temperature beyond the polymer's maximum service temperature. The maximum service temperature of the polymer would typically be 20°C below the glass transition temperature.

Welding shall not influence the TCP or any seals in the end fitting.

— If the temperature cannot be kept below the maximum service temperature, then the maximum service temperature for the material qualification in [A.2] shall be the temperature due to welding. See also [3.7.5] and [3.7.6] for maximum temperatures.
— If welding causes temperature cycles around the glass transition temperature, possible recrystallization shall be considered as described in [5.21].

or

— The properties of the area influenced by welding need to be established separately according to the procedures given in this standard for TCP liners, covers and laminates.

8.7 Axial load and bending capacity

The axial load capacity and bending capacity of the end fitting and pipe connection shall be designed for all cases. Short term and long-term static strength and cyclic fatigue resistance shall be considered. Combinations of axial loads, bending and torsion shall also be analysed. If the end fitting is not exposed to some of these loading conditions or the loads are very small, a reduced analysis is sufficient. It should be noted that some resistance to any of these loads is required to create sufficient durability.

The predicted properties shall be confirmed by testing as described in Sec.10.

If a bend restrictor is specified for the TCP system, bending loads on the TCP–end-fitting interface may be less than on the pipe at the minimum bending radius (see [3.5.2]).

8.8 Galvanic protection

Protection against galvanic corrosion shall be provided if TCP fibres can electrically interact with the end fitting, e.g. carbon fibres and metal. See also [5.15].

8.9 End fittings relying on friction

Some end fittings may rely on friction between the metal and the TCP. In such case, special attention shall be paid to the end fitting's axial and bending load capacity.

It shall be shown whether the friction is influenced by internal pressure or thermal loads. If pressure may influence friction, the load-bearing capacity shall be evaluated for the pressurized and unpressurized condition and/or hot and cold conditions.

It shall be evaluated whether creep or stress relaxation may reduce the friction.

Ratcheting, where the TCP moves slowly out of the end fitting, should be considered.

The current version of the standard does not provide any test methods for determining friction performance. Additional testing may be needed to obtain these properties. The holding force due to friction preventing slippage can be seen as an interlaminar or interface shear strength. Characteristic friction strength and fatigue performance values, like the interlaminar properties in [4.6] should be obtained.

Changes to the interface properties due to corrosion or erosion of the metal or lubrication by water or fluids shall be considered.

SECTION 9 PERFORMANCE-BASED QUALIFICATION - FULL-SCALE TESTING ONLY

9.1 General

This standard also gives the option to qualify the TCP, end fittings and components completely by testing. This would be an alternative to the design calculation-based approach given in Sec.5, Sec.6, Sec.7 and Sec.8. However, qualification by testing alone will only be valid for the conditions tested, typically severely limiting the range of conditions under which the TCP can be used.

The selection of test specimens shall comply with the requirements given in [10.1.2].

9.2 Loads and environments

The load cases in the tests shall be combined in a realistic manner. Test results are only valid for the load cases tested.

The environment defined in [3.7] shall be represented realistically. The environmental effect shall be accounted for by:

— carrying out tests on components that have been subjected to a representative pre-conditioning in a representative environment (accelerated or non-accelerated)
— carrying out tests on components combined with aging in a representative environment (accelerated or non-accelerated).

Test results are only valid for the environments tested.

The failure mode(s), failure mechanism(s) and failure location(s) shall be recorded and verified during/after the tests. The partial/safety factor(s) applied shall correspond to the actual failure mechanisms.

If a critical failure mechanism is detected the test should be stopped and possibly a failure analysis should be carried out. Testing to complete destruction usually gives less information and does not allow (or complicates) an analysis of the failure mechanisms developing before ultimate failure.

9.3 Short-term properties

Short-term failure shall be analysed based on the general failure criteria for single or multiple loads as described in DNVGL-ST-C501 [10.3.4]/DNVGL-ST-C501 [6.2.2] *Design criteria for single loads* and DNVGL-ST-C501 [6.2.3] *Design criteria for combined loads*.:

— The partial resistance model factor γ_{Rd} can be set to 1.0 if the tests represent the design and material properties in a satisfactory manner.
— The partial load model factor γ_{Sd} can be set to 1.0 if the tests represent the actual applied loads in a satisfactory manner. If loads represent effects of other phenomena, uncertainties in the conversion from the other phenomena to the loads shall be included in γ_{Rd}, i.e. uncertainties in the transfer function as described in [11.1] and [6.11] shall be included.
— The characteristic strength of the tested component shall be determined based on the test results as described in [A.3] for static data.
— The safety factors shall be chosen based on distribution and COV of the load and COV of the component test results (the material's COV) as in Sec.11.
— The distribution and COV of the load shall be based on the loads the structure will experience in the application, not on the test loads.

At least three specimens shall be tested.

It is recommended to test more specimens to obtain reasonably high characteristic strengths with the required 95% confidence. The relationship between the number of tests and characteristic strength is given in [A.3].

9.4 Long-term properties

Long-term failure shall be analysed based on the principles for obtaining time dependent properties described in [5.22] and [5.23]:

— The partial resistance model factor γ_{Rd} can be set to 1.0 if the tests represent the design and material properties in a satisfactory manner.
— The partial load model factor γ_{Sd} can be set to 1.0 if the tests represent the actual applied loads in a satisfactory manner. If loads represent effects of other phenomena, uncertainties in the conversion from the other phenomena to the loads shall be included in γ_{Sd}, i.e. uncertainties in the transfer function as described in [11.1] and [6.11] shall be included.
— The characteristic strength shall be determined based on the test results as described in [A.6.2] and [A.7.2] for time dependent data.
— The safety factors shall be chosen based on the distribution and COV of the load and COV of the component test results (the material's COV) as in Sec.11. The distribution and COV of the load shall be based on the loads the structure will experience in the application, not on the test loads.

At least ten specimens shall be tested. It is recommended to test more specimens to obtain reasonably high characteristic strengths with the required 95% confidence. The relationship between the number of tests and characteristic strength is given in [A.6.2] and [A.7.2] for data that shall be extrapolated for longer lifetimes, and for data that can be used within the test period.

A regression line can only be obtained if all specimens fail with the same failure mechanism.

If data shall be extrapolated for longer lifetimes than the measured time it shall be shown that no other failure mechanisms may develop between the test time and the expected lifetime of the structure or component. It is usually not possible to show this by component testing only, some analysis and calculations are necessary, see [8.1].

The structure's static strength after long-term exposure shall be the same as the long-term test data from the fatigue or stress rupture tests.

Higher static strength values after long-term exposure may be used if experimental evidence can be provided. A procedure to obtain strength data after long-term exposure is suggested in DNVGL-ST-C501 [4.3.4] *Static strength reduction due to permanent static load* and DNVGL-ST-C501 [4.3.9] *Static strength reduction due to cyclic loads*.

Test data may be extrapolated for longer lifetimes or a number of cycles according to the procedures given in [A.6.3] and [A.7.3].

SECTION 10 PROTOTYPE TEST REQUIREMENTS - FULL-SCALE SAMPLES

10.1 Introduction

10.1.1 Test approach

The main purpose of the testing is twofold:

— verify performance under the main loading conditions
— verify the design analysis.

This section defines a minimum test programme.

Additional testing shall be done if uncertainties in the design analysis cannot be resolved and the test programme described here does not address these uncertainties. This aspect may especially be relevant if an FMECA, in particular of the end fitting design (see [8.2]), identifies failure modes or mechanisms that are not covered in this standard.

All tests given are acceptance tests. The acceptance criteria are based on design calculations, material test data and statistical information.

The following steps shall be followed when defining and carrying out tests:

— The failure mode, failure mechanism and location of the failure, etc., shall be predicted before the test is carried out, based on the design calculations.
— After the test: verify the failure mode, failure mechanism and location of the failure. If these are as predicted above, the design assumptions are considered corroborated. If one or more of these are not as predicted above, the reason for the discrepancy shall be investigated and the validity of design assumptions re-evaluated.
— The onset of leakage shall be predicted for all tests and all tests shall be checked for possible early leakages.
— If a critical failure mechanism is detected the test should be stopped and a failure analysis should possibly be carried out. Testing to complete destruction usually gives less information and does not allow (or complicates) an analysis of the failure mechanisms developing before ultimate failure.

10.1.2 Selection of specimens

All specimens shall be of the same type as the TCP used in the real application. The diameter, thickness and laminate layup shall be the same. The length may be shorter as described for the individual tests.

All prototype testing specimens shall be made using the same production equipment as the actual product.

Changing production equipment later on would require a separate evaluation of whether the process would change properties. Retesting according to this section may be needed if the equivalence of the production method cannot be demonstrated. See also [13.3].

If the TCP may have repairs done during production, representative repairs shall be included in the test specimens, see [13.2].

10.1.3 Permitted modifications to actual end fittings for testing

Many of the tests specified in this section shall be done using actual end fittings. The intention of this requirement is to test the performance of the composite metal interface CMI. The end fitting may be modified for test requirements or simplified, provided the performance of the CMI is not affected by these changes. Typically the end termination or flange are modified.

It shall be demonstrated that the end fitting modifications do not influence the performance of the CMI.

10.1.4 Conditioning/reeling and combining of specimens

If the TCP spends a lot of time on a reel creating permanent deformations or ovalization, test specimens should be preconditioned to attain these deformations before the prototype testing described in this section is carried out, unless it can be demonstrated that the reeling has a non-critical impact on the test results, or this can be demonstrated by design calculations.

It shall also be evaluated whether stress rupture and fatigue testing as described in [10.4] and [10.5] shall be undertaken on the same specimens, and in sequence in order to better represent the existing actual operating conditions.

10.2 Burst and axial testing

10.2.1 Burst testing

At least three burst tests using the actual end fittings (see [10.1.3]) shall be performed.

Testing shall be conducted such that tests at the typical operational temperature, the maximum temperature and minimum temperature are performed

The minimum length should be six times the outer diameter excluding end fittings. Shorter specimens may be used if analysis or strain measurements can document that the central part of the pipe is not influenced by the end fittings, i.e. the stress state in the centre area of a longer specimen would be the same as for the shorter specimen. Specimens should never be shorter than three times the outer diameter excluding end fittings.

The burst pressure and observed sequence of failure mechanisms shall be as predicted from material data.

The burst tests shall be instrumented with strain gauges or displacement gauges. Strains and deformations versus pressure curves shall be as predicted by the analysis within +/- 1 standard deviation. The standard deviation is the predicted standard deviation of the burst test based on the material and component test data used for the prediction.

Since loading rates are often slow for large components (due to limited pump capacity), the test result may be influenced by viscoelastic effects. For this reason, the testing may be carried out in three different ways:

a) The pressure load is increased at a constant rate and the burst pressure is predicted and compared against the experimental results. The minimum test time to reach burst should be about 15 minutes.

— The experimental burst pressure shall be at least the calculated and predicted mean burst pressure - 1 standard deviation.
— The experimental burst pressure should not exceed the predicted mean burst pressure + 1 standard deviation + the estimated allowance for conservatisms in the calculations.

b) The pressure is increased to 80% of the expected burst pressure. The pressure is then kept constant until the sample fails.

— The experimental time to failure shall be at least the calculated and predicted failure time based on stress rupture data for the mean - 1 standard deviation.
— The experimental time to failure should not exceed the predicted mean time + 1 standard deviation + the estimated allowance for conservatisms in the calculations.

c) The pressure is increased at a low constant rate and the burst pressure and time are predicted by calculations. The pressure and time to failure are predicted by a stress rupture Miner sum calculation as given in [5.23].

— The experimental pressure and time to failure shall be at least the calculated and predicted values based on stress rupture data for the mean - 1 standard deviation.
— The experimental pressure and time to failure should not exceed the predicted values + 1 standard deviation + the estimated allowance for conservatisms in the calculations.

The test results are evaluated independently of the design pressure. The experimental results shall show that the calculation methods are accurate.

The component test's standard deviation should be calculated from the standard deviations of the material parameters obtained by measurements described in Sec.4. This can be calculated by predicting burst based on mean material data and on material data taken as the mean minus one standard deviation.

Pressures shall be measured such that dynamic effects do not influence the test results. Preferably the TCP should be connected to the pump at one end and the pressure should be measured at the other end.

Failure is defined as losing the ability to hold pressure. This may be a small leakage or a burst.

10.2.2 Axial testing

At least three axial tests shall be carried out to determine the axial load capacity of the TCP and end fitting.

The axial test is not required if the design calculations show that the combined axial forces not caused by the pressure do not exceed 20% of the axial end cap force due to internal pressure.

The loading shall be done the same way as for the burst tests in [10.2.1], except that the pressure shall be replaced by the axial load. The test results shall also be evaluated in the same way as the pressure test results.

Whether testing shall be done with or without internal pressure shall be determined based on which condition is worse for the end fitting's performance.

10.3 Burst test under bending

At least three burst tests shall be performed using samples bent to the minimum bending radius (MBR).

The MBR shall be the MBR specified for operation under pressure.

The pressurizing shall be done in the same way as for the burst tests in [10.2.1].

If the end fitting is not exposed to bending in actual use, testing may be performed using any end fitting. The end fitting may be tested in the bent state or straight.

If the end fitting is exposed to bending in actual use, testing shall be performed using the actual end-fitting and the transition from the end fitting to the pipe shall be bent to the MBR.

10.4 Cyclic fatigue survival testing

10.4.1 General

Full scale cyclic fatigue testing shall be done to confirm the design's fatigue calculations for the safety classes high and medium.

No fatigue testing is needed for the safety class low or if the TCP is not exposed to any fatigue loads.

The minimum specimen dimensions are the same as for burst testing in [10.2.1].

Testing shall be performed to confirm that the expected weakest failure mechanism in the component, i.e. the failure mechanism that is expected to cause pressure loss, is not activated. Other critical failure mechanisms shall not be activated either.

The minimum number of tests shall be performed for the loading conditions and number of test cycles given in Table 10-1.

Table 10-1 Minimum number of fatigue tests for prototype testing

Loading Type[*]	Safety class high	Safety class medium
Axial fatigue testing shall be done *if* the TCP experiences axial fatigue loads.	2 survival tests at $N_{test} = 10^5$ cycles each	1 survival tests at $N_{test} = 10^5$ cycles
Bending fatigue testing shall be performed *if* the TCP experiences bending fatigue loads.	2 survival tests at $N_{test} = 10^5$ cycles each	1 survival tests at $N_{test} = 10^5$ cycles
Internal pressure fatigue testing shall be performed *if* the TCP experiences internal pressure fatigue loads.	2 survival tests at $N_{test} = 10^5$ cycles each	1 survival tests at $N_{test} = 10^5$ cycles
[*] If the design analysis shows that all the load effects due to one type of fatigue load (axial, bending or internal pressure) are less than 20% of the load effects from the dominating fatigue load, then the TCP does not need to be fatigue tested for that loading type.		

Each fatigue survival test shall end with a burst test. The acceptance criterion for the burst shall be the same as in [10.2.1]. The burst test after the survival test is not required if a burst test according to [10.4.5] is done instead. If the TCP in service will be exposed to collapse after fatigue and this is found to be the severe load, the fatigue survival test should be completed with an external pressure collapse test and the acceptance criterion should be according to [10.6].

Testing may be performed for less than 10^5 cycles if the real number of cycles in the application is less than 10^5 cycles. In that case the number of cycles tested should be at least the same as the number of cycles in the application.

If the end fittings may experience axial fatigue, axial fatigue shall be tested for using the actual end fittings (see also [10.1.3]). If the end fittings are protected from axial fatigue, e.g. by being located outside the zone with axial fatigue loads, axial fatigue may be tested for using with any kind of end fitting (see also [8.7]).

If the end fittings may experience bending loads, bending fatigue shall be tested for using the actual end fittings. If the end fittings are protected from bending loads, e.g. by a bend stiffener, bending fatigue may be tested for using any kind of end fitting (see also [8.7]). In this case bending fatigue may also be tested for as a simple cantilever beam test.

If the design analysis shows that the performance of the pipe part of the TCP can be easily predicted by analysis and the testing is mainly for to verify end fitting performance the test effort may be reduced if the test specimens have an actual end fitting (see [10.1.3]) at both ends of the TCP. In that case testing one pipe with two CMIs can be used to fulfil the requirement of two survival tests for the CMI, provided both CMIs are exposed to the same loading conditions.

10.4.2 Test temperature and conditioning

Testing for safety class high:

This should typically be done at the extreme temperatures. This shall be one test at the minimum and one test at the maximum temperature. The test could also just be at the maximum temperature, if the material evaluation shows that only the maximum temperature is critical.

Testing for safety class medium:

This shall be performed at the most challenging temperature for the structure which is usually the maximum operational temperature.

For safety class high and medium:

— If the TCP is exposed to extreme temperatures for only short periods, the fatigue testing could be undertaken at temperatures representing the actual use conditions.

— Testing should be performed on dry specimens (no absorbed fluids). If the design analysis cannot predict the difference between the fatigue of dry specimens and fatigue of specimens saturated with fluids, additional testing on saturated specimens is needed.

If testing is done at temperatures representing actual use conditions, the number of cycles at each test temperature should reflect conservative proportional fractions of the cycles at that temperature in the design life, as specified in the design input [3.7] and [6.14]. Temperatures should be mixed during the testing. No temperature should be tested for less than 10 cycles.

10.4.3 Test load

Testing shall be performed with a representative internal pressure. For example if the TCP experiences 50% of its lifetime at design pressure and 50% of its lifetime with no internal pressure, then half of the total number of cycles shall be performed with internal pressure and half without internal pressure.

As a minimum 100 cycles shall always be tested without pressure and 100 cycles shall be tested at design pressure, unless it can be shown that fatigue always occurs under only one well defined internal pressure (which could be 0 pressure).

For each loading case (axial, bending and cyclic pressure) the test load shall be calculated from the relevant material's S-N curve, established by the procedures given in [A.6]:

Specific mean material S-N curve:

$$\log \Delta \varepsilon_{mean} = \log \Delta \varepsilon_0 - \alpha \log N$$

for the R ratio and failure mechanism investigated in the prototype test.

The cyclic test load ΔL_{test} is:

for safety class high

$$\log \Delta L_{test} = \log \left(\gamma_{SD} \Delta L_0 \right) + \alpha \log \left(\gamma_{fat} M \right) - \alpha \widehat{\sigma}_{fat} - \alpha \log(N_{test})$$

for safety class medium

$$\log \Delta L_{test} = \log \left(\gamma_{SD} \Delta L_0 \right) + \alpha \log \left(\gamma_{fat} M \right) - 2 \alpha \widehat{\sigma}_{fat} - \alpha \log(N_{test})$$

and

$$\Delta L_0 = \psi \left(\Delta \varepsilon_0 - \frac{P_0}{\chi} \right)$$

where the parameters for the equation are given in Table 10-2. Note that ψ and χ may have to be nonlinear functions instead of a simple parameter.

Table 10-2 Parameters for establishing the fatigue-testing load

Parameter	Explanation	Reference
γ_{Sd}	Fatigue load model factor, describing uncertainty in load calculations	[11.1]
ΔL_0	Calculated applied cyclic reference load	
$\Delta \varepsilon_0$	Parameter from materials fatigue curve	[A.6]

Parameter	Explanation	Reference
ψ	Relation between strain in the laminate and applied load.	
P_0	Applied permanent internal pressure	
χ	Relation between strain in the laminate and applied pressure.	
α	Slope of material´s S-N curve	[A.6]
M	Miner sum for application	[5.22.2]
γ_{fat}	Fatigue safety factor	[11.6], Table 11-6
$\hat{\sigma}_{fat}$	Standard deviation of the fatigue tests (in *logN*)	[A.6]
N_{test}	Number of cycles for the prototype fatigue test	
κ	Shift factor for the material's S-N curve	Table A-3

Note: if the full potential of the TCP shall be utilized $M\gamma_{fat} = 1$, otherwise $M\gamma_{fat} \leq 1$, as given in [5.22.2].

If pressure fatigue testing is done the cyclic pressure can be calculated by replacing the load *L* with the pressure *P* and

$$\Delta P_0 = \Phi \Delta \varepsilon_0$$

where Φ is the relation between strain in the laminate and applied pressure.

The same calculation can also be based on a stress based S-N curve, by replacing strains with stress.

Figure 10-1 shows the principal approach for obtaining the test load based on the design point, characteristic S-N curve, mean S-N curve and test S-N curve.
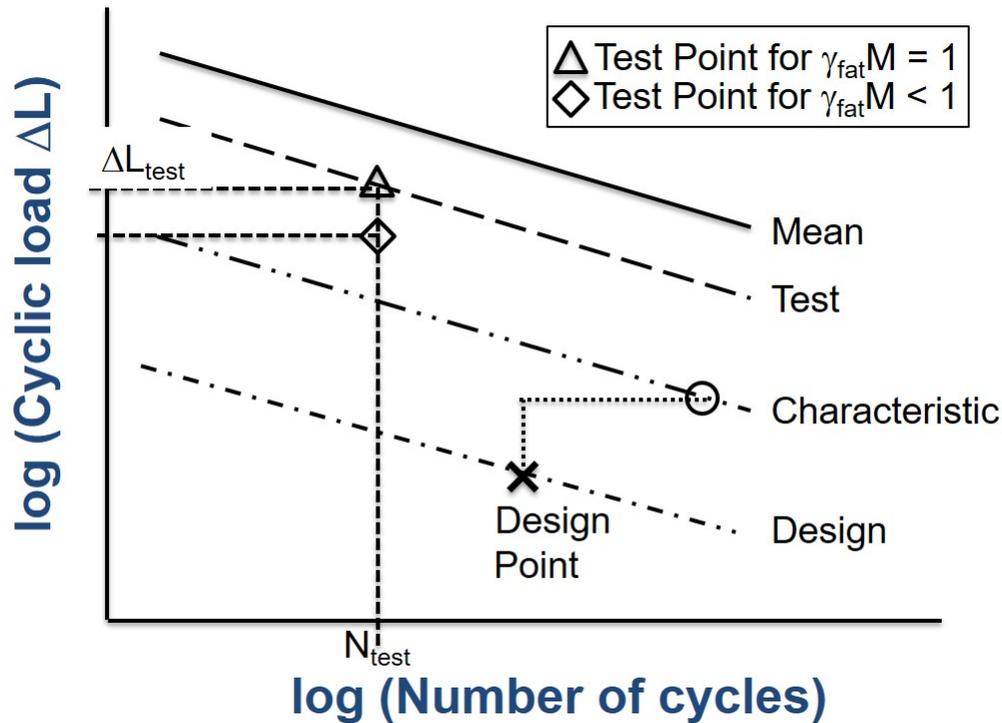
Figure 10-1 Principal approach for obtaining the test load ΔL$_{test}$ for fatigue testing

10.4.4 Early failure during a test

Should one of the survival tests fail before the required number of cycles is reached, at least two new tests shall be undertaken, provided the test did not fail before the number of cylces reaching the characteristic curve as given by

$$\log(N_{test}) = \frac{\log(\gamma_{SD}L_0) + \alpha \log(\gamma_{fat}M) - \kappa\alpha\hat{\sigma}_{fat} - \log\Delta L_{test}}{\alpha}$$

in in which case a re-design is needed. The parameters for the equation are given in Table 10-2.

All tests together shall fulfil the similarity requirements in [4.7.6].

If the new tests also fail, then re-design is needed.

10.4.5 Separate burst test – residual strength after fatigue

As an alternative to performing a burst test after the fatigue tests according to [10.4.1] to [10.4.4] separate specimens may be tested. The specimens shall be fatigue tested at the load $\Delta L_{test-burst}$:

$$\log \Delta L_{test-burst} = \log\left(\gamma_{SD}L_0\right) + \alpha \log\left(\gamma_{fat}M\right) - \kappa\alpha\hat{\sigma}_{fat} - \alpha \log(N_{test})$$

where the parameters for the equation are given in Table 10-2. All other test conditions shall be as described in [10.4.1] to [10.4.4].

After the fatigue testing a burst test shall be performed according to [10.2].

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The acceptance criterion for the burst shall be the same as in [10.2].

The burst testing of separate specimens according to this section is more accurate for establishing the sufficient residual strength of the TCP after fatigue loading. Testing only according to [10.4.1] to [10.4.4] is conservative and requires less testing.

10.5 Stress rupture survival test

10.5.1 General

Full-scale stress rupture testing shall be performed to confirm the design's stress rupture calculations for safety class high and medium.

No stress rupture testing is needed for safety class low.

The minimum specimen dimensions are the same as for burst testing in [10.2].

Testing shall be performed to confirm that the expected weakest failure mechanism in the component, i.e. the failure mechanism that is expected to cause pressure loss, is not activated. Other critical failure mechanisms shall not be activated either.

The minimum number of tests and testing times are given in Table 10-3.

Table 10-3 Minimum number of stress rupture tests for prototype testing

Loading type [*]	Safety class high	Safety class medium
Axial stress rupture testing shall be performed *if* the TCP experiences long-term axial loads.	2 survival tests for 1000 hours or formula [10.5.3]	1 survival test for 1000 hours or formula [10.5.3]
Bending stress rupture testing shall be performed *if* the TCP experiences long-term bending loads.	2 survival tests for 1000 hours or formula [10.5.3]	1 survival test for 1000 hours or formula [10.5.3]
Internal pressure stress rupture testing shall be performed *if* the TCP experiences long-term internal pressure loads * (only if no axial or bending stress rupture test is done).	2 survival tests for 1000 hours or formula [10.5.3]	1 survival test for 1000 hours or formula [10.5.3]
[*] If the design analysis shows that all load effects due to one type of fatigue load (axial, bending or internal pressure) are less than 20% of the load effects from the dominating fatigue load, then the TCP does not need to be fatigue tested for that loading type.		

Each stress rupture survival test shall end with a burst test. The acceptance criterion for the burst shall be the same as in [10.2]. The burst test after the survival test is not required if a separate burst test according to [10.4.5] is done instead. If the TCP in service will be exposed to collapse after fatigue and this is found to be the severe load, the fatigue survival test should end with an external pressure collapse test and the acceptance criterion should be according to [10.6].

If the end fittings may experience axial stress rupture, axial stress rupture shall be tested for using the actual end fittings (see also [10.1.3]). If the end fittings are protected from axial stress rupture, e.g. by being located outside the zone with axial loads, axial stress rupture may be tested for using any kind of end fitting (see also [8.7]).

If the end fittings may experience bending loads, bending stress rupture shall be tested for using the actual end fittings (see also [10.1.3]). If the end fittings are protected from bending loads, e.g. by a bend stiffener, bending stress rupture may be tested for using any kind of end fitting. In this case bending stress rupture may also be tested as a simple cantilever beam test or this may be combined with the axial test.

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If the design analysis shows that the performance of the TCP's pipe part can easily be predicted by analysis and the testing is mainly to verify the end fitting performance the test effort may be reduced if the test specimens have a relevant end fitting at both ends of the pipe. In such case, testing one pipe with two CMIs can fulfil the requirement of two survival tests for the CMI, provided both CMIs are exposed to the same loading conditions.

10.5.2 Test temperature and conditioning

Testing shall be performed at maximum operational temperature. If the TCP is exposed to extreme temperatures for only short periods, the stress rupture testing could be performed at temperatures representing the actual use conditions. If testing is done at temperatures representing actual use conditions, the testing time at each test temperature should reflect conservative proportional fractions of the times at that temperature in the design life, as specified in the design input [3.7] and [6.14]. Temperatures should be mixed during the testing. No temperature should be tested for less than 15 minutes.

Testing should be performed on unsaturated dry specimens. If the design analysis cannot clearly predict the difference between dry stress rupture testing and stress rupture testing of specimen saturated with fluids, additional testing on saturated specimens is needed.

10.5.3 Test load

Testing shall be performed at a representative internal pressure. For example if the TCP experiences 50% of its lifetime at design pressure and 50% of its lifetime with no internal pressure, then half of the total number of cycles shall be performed with internal pressure and half without internal pressure.

As a minimum 100 hours shall always be tested without pressure and 100 hours shall be tested at design pressure, unless it can be shown that permanent stresses always occur under only one well defined internal pressure (which could be 0 pressure).

For each loading case (axial, bending and pressure) the test load shall be calculated from the relevant material's stress rupture curve established by the procedures given in [A.7].

Specific mean material stress rupture curve:

$$\log \sigma = \log \sigma_0 - \beta \log t$$

The test load L_{test} is:

for safety class high:

$$\log L_{test} = \log(\gamma_{SD} L_0) + \beta \, \log \left(\gamma_{fat} M \right) - \beta \hat{\sigma}_{fat} - \beta \log(t_{test})$$

for safety class normal:

$$\log L_{test} = \log(\gamma_{SD} L_0) + \beta \, \log \left(\gamma_{fat} M \right) - 2\beta \, \hat{\sigma}_{fat} - \beta \log(t_{test})$$

and

$$L_0 = \psi \left(\sigma_0 - \frac{P_0}{\chi} \right)$$

where the parameters for the equation are given in Table 10-4. Note that Ψ and χ may have to be nonlinear functions instead of a simple parameter.

Table 10-4 Parameters for establishing the load for stress rupture testing

Parameter	Explanation	Reference
γ_{Sd}	Fatigue load model factor, describing uncertainty in load calculations	[11.1]
L_0	Calculated applied reference load	
σ_0	Parameter from materials stress rupture curve	[A.6]
ψ	Relation between strain in the laminate and applied load.	
P_0	Applied internal pressure	
χ	Relation between strain in the laminate and applied pressure.	
β	Slope of material´s stress rupture curve	[A.7]
M	Miner sum for application	[5.23.2]
γ_{fat}	Fatigue safety factor	[11.6], Table 11-6
$\hat{\sigma}_{stressrupt}$	Standard deviation of the stress rupture tests	[A.7]
t_{test}	Test time for the prototype stress rupture test	
κ	Shift factor for material's S-N curve	Table A-3

Note: if the full potential of the TCP shall be utilized $M\gamma_{fat} = 1$, otherwise $M\gamma_{fat} \leq 1$, as given in [5.23.2].

If pressure stress rupture testing is performed the permanent pressure can be calculated by replacing the load L with the pressure P and

$$\Delta P_0 = \Phi \Delta \varepsilon_0$$

where Φ is the relation between strain in the laminate and applied pressure.

Figure 10-1 shows the principal approach for obtaining the cyclic fatigue test load based on the design point, characteristic S-N curve, mean S-N curve and test S-N curve. The same approach is used here for stress rupture testing. S-N curves are replaced by stress rupture curves and the number of cycles is replaced by time.

10.5.4 Early failure during a test

Should one of the survival tests fail before the required testing time is reached, at least two new tests shall be carried out, provided the test did not fail before the number of cycles reaching the characteristic curve as given by

$$\log(t_{test}) = \frac{\log\left(\gamma_{SD}L_0\right) + \beta \log\left(\gamma_{fat}M\right) - \kappa\beta\hat{\sigma}_{fat} - \log\left(L_{test}\right)}{\beta}$$

in which case a re-design is needed. The parameters for the equation are given in Table 10-4

All the tests together shall fulfil the similarity requirements stated in [4.7.6].

If the new tests also fail, then re-design is needed.

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10.5.5 Separate burst test – residual strength after permanent loading

As an alternative to performing a burst test after the stress rupture tests according to [10.5.1] to [10.5.4] separate specimens may be tested. The specimens shall be stress rupture tested at the load $\Delta L_{test-burst}$:

$$\log \Delta L_{test-burst} = \log\left(\gamma_{SD} L_0\right) + \beta \log\left(\gamma_{fat} M\right) - \kappa \beta \hat{\sigma}_{fat} - \beta \log\left(t_{test}\right)$$

where the parameters for the equation are given in Table 10-4. All other test conditions shall be the same as described in [10.5.1] to [10.5.4].

After the stress rupture testing a burst test shall be carried out according to [10.2].

The acceptance criterion for the burst shall be the same as in [10.2].

The burst testing separate specimens according to this section is more accurate for establishing the sufficient residual strength of the TCP after stress rupture loading. Testing only according to [10.5.1] to [10.5.4] is conservative and requires less testing.

10.6 External pressure test

An external pressure test shall be carried out on the actual TCP, unless the TCP is not exposed to external pressure as described in [3.6.5]

The specimen length shall be chosen to represent a very long TCP and potential collapse is no longer influenced by the support of the end fittings. The length of the test specimen shall be calculated.

Typically, a length of six times the outer diameter between the end fittings fulfils these requirements.

The external pressure test may be done in two ways: a fairly rapid test (similar to the burst test procedure) or a long-term stress rupture test.

— If the rapid test is chosen, the test pressure $P_{hydro\text{-}test}$ and test time shall be obtained following the same criteria as given in [10.2] for the fairly rapid test.
— If a stress rupture test is chosen the test time should be obtained according to [10.5.3]. However, the test time should be related not to the design lifetime of the TCP, but to the time the TCP may experience external pressure, see [3.7.7]. The minimum test time shall be 10 hours.

If buckling is the critical failure mode (see [7.5]), the test load shall be calculated as the mean failure load due to buckling reduced by 10%.

If the resistance to hydrostatic pressure is not critical according to [7.5], hydrostatic pressure may be tested at $P_{hydro\text{-}test}$ twice the maximum external hydrostatic pressure, as given in [3.7.7] and [3.7.6]. The minimum test time shall be 1 hour. In that case, before and at the end of the test programme the sample shall be exposed to 10 external pressure cycles between 0 and $P_{hydro\text{-}test}$.

If the FMECA of the end fitting ([8.2]) indicates that resistance to external pressure is critical, testing shall be done using the actual end fitting (see [10.1.3]). Otherwise any end fitting may be used for testing.

If design calculations or fatigue or stress rupture testing (see [10.4.1] and [10.5.1]) show that the TCP will develop matrix cracking or ovality, the external pressure testing shall be done with these damage forms present. This requirement applies only if the TCP in service is subject to external collapse pressure entailing this damages.

10.7 Torsional balance

The torsional rotation at the design load shall not exceed the design requirements stated in [3.5.2].

A section of TCP shall be subjected to the design axial load. The torsional rotation shall be below or at the rotation predicted by the design calculations.

Testing may be done at room temperature.

This test may be conveniently combined with a burst or axial stress rupture test, since both tests introduce axial loads in specimen.

If no torsional requirement is given in [3.5.2] or if the requirement is non-critical, the test is not required.

If relevant for the design, the torsional stiffness shall be measured.

10.8 Gauge test

A pig with a gauge plate shall be sent through the prototype TCP with end fittings and the gauge shall be measured. The gauge measurement shall be within the specified inner diameter and ovalization tolerances satated in [3.5.2]. This test shall be repeated as a factory acceptance test on the real product, see [13.5.7].

The test may be carried out on one of the other test specimens before they are tested.

If no tolerances are given, the gauge test is not required.

10.9 Impact test or trawling test

10.9.1 General

If an impact resistance requirement is specified for the application, see [3.6.6], it shall be tested for.

Impact requirements related to trawling stated in DNVGL-RP-F111 may also be relevant.

The specified impact condition or trawling load shall be applied to the TCP when empty and when under pressure.

If no specific conditions are specified for applying the impact, the TCP shall be placed on a concrete floor during impact testing. A softer support may be used if it can be demonstrated that the chosen support is the worst case for the application.

Impact testing may be done in three ways.

[10.9.2] describes impact testing based on a specified impact event. The testing should demonstrate that the TCP can survive the impact. The TCP should be taken out of service or repaired after the impact event.

[10.9.3] describes impact testing based on defining impact limits. The impact limits shall be determined. Subsequently the specified impact events shall be tested and the damage checked. The TCP should be taken out of service or repaired after the impact event.

If the TCP shall be operated with the impact damage present, [10.9.4] shall be applied.

10.9.2 Testing based on specified impact events

Representative boundary conditions shall be chosen when applying the trawling load.

The TCP shall be checked for possible denting due to the impact. The size of the dent shall not exceed the requirements in [5.12].

A burst test according to [10.2] shall be carried out on the specimen with impact damage. The calculated mean burst pressure should include the calculated effect of impact damage.

If no reduction in strength due to impact was calculated, the burst strength should not be reduced by more than 10% compared to the mean minus one standard deviation of the burst strength of undamaged TCP specimens. This approach means that a TCP that experiences impact should be taken out of service after the event.

10.9.3 Testing based on defining impact limits

The TCP shall be exposed to impacts with different impactor energies and shapes .

Subsequently, the impacted regions shall be cut from the pipe section and the material cross section shall be investigated by microscopy.

Impact events are not acceptable if they cause:

— Fibre damage in the load-bearing laminate.

— Thickness-penetrating cracks in the cover or liner.
— The debonding of liner and TCP laminate.
— Dents beyond the requirements in [5.12].

Impact events creating less damage can be viewed as acceptable for a limited period of service time.

If resistance to certain impact events is specified in [3.6.6] this impact shall create less damage to the TCP than that which has been found acceptable in this test programme.

The impact shall be tested as described in [10.9.3]. However instead of a pressure test after the impact the damage shall be investigated and compared to the acceptable limits established in this section.

10.9.4 Testing for permanent service with impact damage

The full and permanent acceptance of a certain level of impact damage requires the burst, stress rupture and fatigue tests of this section to be performed with the specified impact damage to show that the TCP can tolerate this damage.

10.10 Use of test results from similar specimens for long term tests

The long-term fatigue and stress rupture tests stated in [10.4] and [10.5] respectively may be waived if:

— the results from previous tests on TCPs exist
— all the other test results stated in this section gave the expected and scaled results when the new TCP is compared to the previous TCP
— if the materials and production processes are identical or similar and the new and previous TCPs can be scaled.

The similarity of materials shall be evaluated based on the requirements in [4.7].

The TCP can be scaled if analytical or finite element calculations can demonstrate that:

— All critical stress states and local stress concentrations in the joint of the scaled specimen and the actual TCP are similar, i.e., all stresses are scaled by the same factor between the new and previous TCP.
— The behaviour and failure of the new and previous TCP can be calculated based on independently obtained material parameters. This means no parameters in the analysis should be based on adjustments to make large scale data fit.
— The sequence of predicted failure modes is the same for the new and previous TCP over the entire lifetime of the TCPs.
— An analysis method that predicts the test results properly but not entirely based on independently obtained materials data, may be used for other joint geometry. In such case, it should be demonstrated that the material values that were not obtained by independent measurements can also be applied to the new conditions.

SECTION 11 SAFETY FACTORS

11.1 Introduction

This standard uses partial safety and model factors as described in Table 11-1.

Table 11-1 List of partial safety and model factors

Symbol	Designation	Reference section	Type
γ_F	General partial load factor	[11.2]	safety factor
γ_{FF}	Partial load factor for functional loads	[11.2]	safety factor
γ_E	Partial load factor for environmental loads	[11.2]	safety factor
γ_P	Partial load factor for pressure loads	[11.2]	safety factor
γ_M	Partial resistance factor	[11.3]	safety factor
γ_{Sd}	Load model factor	[11.4.1]	model factor
γ_{Rd}	Resistance model factor	[11.4.2]	model factor
γ_S	System factor	[11.5]	model factor
γ_{fat}	Partial factor for fatigue and stress rupture analysis	[11.6]	safety factor

Partial resistance safety factors depend on the material's coefficient of variation (COV). The COV is given by the standard deviation divided by the mean value of the strength, as defined in [A.3].

If various strength values are combined in a failure calculation, the COV to be used for the safety factor selection shall be calculated as described for the specific design criterion given in Sec.5 and DNVGL-ST-C501. The highest COV value may be chosen as a simple conservative method.

Material factors also depend on the failure type: ductile or brittle failure. Definitions of ductile and brittle failure are given in [2.2.4].

11.2 Partial load factors

The partial load factors are given in Table 11-2. For the ultimate limit state (ULS) two sets of load factors shall be applied for all TCP designs. The set leading to the highest design load or design load effect shall be applied as the set governing the design in the ULS. For the fatigue limit state (FLS) and accidental limit state (ALS), only one set of factors needs to be applied.

The partial load factors shall be used with the characteristic loads described in [3.6.2] and incidental pressure as defined in [3.6.5].

There are two approaches to establishing the design load effect associated with a particular load.

The more conservative of the two approaches shall be used for the design.

(1) The design load effect (local stress or strain) is obtained from a structural analysis of the design load, where the design load is obtained by multiplying the characteristic load by a specified load factor γ_F.

(2) The design load effect (local stress or strain) is obtained by multiplying the characteristic load effect by a specified load factor γ_F where the characteristic load effect (local stress or strain) is determined by a structural analysis of the characteristic load. The factors shall be applied to the design criteria given in [5.2],

[5.3], [5.4], [5.5], [5.7] and [5.8]. The design criteria only state the general load factor γ_F. In both cases, the general load factor γ_F shall be substituted by γ_{FF}, γ_E, or γ_P, as appropriate.

Table 11-2 Partial load factors

Limit state	Functional load	Environmental load	Pressure load
	γ_{FF}[1]	γ_E[2]	γ_P
ULS	1.1	1.3	1.0
ULS	1.4	0.7	1.0
FLS	1.0	1.0	1.0
ALS	1.0	1.0	1.0
Reeling[3]	1.0	NA	1.0

Notes:

[1] If the functional load effect reduces the combined load effects, γ_{FF} shall be taken as 1/1.1 or 1/1.4 as applicable.

[2] If the environmental load effect reduces the combined load effects, γ_E shall be taken as 1/1.3 or 1/0.7 as applicable.

[3] For the special case of reeling, see [11.7].

11.3 Partial resistance factors

The material safety factors are given in Table 11-3 and Table 11-4 for brittle and ductile failure respectively. The definition of brittle and ductile failure is given in [2.2.4].

The factors shall be applied to the design criteria given in [5.2], [5.3], [5.4], [5.5], [5.7] and [5.8].

Table 11-3 Partial resistance factor γ_M for brittle failure

Safety class	COV of strength or strain to failure		
	2% - 5%	5%-10%	10%-12.5%
Low	1.3	1.25	1.3
Medium	1.45	1.4	1.5
High	1.6	1.55	1.75

Table 11-4 Partial resistance factor γ_M for ductile failure

Safety class	COV of strength or strain to failure		
	2% - 5%	5%-10%	10%-12.5%
Low	1.2	1.1	1.1
Medium	1.3	1.25	1.3
High	1.45	1.4	1.5

For the special case of reeling see [11.7].

11.4 Model factors

11.4.1 Load model factors

Load model factors γ_{Sd} account for inaccuracies, idealizations and biases in the engineering model used to represent the structure's real response, e.g. simplifications in the transfer function (see [6.11]). The effects of geometric tolerances shall also be included in the load model factor. The factor is treated here as a deterministic parameter.

11.4.2 Resistance model factors

Model factors shall be used for each failure criteria. The factors are given in DNVGL-ST-C501 Sec.6 *Failure mechanisms and design criteria*. Detailed references are given in Table 11-5.

Table 11-5 Summary of resistance model factors.

Design criterion	Model factors γ_{Rd}	Reference in DNVGL-ST-C501	Reference in this standard
Fibre failure	1.0	DNVGL-ST-C501 [6.3.2.2]	[5.2]
Matrix cracking	1.0-1.15	DNVGL-ST-C501 [6.4.1] and DNVGL-ST-C501 [6.4.4]	[5.3]
Delamination, debonding	1.3 or 1.0-2.0	DNVGL-ST-C501 [6.5]	[5.4], [5.10]
Laminate failure	1.05-1.15	·/·	[5.5]
Fluid tightness, permeability	1.0	·/·	[5.6]
Yielding	1.0	DNVGL-ST-C501 [6.6]	[5.8]
Ultimate failure of orthotropic homogenous materials	1.0 or 1.25	DNVGL-ST-C501 [6.7]	[5.7]
Buckling	Same range as all other criteria*	DNVGL-ST-C501 [6.8]	[7.4]
Displacements	1.0	DNVGL-ST-C501 [6.9]	[5.9]
Stress rupture	0.1-1.0	DNVGL-ST-C501 [6.10.4]	[5.23]
Fatigue	0.1-1.0	DNVGL-ST-C501 [6.11.3]	[5.22]
* The other design criteria are used in the buckling calculations.			

11.5 System effect factor

The safety factors are given for the entire system. Depending on how the components are connected to form a system, the nominal probability of failure of individual components may need to be lower than the entire system's nominal probability of failure.

In order to take this system effect into account, a system effect factor γ_S shall be introduced. If the system effect is not relevant, $\gamma_S = 1.0$. Otherwise a system factor shall be documented. A value of $\gamma_S = 1.10$ can be used as a first approach.

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For example in the case of a riser string, the failure of one section (i.e. plain pipe or end fitting) is equivalent to the failure of the entire system. This is a chain effect in which any component of the string can contribute. As a consequence, the nominal safety of the individual section should be higher than the nominal safety of the entire system, in order to achieve the overall nominal safety.

In some cases a system may consist of parallel components that support each other and provide redundancy, even if one component fails. In that case a system factor of less than 1 may be used if it can be based on a thorough structural reliability analysis.

11.6 Fatigue and stress rupture safety factors

The safety factors for fatigue and stress rupture calculations are given in Table 11-6 and are applied to the number of cycles or length of time.

Table 11-6 Safety factors for fatigue and stress rupture calculations

Safety class		
Low	Medium	High
15	30	50

11.7 Safety factors for reeling

For the special loading condition TCP reeling, the bending strains and moment based on the geometry of the reel are given with less uncertainty than for general loading conditions. For this loading condition the functional load factor is given in [11.2]Table 11-2. The resistance factors are given in Table 11-7

Table 11-7 Partial resistance factors γ_M related to fibre-dominated or matrix-dominated failure during reeling

COV of strength or strain to failure		2%	5%	10%	12.5%
Safety class					
Brittle failure	Ductile failure				
	Low	1.2	1.2	1.2	1.3
Low	Medium	1.2	1.2	1.3	1.5
Medium	High	1.3	1.3	1.5	1.7
High		1.3	1.3	1.6	1.9

For matrix dominated failure, the resistance factors in Table 11-7 are valid if the diameter to thickness ratio of the TCP D/t > 4 and the local ply stresses caused by internal pressure are not greater than the stresses caused by reeling.

Values may be interpolated for COVs other than those given in Table 11-7

11.8 Alternative safety factors

General safety factors can also be found in DNVGL-ST-C501. The applicable load factors given in DNVGL-ST-C501 shall be applied to local characteristic load effects.

SECTION 12 OPERATIONAL PHASE: INSPECTION, MAINTENANCE AND REPAIR

12.1 Inspection

If the TCP is designed according to this document and handled and operated within the limits described in Sec.3 and in the supplier's operation manual, it should not be necessary to inspect the TCP.

If inspection requirements were specified in [3.5.2], Table 3-1 inspection and condition monitoring, it shall be shown that these requirements have been met.

If the TCP has been exposed to conditions outside the design conditions described in Sec.3, an inspection shall be carried out to investigate the consequences of exceeding the design requirements.

The capability, reliability and functionality of each inspection method shall be documented. The type and size of defect that the method can detect shall be shown.

Available inspection methods often cannot detect all failure mechanisms. However, the methods may detect preceding failure mechanisms. Detecting a preceding failure mechanism may be used as an alternative to detecting the actual failure mechanisms provided a clear link can be established between the detectable failure mechanisms and actual failure mechanisms.

In many cases, a complete inspection programme cannot be developed due to the limited capabilities of available equipment. In such case, the following alternatives may be used:

— Inspection to detect damage due to accidental loads or overloads may be compensated for by monitoring the loads and comparing them to the design loads. If this method is used, the component shall be re-evaluated or replaced after all overloads or other events exceeding the design requirements. This approach shall be agreed upon by the manufacturer, purchaser and, if relevant, a third-party verifier.
— Inspection frequencies and acceptance criteria should be determined for each project.
— For inspection related to production, see [13.4].

12.2 Maintenance

The manufacturer shall state a maintenance procedure for each TCP component.

Appropriate cleaning agents should be described.

Suitable pigs should be identified.

If the component is painted, suitable paints should be identified and methods for removing and applying of the paint should be stated if relevant.

12.3 Repair

A repair should restore a damaged TCP to its original function.

The repair shall be evaluated as a new design according to this standard.

If any functional requirement, such as fluid tightness, stiffness and/or strength cannot be restored, the performance of the component and total system under the new conditions shall be re-qualified.

A clearly defined and reproducible repair procedure shall be established.

When a repair is similar to a joint introduced into the TCP, it shall be qualified in the same way as an end fitting in Sec.8.

Evaluating the production aspects related to the repair shall be part of the qualification.

Suitable conditions for repair work shall be arranged and maintained during the repair. This is mandatory, irrespective of whether the repair is carried out on site or elsewhere. If suitable conditions cannot be arranged and maintained on site, the component should be moved to a suitable site.

If fully qualified repair solutions according to this standard are not available, repairs are not permitted.

12.4 Decommissioning

Decommissioning of all the TCP components shall be documented in accordance with the requirements stated in [3.5.2].

SECTION 13 PRODUCTION QA TEST REQUIREMENTS

13.1 Introduction

The purpose of the production QA tests is to check the product's properties (dimensional, physical, mechanical) against acceptance criteria, to monitor consistent production and to detect non-compliance issues.

For general production QA, see [2.1.2].

13.2 Discontinuities and repair in production

TCPs are typically made in a continuous process involving the winding of tapes or fibres on a liner/mandrel.

Actions and remedies related to interruptions to the process, such as fibre breakages, tape breakages, machine stoppages, exceeding process temperature tolerances and exceeding speed control tolerances, shall be planned. If necessary, repairs shall be described.

Splices shall be characterized as described in [7.8.14].

Any incidents shall be recorded with respect to time and location along the length and thickness.

Tolerances shall be defined regarding how close neighbouring incidents and repairs may be located. The design documentation shall demonstrate that functionality is maintained with the given tolerances.

Prototype testing in Sec.9 or Sec.10 shall be done with representative incidents and repairs.

13.3 Changing end fitting production equipment

Changing production equipment or procedures for assembling the end fitting may require re-testing as described in [10.1.2] if the equivalence of the production method cannot be demonstrated.

13.4 Inspection

The inspection of components during or right after manufacturing may be replaced by well documented production control procedures.

13.5 Factory acceptance tests

13.5.1 Hydrostatic pressure test

All TCPs used in the field shall be pressure tested before leaving the factory. This pressure test may be done on a reeled TCP. The TCP shall have the actual end fittings fitted to it.

The FAT's minimum pressure is 1.3 times the design pressure, see [3.6.5].

If the TCP contains non-composite parts that were designed according to a standard that requires a pressure test up to a higher test pressure than 1.3 times the design pressure, the pressure test shall be carried out at that higher pressure.

The FAT test pressure shall also not be lower than any required system pressure tests or installation tests.

A detailed test programme should be defined. The following should be stated as a minimum:

— rates of pressure increase
— holding times
— time over which the pressure in the system shall not drop without actively applying pressure, i.e. a leakage test.

Strain gauge or displacement measurements shall be taken to check whether the stiffness of the TCP is as expected and deformations match calculations and prototype tests. The measured values shall be within

±10% of the predictions, otherwise the model needs to be changed. The strain measurements may be done on additional specimen taken from a cut off from the production run instead of the FAT test of the actual pipe.

A test schedule should be developed for each application. The testing should allow the detection of as many defects in the structure as possible. As a general guide the following schedules are recommended:

— the minimum time over which the maximum test pressure in the system should not drop without actively applying pressure should be at least 8 hours for systems that do not creep. The pressure should stay constant within 5% of the value at the start of the test. Pressure changes due to temperature changes may be compensated for. If the whole TCP assembly is inspected for leaks immediately after the pressure test, testing according to bullet point three may be used.
— if the test fluid could possibly migrate slowly through cracks, materials or interfaces, testing up to 24 hours may be necessary to detect leaks.
— for systems that show creep the maximum test pressure should be maintained for 1 hour by applying active pressure. The pressure should be monitored for another hour without actively applying pressure. The pressure drop should be predicted before the test and the test result should be within 10% of the prediction.

FAT test pressures for TCPs of safety class low should be applied for at least 1 hour.

Most governmental authorities issue general test requirements for pressure vessels, and these may also apply to pressurized TCPs. The governmental authorities' requirements governing the location of the application should be followed.

The final test procedure shall be agreed on between the manufacturer, purchaser and possibly a third party.

13.5.2 Electrical conductivity and resistance test

If any electrical conductivity requirements along the length of the TCP are given, e.g. in [3.5.2], the conductivity shall be measured and compared against the requirements.

13.5.3 Gas venting system test

Most TCP designs will not have a gas venting system. If the TCP has a gas venting system, the system's functionality shall be tested according to the requirements of API 17J.

13.5.4 Inner liner test requirements

The liner's dimensions and ovality shall be measured before manufacturing. The liner shall also be inspected for defects.

13.5.5 Cover test requirements

Thickness and homogeneity around the circumference shall be investigated by spot checks during production.

13.5.6 Specimen geometry

The length of each TCP shall be measured and checked against the specified tolerances.

The length may be measured during the production process.

The outer diameter shall be measured at one easily accessible end and checked against the specified tolerances.

13.5.7 Gauge test

If the dimensions of the inner diameter are critical as described in [10.8], the size of the inner diameter shall be verified by sending a gauge plate pig through the entire length of the TCP with end fittings. The gauge measurement shall be within the specified tolerances.

13.6 Periodic destructive quality tests

A burst test according to [10.2], an external hydrostatic pressure test according to [10.6] and a hardness test according to Table 4-4 and Table 4-6 shall be carried out in the time intervals described in Table 13-1.

If the manufacturer can establish a relationship between the hydrostatic test results and ring test compression results (see Table 4-9), the hydrostatic pressure testing may be replaced by a ring test.

Table 13-1 Destructive test requirements for production QA

Safety class	Maximum time interval	Maximum length interval [*]
Low	Every 3 years	Every 5000 m
Medium	Every 1 year	Every 1000 m
High	Every ½ year	Every 500 m
[*] if the product is longer than the maximum length interval a test after completing the product is sufficient		

The burst pressure test and external hydrostatic pressure test shall fulfil the same requirements as the qualification testing.

The hydrostatic burst test should be performed at a constant pressure that gives a lifetime of about 10 hours. Acceptance criteria shall be obtained in the way described in [10.5].

If a single production run produces a TCP longer than the minimum length interval, only one test is needed. For example, a 4000 m long TCP of safety class high would need one burst test.

If no product was produced within the minimum time interval the test can be postponed until a new product is produced.

13.7 QA of end fitting assembly

The procedure for assembling the end fitting and attaching this to the TCP shall be described in detail. All parameters and tolerances shall be specified.

All prototype testing shall be performed with end fittings attached in accordance with the procedures.

SECTION 14 MARKING AND PACKAGING

14.1 Marking

The TCP body and its end fittings shall have permanent markings allowing the product to be identified over its design lifetime.

The markings shall be such that the design life is not affected in any way.

The markings shall be repeated at least every 3m.

As a minimum, the following markings shall be applied:

— manufacturer's name
— serial and identification number of the TCP

The following markings may be applied.

— reference to this standard
— manufacture date
— design pressure
— nominal diameter
— storage MBR
— length identification lines
— longitudinal lines to identify twist.

14.2 Packaging

The TCP shall be packaged according to the manufacturer's specifications.

The required protection from the environment during storage and transport shall be considered in the manufacturer's specifications.

The TCP shall not be stored on reels etc. with a radius of less than the MBR for reeling.

The end fittings should be wrapped and well protected and should not protrude from the reeled pipe package unless they are otherwise protected.

No other parts shall interfere with the TCP, especially parts with sharp edges.

The openings of the TCP should be sealed to keep the inside of the TCP clean.

SECTION 15 DOCUMENTATION

15.1 General

The documentation requirements are:

The manufacturer shall provide the purchaser with the following documents no later than at the specified times:

a) design premise - prior to TCP design
b) design load report - prior to TCP manufacture
c) risk analysis – prior to TCP manufacture
d) design report- prior to TCP manufacture
e) manufacturing quality plan - prior to TCP manufacture
f) fabrication specification - prior to TCP manufacture
g) as-built documentation - with supplied TCP
h) operation manual - prior to delivery of the TCP.

The manufacturer's issuance of the documents in this section to the purchaser shall be in accordance with the specifications stated in Sec.3.

15.2 Risk analysis

A general risk analysis (HAZOP) shall evaluate the system the TCP is part of, as specified in [2.4].

15.3 Design premise

The design premise shall contain the parameters required and specified in Sec.3. Reference to their name shall be included. Any assumed values shall be identified.

15.4 Design load report

The design-load report shall include the results of analyses of load cases defined in the design premise. Calculated stresses and strains shall be reported for each design load case, as required in Sec.6. The design load effect report may be incorporated into the design report.

For dynamic applications, this report shall describe the extreme, fatigue and interference analyses and shall compare the results of those analyses to the relevant acceptance criteria.

15.5 Design report

The design report shall contain a detailed description, including drawings, of each pipe component. The description shall include a layer-by-layer description of the pipe, including materials, laminate layup, diameter, thickness, splices, and so forth.

Unless separate material specification documentation is issued, the material specification and data shall be included in the design report.

Each component shall be documented as having sufficient structural capacity to sustain the design loads and stresses listed in the design load report, with the safety margin specified in the design premise.

The design report shall specify the following properties for the TCP:

— MBR (storage and operating)
— axial stiffness (in both tension and compression, and as a function of pressure, and temperature)
— bending stiffness (as a function of tension, pressure, and temperature)
— torsional stiffness (as a function of twist direction, tension, pressure and temperature).

The design report shall define the following properties for the TCP if specified by the purchaser:

a) permissible tension (as a function of bend radius)
b) permissible axial compression
c) permissible crushing (radial)
d) permissible twist (as a function of relevant parameters if applicable)
e) pressure- and temperature-induced axial and radial expansion
f) pressure- and tension-induced twist.

The results of the prototype testing (Sec.10) shall be included in the design report. Test results shall be compared with the design calculations.

15.6 Manufacturing quality plan

The manufacturing quality plan shall specify all quality control procedures, including inspection points and test procedures. The manufacturing quality plan may be included in the fabrication specification.

The production QA test results (FAT results) specified in Sec.13 shall be reported.

15.7 Fabrication specification

The fabrication specification shall describe each step in the manufacturing process, including the welding, heat treatment, type and extent of NDE and acceptance criteria, factory acceptance test procedures, fabrication method and allowable repair procedures. The specification shall ensure that the pipe is in accordance with the design.

A detailed fabrication specification shall be on file at the manufacturer. A general fabrication specification shall be delivered to the customer.

15.8 As-built documentation

The as-built documentation shall include, as a minimum, the following:

a) the purchase order reference number
b) equipment descriptions
c) references to design specifications and drawings
d) material certificates
e) dimension control measurements
f) factory acceptance test results
g) all major non-conformances identified during manufacture, and the repairs performed
h) welding procedure specifications and qualifications
i) welder qualification records
j) splices and splice map
k) NDE operator qualifications and NDE test records
l) heat treatment records.

15.9 Operation manual

An operation manual shall be prepared for the system and address all the maintenance tasks and restrictions, and emergency procedures, including repair procedures to be used on board the installation vessel, specified by the manufacturer or purchaser. The manual shall include the following as a minimum:

a) a layer-by-layer description (material specifications, thickness, lay angle, laminate layup, and so forth)
b) diameters (internal and external)
c) the weight per metre (in-air empty and seawater filled, and in-seawater empty and seawater-filled)

d) design minimum and maximum pressures and test pressures (specify if the design pressure is the absolute value or differential)
e) design minimum and maximum temperatures
f) the design water depth
g) installation requirements
h) interface requirements
i) repair procedures
j) handling, storage, winding/unwinding procedures
k) the gas venting system description (if it exists) and permeation rate
l) the decompression rate (gas service)
m) restrictions on internal fluid components (including H_2S and CO_2) and inhibitors
n) pigging and TFL capabilities
o) allowable loads
p) the maximum time with seawater or inhibited seawater in pipe and inhibitor requirements
q) a reference for as-built documentation
r) allowable cleaning products.

If specified by the purchaser, a separate installation manual shall be supplied, and shall document the installation procedures.

APPENDIX A TESTING BACKGROUND

A.1 TCP conditioning (laminates, liner, cover)

A.1.1 General

This appendix describes procedures for how laminates, liners and covers should be conditioned before the tests are performed.

A.1.2 Additives and environments

The polymer's properties shall be determined for dry specimens and for specimens saturated with media representative of the environments and service fluids (stated in [3.7]) for the application. Typically, this would be a hydrocarbon-based fluid and water, see [A.1.4]. For the possibility of a limited test programme, see [4.2.4].

If the polymer contains additives, it shall be evaluated whether the additives may be leached out by the fluids or evaporate in air.

Typical additives that can be leached out are plasticizers or low-molecular co-polymers. Leaching out these additives may make the polymer stiffer and more brittle.

It shall be evaluated whether the leached-out additives will be replaced by molecules of the fluids inside the TCP or the water on the outside.

A.1.3 Dry specimens

Specimens tested under dry conditions shall be dry according to ISO 291. Weight measurements versus time shall be carried out to ensure that specimens have reached a stable weight and have not absorbed any fluids or water. It is recommended to follow the procedures stated in ISO 175.

A.1.4 Representative service fluids and environments

For a general evaluation of the TCP it is recommended to test material properties in a representative fluid.

A representative fluid could be the test fluids defined in ISO 23936-1 or NORSOK M710 Table A1 for sweet and sour service.

Other alternatives would be fluids made of

— pentane/octane
— toluene
— methanol
— water.

Acid/base conditions that are relevant for the field should be chosen.

Whether the representative test mixtures are sufficient for the qualification of a specific field shall be agreed on between manufacturer and purchaser and if relevant a third-party verifier, considering [3.7], [5.15], [5.16] and [5.17].

A.1.5 Temperature while conditioning specimens

The temperature for the leaching/saturation process is conveniently chosen to be high in order to accelerate diffusion. However, the saturation process should cause no phase transformations or morphology changes. Possible recrystallization should be considered. The saturation process may also introduce some aging when carried out at high temperatures.

A.1.6 Leaching out additives and saturation with water

The test specimens shall be put into a water bath and left in the water until additives are removed and water has saturated the specimens.

The water may be seawater or fresh water, depending on what is relevant for the application. If fresh water is chosen for convenience it shall be documented that aging in fresh water is as severe as aging in seawater for the test and material.

If additives are removed from a specimen the mass of the specimen may decrease. The loss of additives can be measured by high performance liquid chromatography (HPLC) or other suitable methods. (Additional specimens may need to be added for the analysis.) If the analysis does not reveal any significant amounts of additives anymore, the additives can be seen as depleted. Note that some materials may only diffuse out after some time. Water should be replaced by new water at frequent intervals to prevent high concentrations of additives in the water slowing down the diffusion process.

The saturation time shall be established by measuring the weight of the samples. Saturation is reached when the mass of the samples no longer increases. The approach described in ISO 62, ISO 175 or ASTM D5229 should be used, but the specimen size shall be chosen according to the test requirements. It is recommended to test thin specimens to reduce the saturation times.

The volume of the water should be large compared to the surface area of the specimens. The water volume shall be at least 8 ml per square centimetre of surface area and ideally never less than 300ml per specimen. If smaller water volumes are used either good circulation shall be ensured or it shall be shown that the water does not become saturated with leached-out materials thus reducing further leaching.

If it can be shown that additives do not leach out, conditioning shall be done for saturation with water and additive depletion may be ignored.

A.1.7 Leaching out of additives and saturation with hydrocarbons

The leaching out of additives and saturation with hydrocarbons shall be done in the same way as described for water ([A.1.6]). The hydrocarbons should be representative for the application. Typically a simple low molecular weight hydrocarbon is chosen to represent the more complex real fluid ([A.1.4]).

A.1.8 Leaching out of additives and saturation with water and hydrocarbons

Additives shall be leached out in the medium most suitable for removing them. Subsequently the samples shall be exposed to a representative mix of water and hydrocarbons to obtain saturation.

The methods described in [A.1.6] and [A.1.7] shall be used.

Good mixing of the multiphase fluid shall be ensured.

If it is known that the polymer will absorb only one or a few components of the multiphase fluid, the absorption bath may contain just these components.

A.1.9 Removing additives in air

If the additives may evaporate into air they should be removed in air if the polymer is used under dry conditions.

If the polymer is mainly used immersed in water or hydrocarbons, the additives can be leached out as described in [A.1.6] and [A.1.7] provided they are soluble in these liquids.

A.1.10 Transition temperatures T_g and T_m

The glass transition temperature T_g of a polymer shall be determined by DMA or DMTA. The melting temperature T_m of a polymer shall be measured by DMA/DMTA or DSC.

If the reinforcement fibres are polymers, their glass transition temperature T_g and melting temperature T_m shall also be determined.

DSC or HDT measurements shall not be used for T_g measurements.

The temperature range of the glass transition shall be described by the temperatures T_g^{min} and T_g^{max}. T_g^{min} is the temperature where the elastic modulus starts to drop quickly when going from low to high temperatures. T_g^{max} is the temperature where the elastic modulus starts to increase rapidly when going from high to low temperatures.

These transition points can be obtained by two methods:

— By drawing tangents to the plateaus and the transition region of the modulus versus temperature curve and identifying where these tangents meet. T_g is the temperature where the curvature of the elastic modulus versus temperature changes. This is shown in Figure A-1.

— Drawing tangents to the plateau regions and defining T_g^{min} where the modulus drops 10% compared to the upper plateau level and T_g^{max} where the modulus increases more than 10% compared to the lower plateau level.

The lower T_g^{min} and higher T_g^{max} of the two methods shall be used.
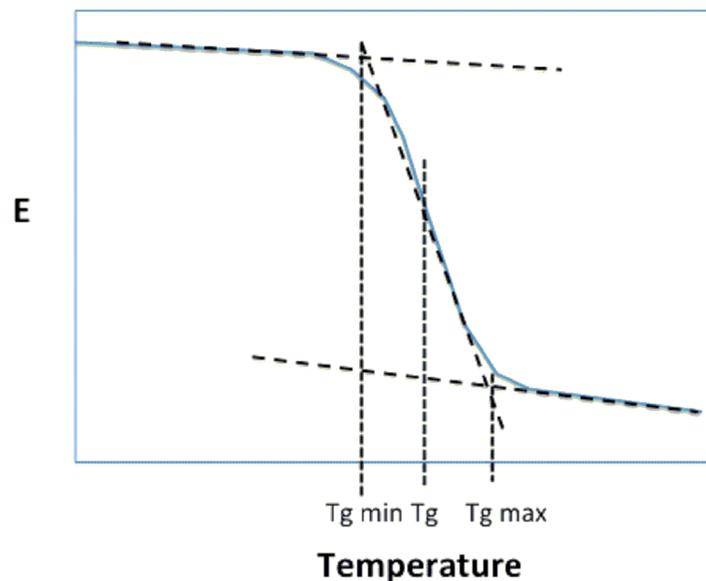
Figure A-1 Change of elastic modulus *E* with temperature in the glass transition region

The glass transition temperature will change with additive content. Therefore, T_g^{max}, T_g and T_g^{min} should be measured for the characterization conditions given in [A.1.1] and Table 4-3.

The glass transition is loading rate dependent. It shall be evaluated how dependent T_g is on the test frequencies used in the DMTA. It may be required to extrapolate T_g to low frequencies that would be representative of the loading rates experienced by the TCP. The loading-rate dependency of T_g can be found by measuring T_g for different test frequencies and using time-temperature superposition (WLF equation) to extrapolate to realistic loading rates. The extrapolated T_g values shall be used when describing the material.

The glass transition temperature may also be pressure-dependent. High pressure can increase T_g and the increased value should be considered in the design.

For semi-crystalline polymers, the melting temperature T_m can be determined by DSC. At a degree of crystallinity below 40%, the melting temperature is often not a sharp transition. In such case, the minimum melting temperature T_m^{min} shall be determined following the same procedures as described for the glass transition temperature using DMA or DMTA.

A.2 Testing temperatures and loading rates

A.2.1 Extreme temperatures

The temperature dependence of the polymer's properties shall be established by testing at the lowest operational temperature T_{op}^{min} and highest operational temperature T_{op}^{max}, as defined in [6.14]. It may be beneficial for the design to also obtain the properties of the typical operational temperature T_{op}. Designing the TCP just for extreme conditions may be overly conservative. Testing at T_{op}^{min}, T_{op}^{max}, and T_{op} is referred to as testing at extreme temperatures "E" in the Tables of Sec.4.

Different extreme test temperatures may be required for different service fluids and environments, since the combination should be physically possible and relevant for operational conditions.

See [A.2.4] for possible corrections to the test temperatures described here.

The approach described herein assumes that the TCP fibres do not experience any phase transition. If the fibres may be exposed to temperatures below and above their T_g, the approach described here for the matrix should be extended to the fibres. This will considerably increase the testing effort.

A.2.2 Convenient temperatures

Polymers have temperature dependent properties mainly near the transition temperatures T_g and T_m. If the operational temperatures are not near the transitions temperatures, it is sufficient to perform most testing at a convenient temperature.

Testing at only one convenient temperature between T_{op}^{min} and T_{op}^{max} may be done if:

— the Charpy impact test delivers the same results within ±15% at T_{op}^{min} and T_{op}^{max}

— the tensile stress strain curves are identical within ±5% at T_{op}^{min} and T_{op}^{max}.

— $T_{op}^{max} < T_g^{max}$ or $T_g^{max} < T_{op}^{min} < T_{op}^{max} < T_m^{min}$

All deviation limits are relative percentages of the tested values.

The prerequisite for testing at only one convenient temperature shall be established for each condition of additives and fluid absorption in the polymer, as described in [3.7] and [A.1.1].

Note, if the polymer is used below and above its T_g, i.e., $T_{op}^{min} < T_g < T_{op}^{max}$, the material may undergo unknown morphological changes, see [5.21].

A.2.3 Loading rates

TCPs will be exposed to relatively low loading rates during their service life. It is assumed here that typical laboratory testing rates are representative of the service life conditions, i.e. static mechanical properties are not very rate-dependent.

If fibres show creep strains of more than 15% of their static strain to failure additional testing may be needed.

Creep of the thermoplastic polymers in the TCP shall be considered as "matrix degradation" according to [5.3].

A.2.4 Test temperature modification

Testing shall be done between T_{op}^{min} and T_{op}^{max}, as described in [A.2.1]. T_g is not constant, but depends on the loading rate, pressure, plasticizer content etc. A changing T_g may lead to test conditions being above T_g while service conditions are below T_g or vice versa.

It shall be evaluated whether this effect could be relevant for the test programme.

If it is relevant, test temperatures may have to be modified to test all relevant and the most severe conditions.

A.3 Characteristic values

A.3.1 Strength

All strength data and strains shall be reported as the mean, standard deviation and number of tested specimens. From this information characteristic values can be calculated. The characteristic values can only be obtained if the standard deviation and number of tested specimens are available.

The sample mean $\bar{x}$ of a set of measurements shall be taken as:

$$\bar{x} = \frac{1}{n}\sum_{i=0}^{n} x_i$$

where x_i is the individual measurement and n is the number of measurements.

The standard deviation ($\hat{\sigma}$) shall be estimated from measurements by:

$$\hat{\sigma}^2 = \frac{1}{n-1}\sum_{i=0}^{n}(x_i - \bar{x})^2$$

The coefficient of variation (COV) shall be estimated by:

$$\widehat{COV} = \frac{\hat{\sigma}}{\bar{x}}$$

A general characteristic value (x_c) should be calculated as:

$$x_c = \bar{x} - k_m\hat{\sigma}$$

The coefficient k_m depends on the number of measurements, the safety class and the failure type as given in Table A-1.

Table A-1 Coefficient for calculating characteristic values k_m, from [DNVGL-ST-C501]

Number of test specimens	Safety class low and ductile failure	Safety class low and brittle* failure or Safety class medium and ductile failure	Safety class medium and brittle failure or Safety class high and ductile failure	Safety class high and brittle failure
3	3.0	3.7	5.0	7.4
4	2.7	3.2	4.0	5.3
5	2.5	2.9	3.5	4.4
6	2.4	2.8	3.3	4.0
7	2.4	2.8	3.1	3.7
8	2.3	2.6	3.0	3.5
10	2.3	2.5	2.8	3.2
15	2.2	2.3	2.6	2.9
Infinite	1.96	1.96	1.96	1.96
* for the definition of brittle and ductile failure see [2.2.4].				

A.3.2 Elastic properties

Characteristic values for elastic properties are typically given as mean values. The standard deviation of the measurements shall be reported.

In some cases the mean value may be non-conservative. If the forces due to bending are calculated the maximum stiffness shall be used. If the deformation due to a given force shall be calculated the minimum values shall be used.

A.4 Obtaining ply properties for thermoplastic composite pipe laminates

A.4.1 Ply properties

The TCP laminate is typically made of unidirectional tape. It shall be described as layers of unidirectional plies. The ply coordinates are:

1: in fibre direction

2: in plane normal to the fibres

3: through-thickness normal to the fibres.

The ply coordinates and laminate coordinates are shown schematically in Figure A-2. Laminate coordinates are cylindrical, but they are given in the more commonly used x, y, z notation for flat composite laminates.

If the TCP laminate is made in a different way, e.g. filament winding, the laminate should still be described as a sequence of unidirectional plies.

A key parameter influencing all ply properties is the fibre-volume fraction v_f.

The glass transition temperature and melting temperature have the same meaning as for polymers ([A.1.10]).

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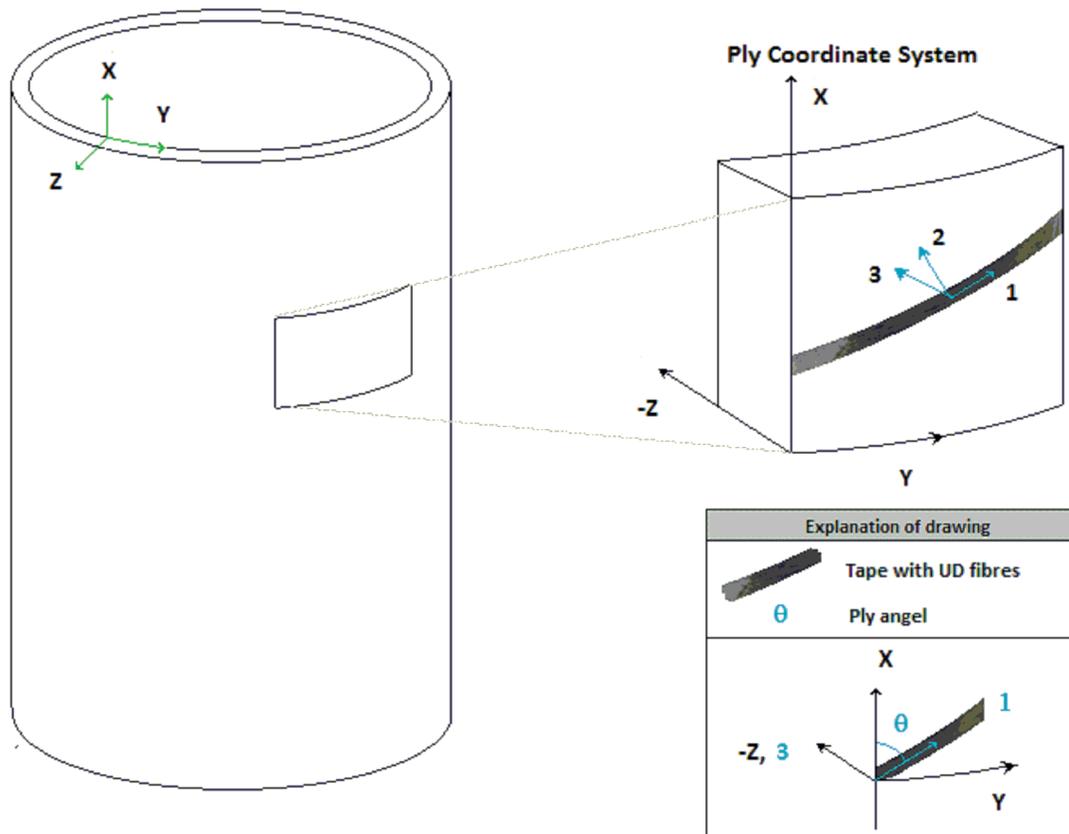
Figure A-2 Laminate and ply coordinates

The Young's moduli in tension are E_{1T}, E_{2T} and E_{3T} respectively.

The Young's moduli in compression are E_{1C}, E_{2C} and E_{3C} respectively

The tensile and compressive moduli are the same for a linear material. However, experimental results are often slightly different. This approach allows both values to be reported.

The shear moduli are G_{12}, G_{13} and G_{23} respectively.

Poisson's ratios are v_{12}, v_{13} and v_{23} respectively

Tensile strengths are X_T, Y_T and Z_T, where X_T is parallel to the fibres, Y_T is transverse to the fibres in plane and Z_T is through the thickness.

The compressive strength follows the same system and is called: X_C, Y_C and Z_C.

The shear strengths are S_{12}, S_{13} and S_{23} respectively.

The strains to failure are ζ_{1T}, ζ_{2T} and ζ_{3T}, where ζ_{1T} is parallel to the fibres, ζ_{2T} is transverse to the fibres in plane and ζ_{3T} is through the thickness.

Compressive strains to failure follow the same system and are called: ζ_{1C}, ζ_{2C} and ζ_{3C}.

Shear strains to failure are ξ_{12}, ξ_{13} and ξ_{23} respectively.

It should be noted that, in linear FE analysis, the strength and strain to failure are in principle related to each other by the Young's modulus. However, nonlinear material behaviour will cause deviations. Slightly different statistical variations between the strength and strain to failure may also cause deviations from the theoretical

strength and strain to failure relationship. Most finite element programmes and laminate theory only accept strength and strain to failure as an input parameter. The designer needs to establish a consistent set of data for the analysis.

The critical energy release rates for the three opening modes are G_{Ic}, G_{IIc}, and G_{IIIc}. The critical energy release rate describes the resistance to crack growth in the ply interface.

The ply's thermal expansion coefficients are typically reported as linear coefficients independent of the actual temperature.

α_1 – longitudinal thermal expansion coefficient

α_2 – transverse thermal expansion coefficient, in plane

α_3 – out-of-plane thermal expansion coefficient

Note that the reference temperature giving no thermal stresses in the laminate is roughly the laminate's melting or processing temperature. Due to relaxation processes this reference temperature may change with time.

Swelling coefficients are typically given as the saturation swelling for water. In more general terms swelling is diffusion controlled and saturation is only reached after a certain time. Swelling will also depend on the liquid, which may not always be water.

β_1 – longitudinal swelling coefficient

β_2 – transverse swelling coefficient - in plane

β_3 – transverse swelling coefficient – through thickness

The ply properties are also summarized in Table 1-7.

Table A-2 Examples of test materials and methods for obtaining ply properties

No.	Test material	Recommended test methods	Calculation of ply properties
A	Flat panels: individual plies or laminates made from plies all oriented in the same direction (UD laminate).	Typical standard tests published by ISO and ASTM.	Converting test results to ply properties is straightforward, as described in many test standards.
B	Pipes or rings: unidirectional wound pipes, where all fibres are oriented in the hoop direction.	Some tests are published as standards by ISO or ASTM. Other tests may have to be developed.	The tests usually give good representative ply properties for TCPs made by tape winding. For pipes made by filament winding the results are typically representative of fibres in the hoop direction, but not in the axial direction[+][+].
C	Flat panels: laminates where individual plies are oriented in various directions.	Typical standard tests published by ISO and ASTM. Some tests are published as standards by ISO or ASTM. Other tests may have to be developed.	Ply properties are back-calculated from tests on multidirectional laminates, e.g. cross-plied laminates, provided the properties can be obtained in an unambiguous way (e.g. DNV Laminate Theory Manual, DNV Research, Report No. 91-2052, Rev. 02, K. Lasn, A. Klauson, A.T. Echtermeyer, or FE analysis, see [1.4.5]). Note, depending on the layup, it is not always possible to back-calculate all ply properties.

No.	Test material	Recommended test methods	Calculation of ply properties
D	Actual TCPs or scaled* TCPs. Properties of representative subsections of the laminate may also be measured, if the complete laminate can be built from the representative subsections.	Few tests are published as standards by ISO or ASTM. Other tests may have to be developed.	A combination of all methods described in this Table. See also [4.5] and [4.5.3]
* scaling can be done for the radius and thickness.			
++ axial fibres in a filament-wound pipe are typically wavier and produced with less tension.			

A.4.2 Calculation of ply properties instead of testing

Some properties may be calculated instead of measured.

The equations stated here are based on the assumption that the plies are transversely isotropic. This should be valid in most cases, unless the microstructure of a ply does not represent the symmetry conditions required for an orthotropic ply.

The through-thickness Young's modulus E_3 may be calculated from the in-plane transverse modulus as E_2:

$$E_2 = E_3$$

The through-thickness shear moduli G_{13} and G_{23} may be calculated from the in plane shear modulus G_{12}:

$$G_{12} = G_{13}$$

$$G_{23} = \frac{E_2}{2(1+v_{23})}$$

The trough-thickness Poisson's ratios v_{13} and v_{23} may be estimated from the in-plane Poisson's ratio v_{12} as:

$$v_{12} = v_{13}$$

For most laminates the interface between the plies has somewhat different properties than the ply itself. The interfaces tend to be rich in polymer and are often weaker. In such case, only the simple formula for typical ply/laminate may be used:

Typical ply/laminate	$S_{13} = S_{23}$

Only for a transversely isotropic ply (with no detectable interface), the matrix-dominated strength in the in-plane and through-thickness directions may be set at:

Only for a transversly isotropic ply	$Y_T = Z_T$ $Y_C = Z_C$	$S_{12} = S_{13}$ $S_{23} = \min\{ S_{12}, Y_T \}$

Matrix dominated strains to failure in in plane and through thickness direction may be set equal:

$\zeta_{2T} = \zeta_{3T}$ $\zeta_{2C} = \zeta_{3C}$	$\xi_{12} = \xi_{13}$ $\xi_{23} = \xi_{12}$

The thermal expansion coefficients and swelling coefficients in the in-plane and through-thickness directions may be set at:

$\alpha_2 = \alpha_3$	$\beta_2 = \beta_3$

Micromechanics or multiscale calculations are sometimes used to predict ply properties. These methods shall only be used if they can be confirmed by experimental evidence for the particular material.

A.4.3 Fibre-volume fraction changes

Composite ply properties are very sensitive to the fibre-volume fraction.

Properties may be corrected within an absolute variation of 15% of the fibre-volume fractions, e.g. between 45% and 60%.

The following correction formulas should be used:

Young's Modulus in the fibre direction	$E_1 = E_1^0 \dfrac{v_f}{v_f^0}$
Young's Modulus in the normal to fibre direction	$E_2 = E_2^0 \dfrac{1 - v_f^0}{1 - v_f}$ (*)
Inplane shear modulus	$G_{12} = G_{12}^0 \dfrac{1 - v_f^0}{1 - v_f}$ (*)
Tensile strength in fibre direction	$X_1 = X_1^0 \dfrac{v_f}{v_f^0}$
Compressive strength in fibre direction	$X_T = X_T^0 \dfrac{v_f}{v_f^0}$ if $v_f < v_f^0$ $X_T \approx X_T^0$ if $v_f > v_f^0$
Tensile strength normal to fibres	$Y_T \approx Y_T^0$ (*)
Compressive strength normal to fibres	$Y_C \approx Y_C^0$
Inplane shear strength	$S_{12} \approx S_{12}^0$ (*)
The superscript 0, identifies originally measured data. (*) Should preferably be measured at the maximum fibre content.	

A.5 Nonlinear behaviour

Some material properties may be nonlinear.

Nonlinearity may be elastic, viscoelastic or plastic. The linear limit may also not be clearly defined. The stress strain curve in Figure A-3 shows an example of a stress strain curve with no easily identifiable linear limit.
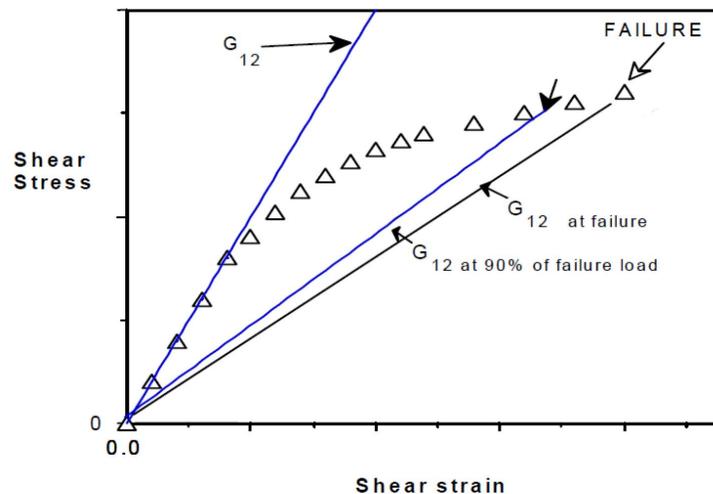
Figure A-3 Example of a nonlinear shear stress strain curve, [from DNVGL-ST-C501]

The best way to distinguish between elastic and plastic behaviour is to repeatedly measure loading and unloading stress strain curves, gradually increasing the maximum load. When the unloading curve no longer follows the loading curve, plasticity or viscoelasticity sets in. This transition can be defined as the yield point for analysis purposes. Other approaches may be used if suitable for the analysis.

As a simple approach, the yield strength and yield strain may be taken as the point where the plastic strain is more than 20% of the linear elastic strain.

The elastic modulus that should be chosen for analysis purposes needs to be determined based on the requirements of the analysis. Choosing values representative of the stresses or strain levels used in the actual TCP component should be a suitable choice.

A.6 Cyclic fatigue properties – for dynamic thermoplastic composite pipes

A.6.1 General

Cyclic fatigue properties shall be tested and documented for the design of each component of a dynamic TCP. Fatigue analysis in this standard is based on S-N curves (Wöhler curves). This section describes how the S-N curves should be obtained for the materials used in the pipe.

A.6.2 Obtaining characteristic S-N curves

Characteristic S-N curves shall be used in all design calculations.

Generally, all cyclic fatigue data for the TCP laminate, liner and cover shall be measured in load control,

If it can be shown that the TCP laminate is only exposed to displacement-controlled conditions, S-N data may be measured in displacement control.

Liner and cover data may be measured in displacement control if it can be demonstrated that the liner only follows the TCP laminate and is not load bearing.

The liner and cover are typically load-bearing components at the end fitting, especially for interlaminar shear. In that case S-N curves shall be measured in load control.

The R-ratio should be kept constant during one test series. The R-ratio is defined as:

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$$R = \frac{\sigma_{min}}{\sigma_{max}}$$

where σ_{min} and σ_{max} are the minimum and maximum stresses during a fatigue cycle respectively.

If S-N curves are measured in load control, the displacement versus the number of cycles shall be recorded periodically. It is sufficient to measure displacement infrequently as long as the change in the trend and behaviour of the displacement according to the number of cycles is clear.

The test data should be fairly evenly distributed over the measurement range in the double logarithmic plot as shown schematically in Figure A-4.

A regression line can only be obtained if all specimens fail due to the same failure mechanism.
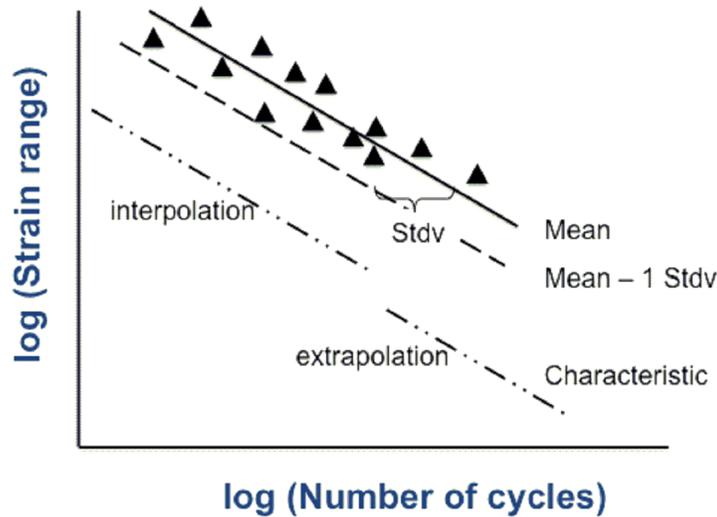
Figure A-4 Schematic S-N curve showing the data, mean curve and characteristic curves for interpolation and extrapolation

Polymer S-N curves are best presented as log stress versus log number of cycles.

TCP composite S-N curves are best presented as log strain versus log number of cycles because that means the data are independent of the fibre-volume fraction. The strain plotted in the S-N curve is the initial strain when the test starts.

If the material shows a significant increase in strain with a number of cycles at the same stress amplitude, the effect shall be reported. The change in elastic properties depending on the number of cycles may have to be taken account of in the design.

A mean curve of the fatigue data shall be obtained by linear regression analysis for:

S-N curve in stress format	S-N curve in strain format
$\log N = \log N_0 - \dfrac{1}{\alpha} \log \Delta\sigma_{mean}$	$\log N = \log N_0 - \dfrac{1}{\alpha} \log \Delta\varepsilon_{mean}$

where N is the number of cycles, $\Delta\sigma$ and $\Delta\varepsilon$ are the stress and strain range respectively and $^1/_\alpha$ describes the slope of the curve.

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The residuals shall be minimized for the dependent variable *log N*, and the standard deviation $\hat{\sigma}_{fat}$ of *log N* shall be calculated. The procedure is described in Neter et al, see [1.4.5].
More commonly the above equations are written as:

S-N curve in stress format	S-N curve in strain format
$\log \Delta\sigma_{mean} = \log \Delta\sigma_0 - \alpha \log \Delta N$	$\log \Delta\varepsilon_{mean} = \log \Delta\varepsilon_0 - \alpha \log \Delta N$
where	where
$\log \Delta\sigma_0 = \alpha \log N_0$	$\log \Delta\varepsilon_0 = \alpha \log N_0$

The characteristic S-N curve shall be calculated according to DNVGL-ST-C501 with 97.5% tolerance and 95% confidence.

S-N curve in stress format	S-N curve in strain format
$\log \Delta\sigma_{char} = \log \Delta\sigma_0 - \kappa\alpha\hat{\sigma}_{fat} - \alpha \log \Delta N$	$\log \Delta\varepsilon_{mean} = \log \Delta\varepsilon_0 - \kappa\alpha\hat{\sigma}_{fat} - \alpha \log \Delta N$

where $\hat{\sigma}_{fat}$ is the standard deviation of the S-N curve as described above and κ is given in Table A-3 . κ depends on the number of tests and whether the characteristic curve is interpolated or extrapolated.

Table A-3 Shift factor κ for characteristic S-N curve, from DNVGL-ST-C501 [4.3.11]

Number of tests	κ	
	Interpolation	*Extrapolation*
10	3.9	4.7
15	3.4	4.0
20	3.1	3.7
50	2.6	3.0
100	2.4	2.6
infinite	2.0	2.0

The strain rate should be kept constant during a test series. Test frequencies should be low enough to prevent internal friction from warming up the specimen. The temperature should not increase by more than 5-10 °C. No phase transformations should happen due to the temperature increase. The test temperature should be monitored during testing.

Note, when using an anti-buckling device under compressive testing, care should be taken to ensure that the anti-buckling device does not carry any loads that create longer life times.

Sometimes the S-N curve is not linear in the log-log presentation described above. In that case, an equivalent statistical approach shall be used for the data analysis, taking account of the nonlinearity.

A.6.3 Number of cycles to test - extrapolation of data

S-N curves shall be measured up to the expected number of cycles $N_{expected}$ during the fatigue life of the TCP, if the number of cycles $N \leq 10^6$.

If more than 10^6 cycles are expected, data may be extrapolated. The characteristic curve shall be calculated using the κ factor for extrapolation, as given in Table A-3.

Data shall only be extrapolated if no change to the failure mechanisms is expected. It should be substantiated that the failure mechanism does not change.

Extrapolation can only be done up to ½ of the range of the measured number of cycles on a logarithmic scale. At least one test for establishing the S-N curve shall fail at or beyond the maximum number of test cycles N_{test}^{max} for the fatigue experiment:

$$\log N_{test}^{max} \geq \frac{\log N_{expected} + 0.5 \log N_{test}^{min}}{1.5}$$

$N_{expected}$ is the expected number of cycles without applying safety factors.

A second test should fail at or beyond $0.5 N_{test}^{max}$.

The remaining test data should be fairly evenly distributed over the measurement range in the double logarithmic plot as shown schematically in Figure A-4.

Run out data may be used to calculate the slope of the S-N curve, but shall not be used to calculate the standard deviation. Run out data shall always have more test cycles than 80% of the tested and failed samples.

The minimum number of cycles for fatigue testing N_{test}^{min} shall not be less than 100 and the material should not yield at the highest test loads.

If the minimum number of test cycles is chosen to be 100, the maximum number of test cycles should at least be as shown in Figure A-5 .
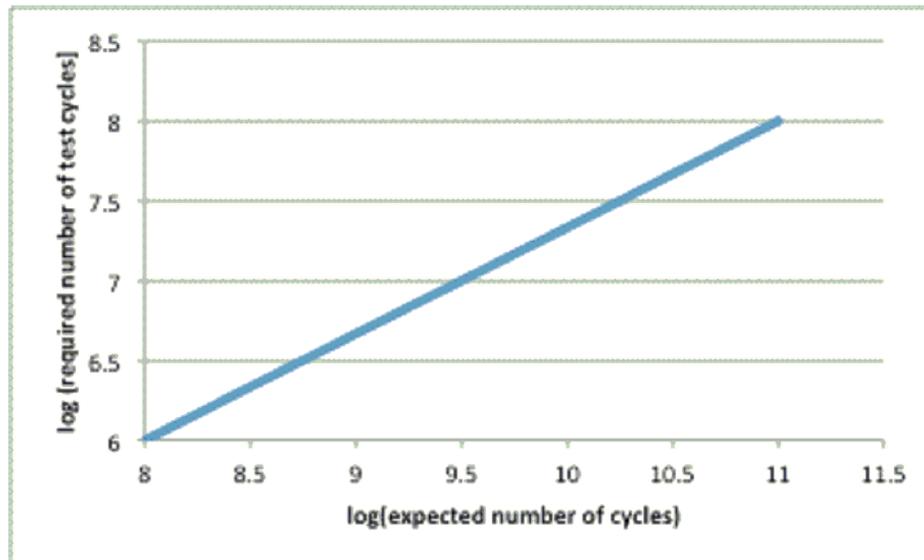
Figure A-5 Required test cycles versus expected number of cycles for a minimum of 100 test cycles (example)

## A.6.4 Fatigue at different R-ratios

Ideally, S-N curves should be established for three R-ratios: R = 0.1 (tension-tension), R = -1 (tension-compression), R = 10 (compression-compression).

If only one S-N curve can be measured and the material is exposed to various loading conditions, it shall be measured at R = -1.

If the material is for used less than 10 cycles in compression, it is sufficient to test at R = 0.1. Similar R-ratios, such as R = 0 or R = 0.05 may also be chosen.

If the material is never used in tension, it is sufficient to test at R = 10. Similar R-ratios may also be chosen.

A constant lifetime diagram (Goodman or Hall diagram as e.g. shown in Figure A-6) shall be constructed from the test data, allowing of fatigue lifetimes to be predicted at various combinations of strain ranges and means. The diagram shall be based on characteristic S-N curves. The tensile and compressive strength used in the diagram shall also be characteristic values. An example of a constant lifetime diagram is given in Figure A-6.
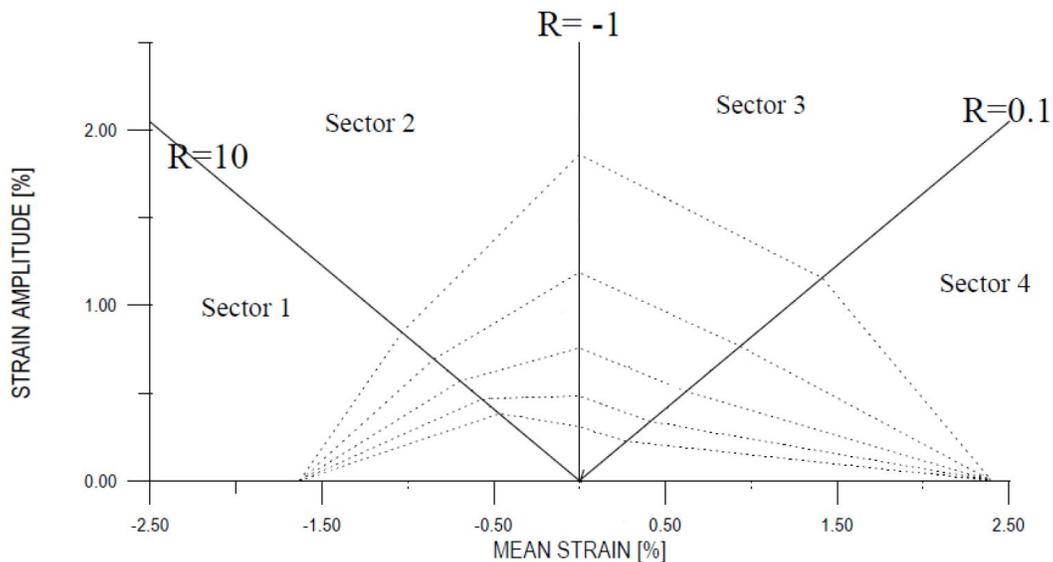
Figure A-6 Constant lifetime diagram (from DNVGL-ST-C501)

Polymers often show a lot of much creep during fatigue testing and can only be tested for R = -1.

A.7 Stress rupture

A.7.1 General

Stress rupture properties shall be documented for the design of each TCP component. In this standard resistance to long-term permanent loads is based on stress rupture curves. This subsection describes how the curves should be obtained for the materials used in the pipe.

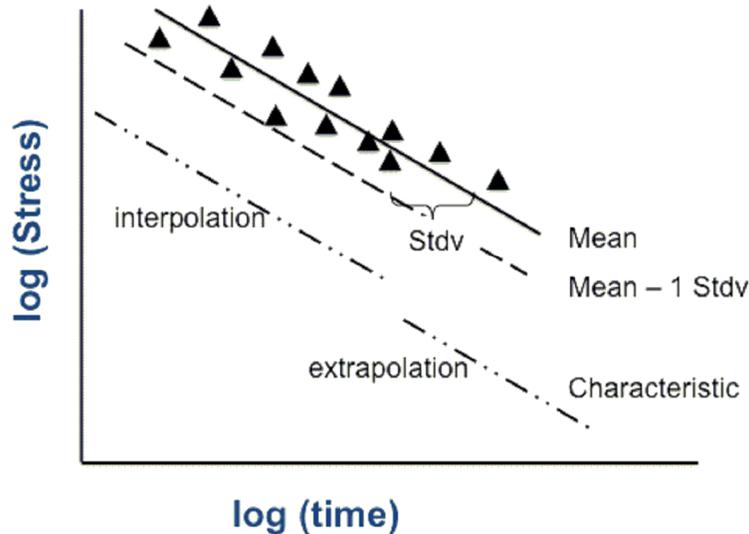## A.7.2 Obtaining characteristic stress rupture curves

Characteristic stress rupture curves shall be used in all design calculations.

All stress rupture data for the TCP materials shall be measured in load control.

The data shall be presented as log stress versus log time. The test data should be fairly evenly distributed over the measurement range in the double logarithmic plot as shown schematically in Figure A-7.

A regression line can only be obtained if all specimens fail with the same failure mechanism.

When measuring stress rupture curves for $\pm\alpha$ laminates, the data shall in addition be presented as the log initial strain versus log time. The initial strain is the strain at time 0 when the testing stress has been reached and the constant stress is applied over time.

Figure A-7 Schematic stress rupture curve showing the data, mean curve and characteristic curves for interpolation and extrapolation

The material's creep characteristics omay be tested while performing the stress rupture tests.

A mean curve of the stress rupture data shall be obtained by linear regression analysis for:

$$\log t = \log t_0 - \frac{1}{\beta}\log \sigma_{mean}$$

where t is the time, σ is the applied stress and $1/\beta$ describes the slope of the curve.

The residuals shall be minimized for the dependent variable *log t*, and the standard deviation $\hat{\sigma}_{stressrupt}$ of *log t* shall be calculated. The procedure is described in Neter et al, see [1.4.5].

More commonly the above equation is written as:

$$\log \sigma_{mean} = \log \sigma_0 - \beta \log t$$

where

$$\log \sigma_0 = \beta \log t$$

The characteristic stress rupture curve shall be calculated according to DNVGL-ST-C501 with 97.5% tolerance and 95% confidence.

$$\log \sigma_{char} = \log \sigma_0 - \kappa\beta\hat{\sigma}_{stressrupt} - \beta \log t$$

where $\hat{\sigma}_{stressrupt}$ is the standard deviation of the stress rupture curve as described above and κ is given in Table A-3. κ depends on the number of tests and whether the characteristic curve is interpolated or extrapolated.

Note, when using an anti-buckling device under compressive testing, care should be taken to ensure that the anti-buckling device does not carry any loads that create longer life-times.

Sometimes the stress rupture curve is not linear in the log-log presentation described above. In that case an equivalent statistical approach shall be used for the data analysis, taking account of the nonlinearity.

A.7.3 Testing time - extrapolation of data

Stress rupture curves shall be measured up to the expected time of application t_{applic} of the permanent load on the TCP if the time is less than 1,000 hours.

If more than 1,000 hours of permanent load are expected, testing should be done at least up to 1,000 hours. For longer times, data may be extrapolated. The characteristic curve shall be calculated using the κ factor for extrapolation, as given in Table A-3.

Data shall only be extrapolated if no change in failure mechanisms is expected. It should be substantiated that the failure mechanism will not change.

Extrapolation can only be done up to ½ of the range of the measured time on a logarithmic scale. At least one test for establishing the stress rupture curve shall fail at or beyond the maximum test time t_{test}^{max} for the stress rupture experiment:

$$\log t_{test}^{max} \geq \frac{\log t_{applic} + 0.5 \log t_{test}^{min}}{1.5}$$

t_{applic} is the time when the static loads are applied without safety factors.

A second test should fayl at or beyond $0.5 \log t_{test}^{max}$.

The remaining test data should be fairly evenly distributed over the measurement range in the double logarithmic plot as shown schematically in Figure A-7.

Run out data may be used to calculate the slope of the stress rupture curve, but shall not be used to calculate the standard deviation. Run out data shall always have test times longer than 80% of the tested and failed samples.

The minimum test time t_{test}^{min} shall be at least 24 hours and the material should not yield at the highest test loads.

If the minimum test time t_{test}^{min} is chosen to be 24 hours, the maximum test time shall at least be as shown in Figure A-8.
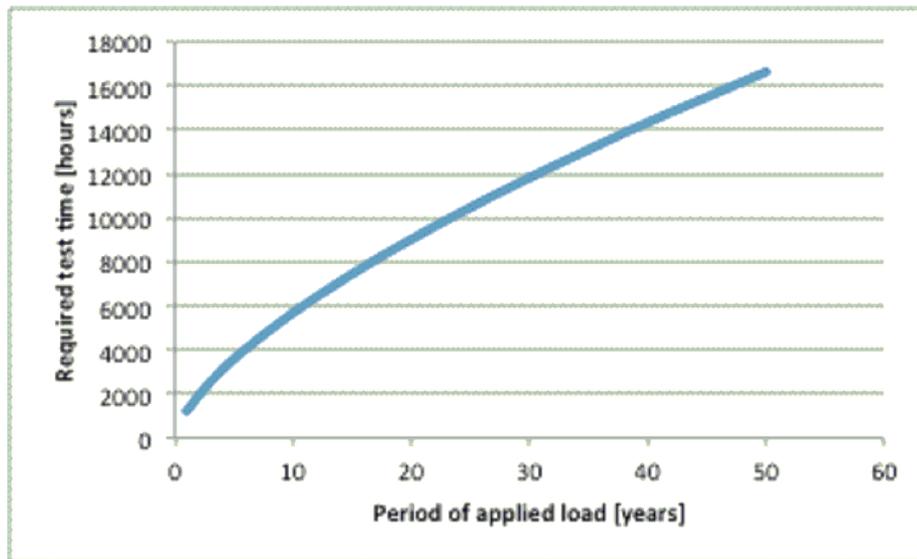
Figure A-8 Required test time versus applied load period for a minimum test time of 24 hours (example)

A.8 The effect of ultraviolet radiation

It shall be demonstrated that the external pipe surface is UV resistant within the design life.

Testing may be done on the TCP cover or the actual TCP. The cover's sample thickness should not exceed the cover's real thickness.

Accelerated experiments carried out in accordance with ISO 4892-1 may be used. Method A of ISO 4892-2 specifies the relative spectral irradiance of Xenon-Arc lamps, fitted with filters, to be used as the light source.

Sufficient tensile properties of the cover after exposure to the actual surface energy in J/m^2 should be demonstrated. The correlation between accelerated and natural exposure shall be demonstrated.

Service experience with a product may also be used to demonstrate UV resistance, provided the period of experience is at least as 90% of the product's lifetime.

A.9 Permeability and diffusion testing

The test methods given in this section are suggestions and only valid for limited fluids and specimens:

— ASTM D5886
— ISO 6179
— ASTM D1434
— ISO 8308.

Other test methods or modifications of existing methods should be used if relevant for TCPs. The validity of the test methods should be evaluated in each case.

A.10 Blistering resistance testing

A.10.1 General

The test methods given in this section are suggestions. Other test methods may be used. The validity of the test methods should be evaluated fin each case.

A.10.2 Polymer testing

Thermoplastic polymers, such as the liner and cover, can be tested according to Norsok M710, ISO 23936-1 or API 17J. These standards require repeated pressurizing and de-pressurizing. If the thermoplastic material does not show any weakening after five cycles, the testing may be stopped.

A.10.3 Composite testing

The fibre-reinforced composite in the TCP should be tested using the principles used for the polymer testing.

A.10.4 Interface testing

If the interfaces between the laminate and liner or cover are weak (see [5.18]), the interface's resistance to blistering shall be measured. Specimens shall be exposed to a relevant gas under high pressure. Calculations shall be made to ensure that the gas diffuses from the surface across the interfaces to be tested. Once the samples have been exposed for long enough to the gas, a test programme similar to the one for polymers shall be conducted.

A.10.5 Crushing ring test

The testing can be done similar to the procedures given in ASTM D2412. The standards main emphasis is on measuring elastic properties and stiffness. Here the resistance to delamination/debonding or the strength of the ring shall be determined. The test should therefore be run until damage develops and the damage should be monitored and recorded.

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CHANGES – HISTORIC

There are currently no historical changes for this document.

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