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Petroleum and natural gas industries — Design and operation of subsea production systems —

Part 11: Flexible pipe systems for subsea and marine applications

Industries du pétrole et du gaz naturel — Conception et exploitation des systèmes de production immergés —

Partie 11: Systèmes de canalisations flexibles pour applications sous-marines et en milieu marin

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Case postale 56 • CH-1211 Geneva 20
Tel. + 41 22 749 01 11
Fax + 41 22 749 09 47
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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

ISO 13628-11 was prepared by Technical Committee ISO/TC 67, *Materials, equipment and offshore structures for petroleum, petrochemical and natural gas industries*, Subcommittee SC 4, *Drilling and production equipment*.

This first edition of ISO 13628-11 cancels and replaces ISO 10420:1994, which has been technically revised.

ISO 13628 consists of the following parts, under the general title *Petroleum and natural gas industries — Design and operation of subsea production systems*:

— *Part 1: General requirements and recommendations*

— *Part 2: Unbonded flexible pipe systems for subsea and marine applications*

— *Part 3: Through flowline (TFL) systems*

— *Part 4: Subsea wellhead and tree equipment*

— *Part 5: Subsea umbilicals*

— *Part 6: Subsea production control systems*

— *Part 7: Completion/workover riser systems*

— *Part 8: Remotely Operated Vehicle (ROV) interfaces on subsea production systems*

— *Part 9: Remotely Operated Tool (ROT) intervention systems*

— *Part 10: Specification for bonded flexible pipe*

— *Part 11: Flexible pipe systems for subsea and marine applications*

A part 12 dealing with dynamic production risers, a part 13 dealing with remotely operated tools and interfaces on subsea production systems and a part 15 dealing with subsea structures and manifolds are under preparation.

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Introduction

This part of ISO 13628 is based on API RP 17B and on matching ISO procedures and API procedures. This ISO standard has been technically updated and revised to cater for the needs of the international oil and natural gas industries. This part of ISO 13628 provides information complementary to ISO 13628-2 and ISO 13628-10.

Users of this International Standard should be aware that further or differing requirements can be needed for individual applications. This International Standard is not intended to inhibit a vendor from offering, or the purchaser from accepting, alternative equipment or engineering solutions for the individual application. This can be particularly applicable where there is innovative or developing technology. Where an alternative is offered, the vendor should identify any variations from this International Standard and provide details.

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Petroleum and natural gas industries — Design and operation of subsea production systems —

Part 11: Flexible pipe systems for subsea and marine applications

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1 Scope

This part of ISO 13628 provides guidelines for the design, analysis, manufacture, testing, installation and operation of flexible pipes and flexible pipe systems for onshore, subsea and marine applications. This part of ISO 13628 supplements ISO 13628-2 and ISO 13628-10, which specify minimum requirements for the design, material selection, manufacture, testing, marking and packaging of unbonded and bonded flexible pipe, respectively.

This part of ISO 13628 applies to flexible pipe assemblies, consisting of segments of flexible pipe body with end fittings attached to both ends. Both bonded and unbonded pipe types are covered. In addition, this part of ISO 13628 applies to flexible pipe systems, including ancillary components.

The applications covered by this part of ISO 13628 are sweet- and sour-service production, including export and injection applications. This part of ISO 13628 applies to both static and dynamic flexible pipe systems used as flowlines, risers and jumpers. This part of ISO 13628 does cover, in general terms, the use of flexible pipes for offshore loading systems.

NOTE Refer also to Reference [30] for offshore loading systems.

This part of ISO 13628 does not cover flexible pipes for use in choke and kill lines or umbilical and control lines.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 13628-2:2006, *Petroleum and natural gas industries — Design and operation of subsea production systems — Part 2: Unbonded flexible pipe systems for subsea and marine applications*

ISO 13628-3:2000, *Petroleum and natural gas industries — Design and operation of subsea production systems — Part 3: Through flowline (TFL) systems*

ISO 13628-10:2005, *Petroleum and natural gas industries — Design and operation of subsea production systems — Part 10: Specification for bonded flexible pipe*

NACE TM0177, *Laboratory testing of metals for resistance to sulfide stress cracking and stress corrosion cracking in H_2S environments*

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3 Terms, abbreviated terms, definitions and symbols

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

3.1 Terms and definitions

3.1.1
annulus
space between two concentric plastic sheaths of an unbonded flexible pipe cross-section

3.1.2
Arrhenius plot
log-linear scale used to plot service life against the inverse of temperature for some polymer materials

3.1.3
basket
device used for storage and transport of flexible pipe

NOTE All pipes are laid freely into the basket.

3.1.4
bird-caging
buckling of the tensile-armour wires, usually caused by extreme axial compression, which results in significant radial deformation

3.1.5
buoyancy module
buoys used in significant numbers at discrete points over a section of riser to achieve wave-shape riser configurations

NOTE See 4.4.6.

3.1.6
carousel
device used for storage and transport of very long lengths of flexible pipe and which rotates about a vertical axis

NOTE Pipe is wound under tension around the centre hub.

3.1.7
Chinese fingers
woven steel wire or fabric sleeve that can be installed over a flexible pipe and drawn tight to grip it for support or applying tension to the pipe

3.1.8
end fitting
termination in a flexible pipe

3.1.9
flexible pipe system
fluid conveyance system for which the flexible pipe(s) is/are the primary component and which includes ancillary components attached directly or indirectly to the pipe

3.1.10
free-hanging catenary
riser configuration that spans the water column in a catenary shape modified by the bending stiffness of the riser

NOTE See Figure 4.

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3.1.11
integrated service umbilical
ISU™[1)]
structure in which the inner core is a standard flexible pipe construction

NOTE 1 Umbilical components are wound around the core pipe and covered with a protective outer sheath (see 4.3.6).

NOTE 2 ISU is a trademark of Coflexip Stena Offshore.

3.1.12
lazy wave
free-hanging catenary modified by a section with distributed buoyancy modules

NOTE See Figure 4.

3.1.13
lazy-S
free-hanging catenary modified by a section with concentrated buoyancy modules

NOTE See Figure 4.

3.1.14
multibore
multiple flexible pipes or umbilicals contained in a single construction with an outer sheath extruded over the bundle

NOTE See 4.3.7.

3.1.15
multiple configuration
riser system with more than one riser connected at a mid-depth location

3.1.16
ovalization
out-of-roundness of the pipe, calculated as follows:

$$\frac{D_{\max} - D_{\min}}{D_{\max} + D_{\min}}$$

where $D_{\max}$ and $D_{\min}$ are maximum and minimum pipe outside diameter, respectively.

3.1.17
piggy back
attachment of two parallel and adjacent independent pipes, rigid or flexible, over a significant length

3.1.18
prototype test
test to establish or verify a principal performance characteristic for a particular pipe design, which may be a new or established design

3.1.19
rapid decompression
sudden depressurization of a system during which gas in the pipe expands rapidly and can cause blistering or collapse of the internal pressure sheath or other gas-saturated layers

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1) ISU™ is an example of a suitable product available commercially. This information is given for the convenience of users of this part of ISO 13628 and does not constitute an endorsement by ISO of this product.

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3.1.20
reel
large-diameter structure used for storage of long lengths of flexible pipe, which rotates about a horizontal axis

3.1.21
riser base
structure positioned on the seabed, used to provide a structural and pressure-tight connection between a flexible riser and a flowline

NOTE 1 See 4.4.8.

NOTE 2 It may be a PLET or a PLEM.

3.1.22
riser hang-off
structure for supporting a riser at the connection to a platform

EXAMPLE Jacket, semi-sub, tanker, etc.

3.1.23
steep wave
lazy wave with a touchdown point fixed to the seabed

NOTE See Figure 4.

3.1.24
steep-S
lazy-S with a touchdown point fixed to the seabed

NOTE See Figure 4.

3.1.25
subsea buoy
concentrated buoyancy system

NOTE This system generally consists of steel or syntactic foam tanks, as used in S-type riser configurations (4.4.5). See also buoyancy module (3.1.4).

3.1.26
tensioner
mechanical device used to support or apply tension to a pipe during installation

3.1.27
umbilical
bundle of helically or sinusoidally wound small-diameter chemical, hydraulic, and electrical conductors for power and control systems

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3.2 Symbols and abbreviated terms

The following symbols and abbreviated terms are used in this document.

CPE chlorinated polyethylene

CR polychloroprene

DA dynamic application

DBS dibutyl sebacate

DOF degrees of freedom

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EPDM ethylene propylenediene monomer rubber

FAT factory acceptance test

FPS floating production system

FPSO floating production storage and offloading

HDPE high density polyethylene

HIC hydrogen-induced cracking

HNBR hydrogenated nitrile rubber

ID inside diameter

ISU integrated service umbilical

MBR minimum bend radius

MDPE medium density polyethylene

MWL mean water level

NBR nitrile butadiene rubber

NR natural rubber

OD outer diameter

PA polyamide

PE polyethylene

PP polypropylene

PLEM pipeline end manifold

PU polyurethane

PVC polyvinyl chloride

PVDF polyvinylidene fluoride

REF riser end fitting

ROV remotely operated vehicle

SA static application

SBR storage bend radius

SSC sulfide stress cracking

TFL through flowline

UV ultraviolet

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VIV vortex-induced vibration

XLPE cross-linked polyethylene

C_d hydrodynamic drag coefficient

C_m hydrodynamic inertia coefficient

D_{max} maximum pipe outside diameter

D_{min} minimum pipe outside diameter

σ_u material ultimate stress

σ_y material yield stress

4 System, pipe, and component description

4.1 Introduction

4.1.1 General

Clause 4 provides a general overview of flexible pipe systems, pipe cross-section designs and ancillary components. In addition, Clause 4 gives an overview of all aspects of flexible pipe technology and identifies the clauses and subclauses of this part of ISO 13628 and of ISO 13628-2:2006 and ISO 13628-10:2005 to be consulted for relevant issues.

In general, flexible pipe is a custom-built product that can be designed and manufactured in a variety of methods. It is not the intent of this part of ISO 13628 to discourage novel or new developments in flexible pipe. On the contrary, it is recognized that a variety of designs and methods of analysis are possible. For this reason, some topics are presented in general terms to provide guidance to the user while still leaving open the possibility of using alternative approaches.

The reader should be aware that flexible-pipe technology (concepts, design and analysis methodologies and criteria, components manufacturing and testing, operational roles and demands, maintenance and inspection, etc.) is in a state of rapid and continuing evolution. Potential users shall, therefore, apply care in their application of the recommendations within this part of ISO 13628.

4.1.2 Recommended practice and specification overview

4.1.2.1 This part of ISO 13628 provides the current best practice for design and procurement of flexible pipe systems and gives guidance on the implementation of the specification for standard flexible-pipe products. In addition, the recommended practice shows guidelines on the qualification of prototype products.

4.1.2.2 All aspects of flexible-pipe technology, from functional definition to installation, are addressed in either this part of ISO 13628 or in ISO 13628-2 and ISO 13628-10. Some issues are addressed in all three documents. The various stages in the procurement and use of flexible pipes are defined in Figure 1.

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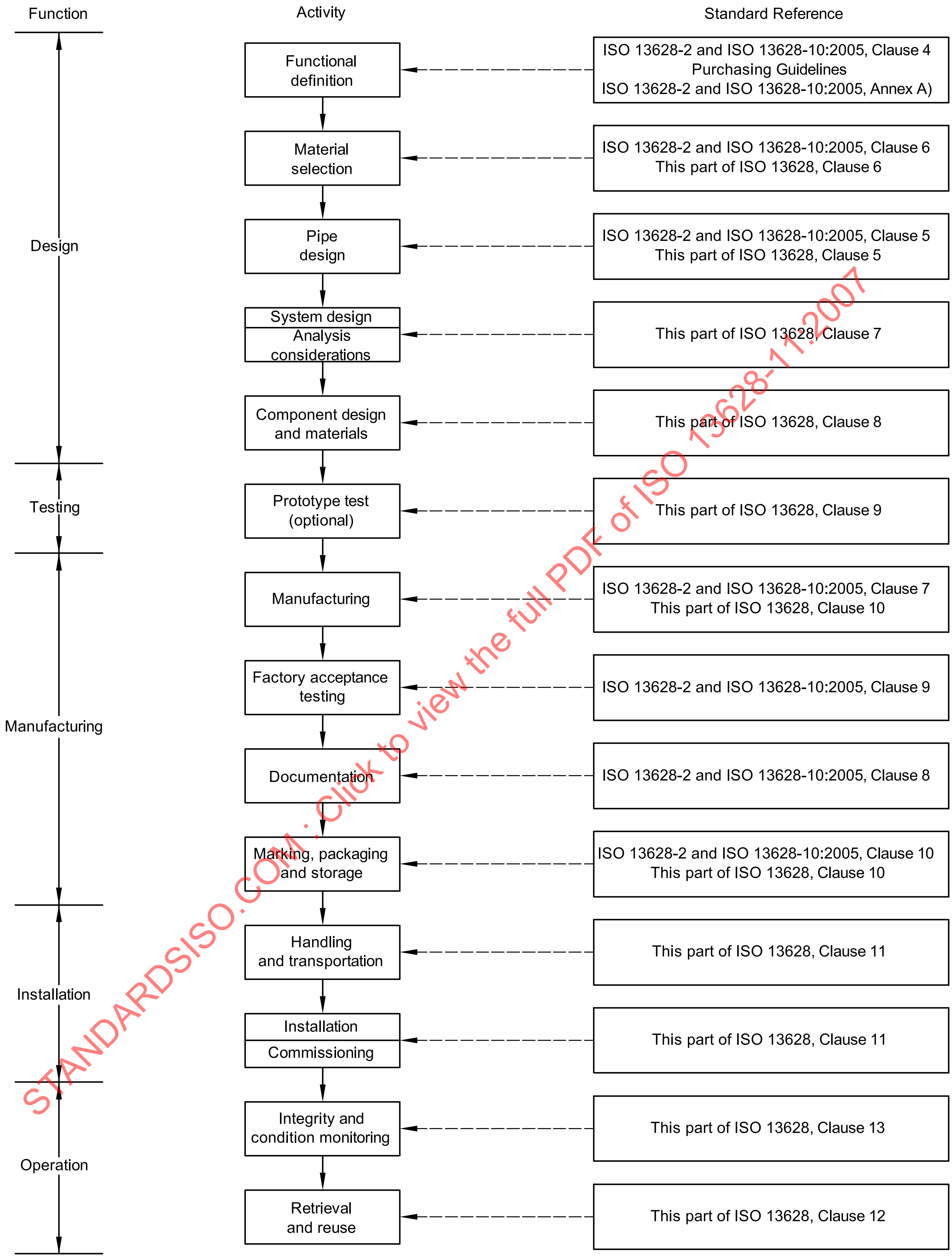

Figure 1 — Flexible pipe overview

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4.2 Flexible pipe systems

4.2.1 Definition of system

4.2.1.1 The flexible pipe system is an important part of the overall field development and can influence or be influenced by the design and specification of other components in the development. The definition of the flexible pipe system should therefore commence at the initiation of the overall project as development strategies evolve. Aspects of the development strategy that can influence the flexible pipe system include field layout (template versus satellite wells) and production-vessel type (platform, tanker including turret location, semi-sub, etc.). Current limitations in flexible-pipe technology, such as application range and manufacturing capability, can also fundamentally influence potential overall field development options.

4.2.1.2 It is necessary to address the flexible pipe system and the flexible pipe or pipes within that system. It is necessary to consider the relevant parameters, as well as the interactions between the pipe design and the system design. Critical parameters that can affect the pipe design should be identified early in the process and can include the following:

a) severe internal conditions, such as high H_2S content (sour service);

b) extreme external environmental conditions;

c) difficult installation conditions (such as extreme environment);

d) frequent, cyclic, large-amplitude pressure and temperature fluctuations;

e) large vessel offsets.

4.2.1.3 To define accurately all relevant parameters, interaction between the purchaser and manufacturer is required at an early stage in the project. An important aspect of this is the identification of critical system issues, such as interfaces. See 7.6 for potentially critical interfaces that should be considered at project commencement.

4.2.1.4 ISO 13628-2 and ISO 13628-10:2005, Annex A, provide purchasing guidelines, which may be used in the definition of the flexible pipe system and which address all aspects from general design parameters to detailed flowline- and riser-specific requirements.

4.2.2 Applications

4.2.2.1 General

4.2.2.1.1 Flexible pipe for offshore and onshore applications is grouped into either a static or dynamic category (Figures 2 and 3). It is used for a multitude of functions, including the following:

a) production: oil, gas, condensate, water;

b) injection: water, gas, downhole chemicals;

c) export: semi-processed oil and gas;

d) services: wellhead chemicals, control fluids.

4.2.2.1.2 The static and dynamic categories place different physical demands on the pipe. While both require long life, mechanical strength, internal and external damage resistance and minimal maintenance, dynamic service pipes also require pliancy and high fatigue resistance.

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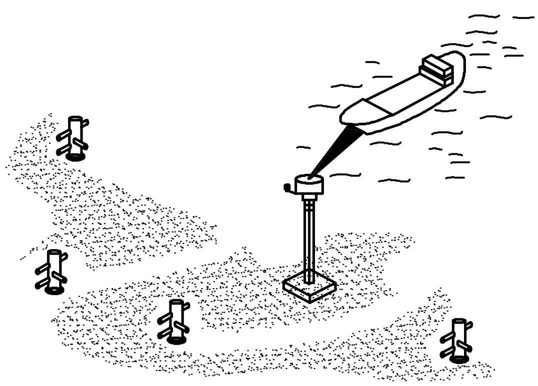
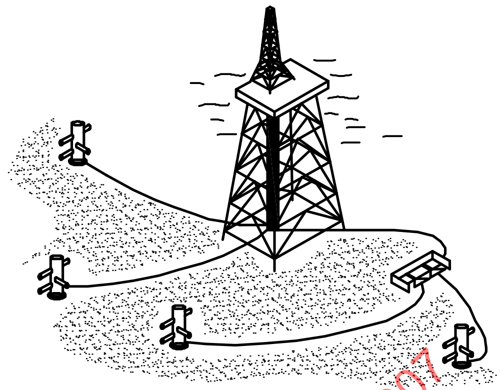
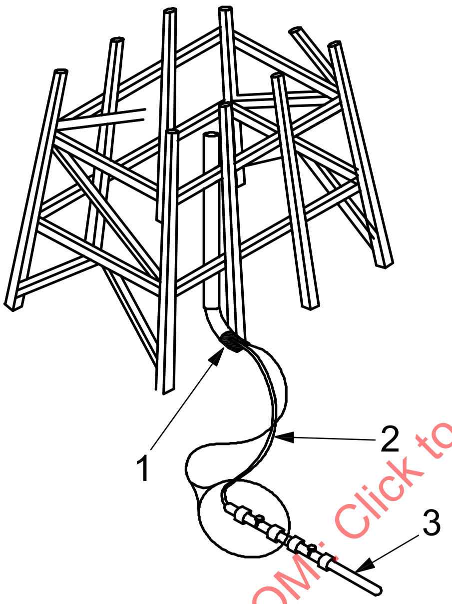


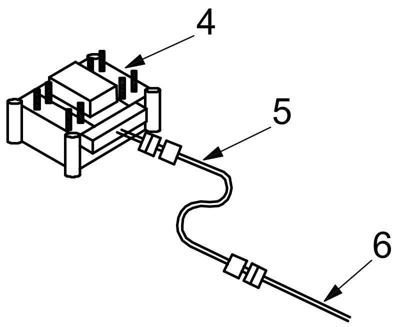
a) **Early field production scheme**



b) **Flowlines repositioned for mature field production scheme**



c) **Flexible pipe connected to a J-tube**



d) **Flexible pipe connected to the manifold**

Key

1 J-tube
2 flexible pipe
3 rigid pipe
4 manifold
5 flexible pipe spool piece
6 rigid steel flowline

Figure 2 — Examples of static applications for flexible pipe

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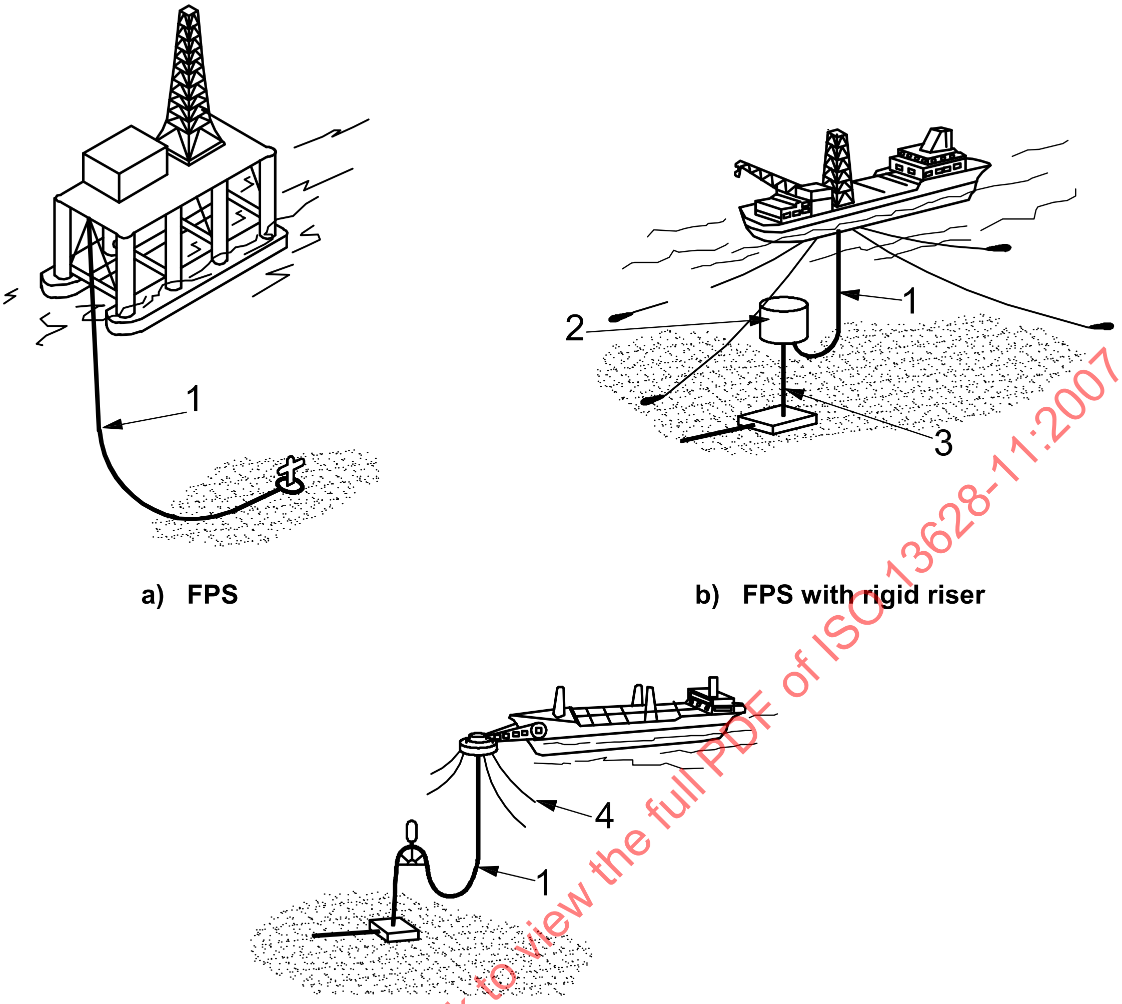

a) **FPS**

b) **FPS with rigid riser**

c) **Floating tanker/terminal mooring**

Key

1 flexible riser

2 subsea buoy

3 rigid riser

4 anchor chain

Figure 3 — Examples of dynamic applications for flexible pipe

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4.2.2.2 Static applications

4.2.2.2.1 The use of flexible pipe for static applications is primarily for flowline and fixed jacket-riser service. Flexible pipe is used in these applications to simplify design or installation procedures, or for its inherent insulation or corrosion-resistant properties. In addition, reduction of installation and end-connection loads and moments may be achieved using flexible pipe. Examples of where the use of flexible pipe results in simplified flowline design or installation include the following (see Figure 2):

a) subsea flowline end connections where expensive or difficult operations, such as exact orientation measurements for spool pieces or the use of large alignment equipment to reposition the flowline, can be eliminated;

b) situations involving gross movements and damage to flowlines because of mudslides can be reduced through the use of slack sections of flexible pipe;

c) applications in which field hardware and flowline location change with the field's production characteristics, which can necessitate the recovery and reuse of the flowlines;

d) applications with uneven seabed to avoid seabed preparation;

e) in deepwater or severe environment applications, where flexible pipe installation is economically attractive relative to rigid pipe installation.

NOTE Instead of mobilizing an expensive pipe-laying spread, it is often preferable to use flexible pipe installed from a dynamically positioned vessel.

4.2.2.2.2 Flexible pipe flowlines generally range in internal diameter from 0,05 m to 0,5 m (2 in to 20 in) although some low-pressure, bonded flexible pipes, such as oil suction and discharge hoses, have internal diameters up to 0,91 m (36 in). Section lengths are limited by transport capabilities and diameter is limited only by current manufacturing capability.

4.2.2.2.3 The functional requirements of a flexible-pipe flowline are generally the same as for a steel-pipe flowline. Significant dynamic loading or motions are generally not experienced, so the flexibility properties of flexible pipe simplify the project transport and installation phases.

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4.2.2.3 Dynamic applications

4.2.2.3.1 Dynamic applications use flexible pipe between supply and delivery points if there is relative movement between these two points while in service. These types of applications usually involve an offshore floating production facility or terminal connected to another floating facility, fixed structure or fixed base (Figure 3). Examples of dynamic applications include the following:

a) flexible-pipe risers for offshore loading systems;

b) flexible-pipe riser connections between floating production facilities and subsea equipment.

4.2.2.3.2 Figure 4 illustrates schematics of the riser configurations typically used. In general, the critical sections in the riser configurations are at the top (or bottom), where there are high tensile forces (and large curvatures); at the sag bend, where there is large curvature (at low tension); and at the hog of a wave buoyancy section, where there is large curvature (at low tension).

4.2.2.3.3 The present dynamic applications of flexible pipes have only been for the production phase. However, with the advent of downhole motors, flexibles may also be used as drilling risers, as described by FPS 2000 [23].

4.2.2.3.4 In addition to riser systems that use flexible pipe throughout, systems that combine flexible pipe and rigid pipe in the flow path have been used. Described as hybrid riser systems, they typically use a lower rigid-riser section (such as a free-standing riser) and an upper flexible-pipe section (jumper line).

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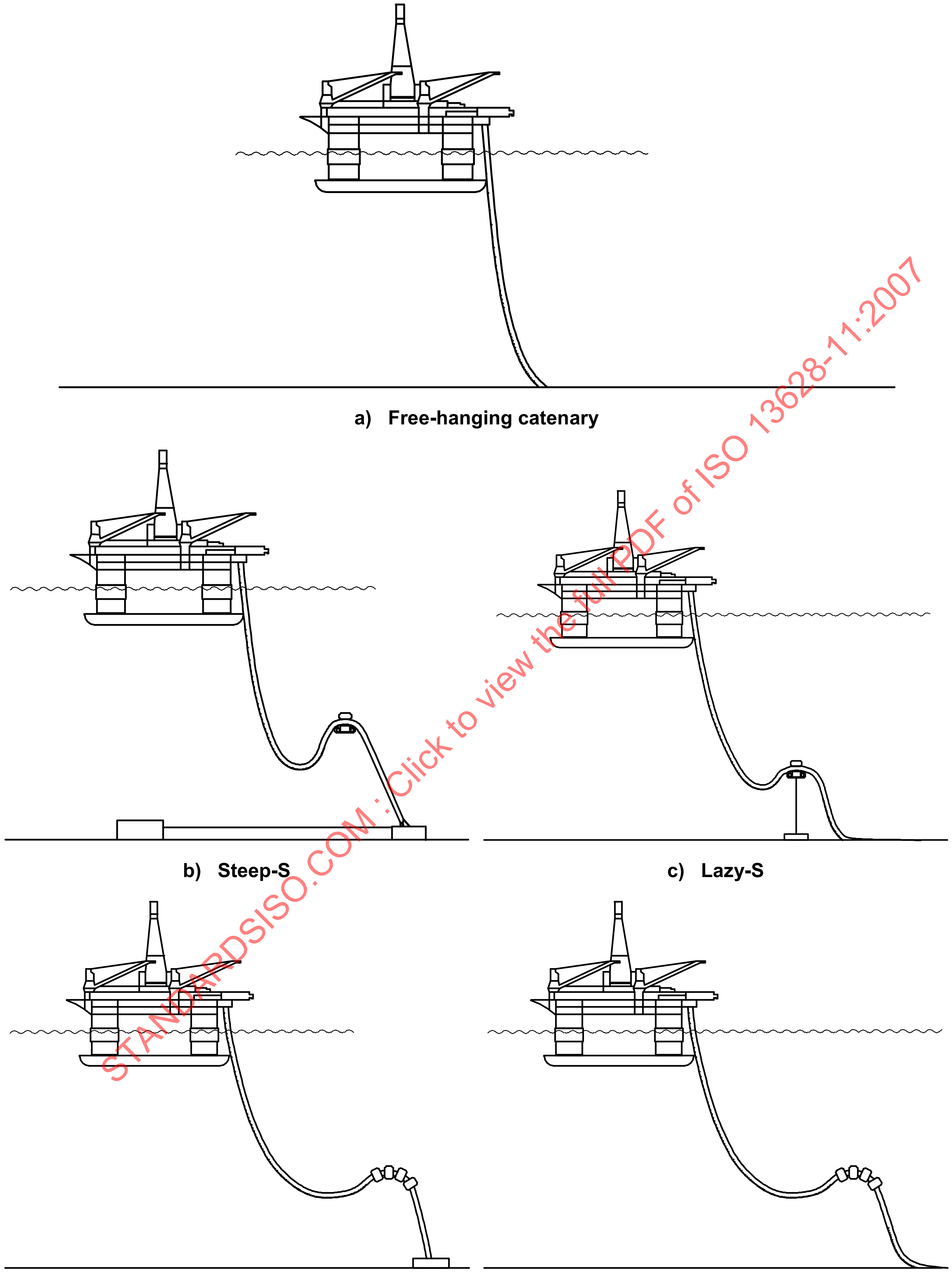

a) **Free-hanging catenary**

b) **Steep-S**

c) **Lazy-S**

d) **Steep wave**

e) **Lazy wave**

Figure 4 — Examples of flexible riser configurations

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4.2.2.4 Jumper lines

4.2.2.4.1 In addition to flowlines and risers, jumper lines, a further category, may be used for either static or dynamic applications. Examples of flexible pipes used in jumper-line applications include the following (Figure 5):

a) static applications:

1) intra-field connection of wellheads and manifolds (typically in lengths less than 100 m),

2) connection of topside wellheads and platform piping on tension leg platforms (TLPs);

b) dynamic applications:

1) connection of wellhead platforms and floating support vessels,

2) lines in FPSO turret motion transfer systems.

4.2.2.4.2 The functions of the dynamic jumper lines (excluding internal turret lines) are similar to riser systems. Their operation, however, is somewhat different. The lines are generally more exposed to wave loading, and the configuration varies between the connected condition and the stand-off condition, which imposes extra requirements on the end connectors and bend stiffeners. The performance of these components should be evaluated carefully for dynamic jumper-line applications.

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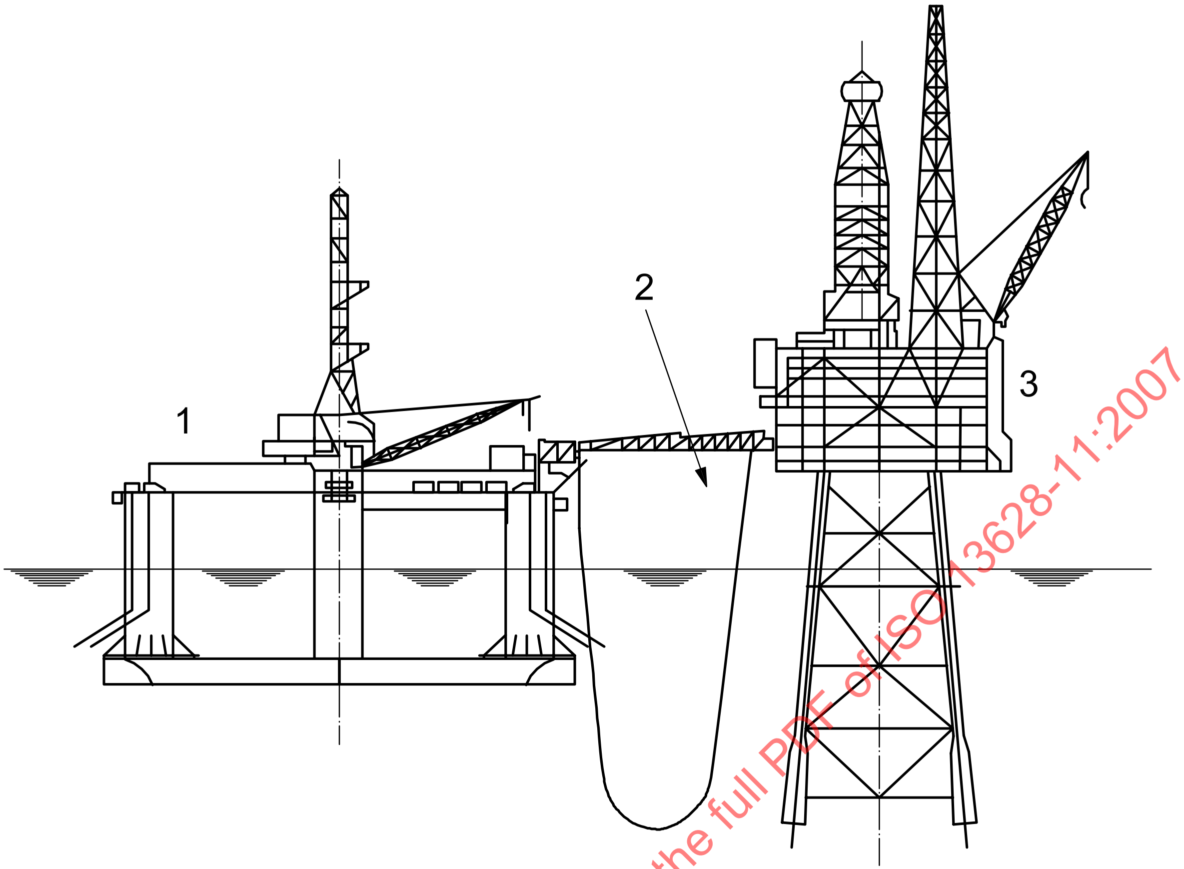
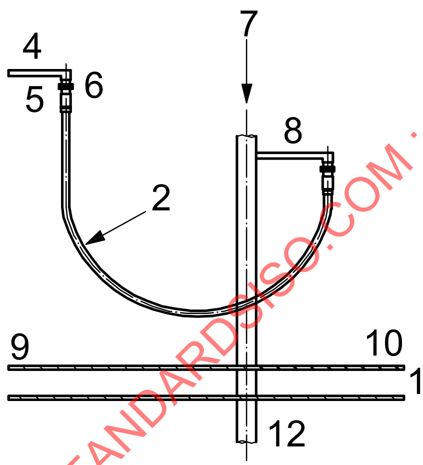
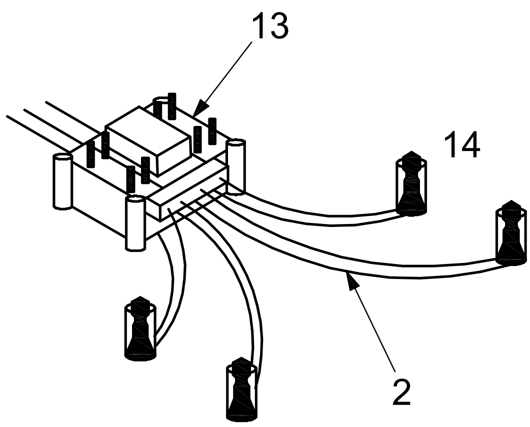


a) Flexible pipe as a fluid transfer line



b) Flexible pipe connected to Xmas tree



c) Flexible pipe connected to manifold

Key

1 support vessel
2 flexible jumper
3 wellhead platform
4 fixed end
5 topsides piping
6 end fitting
7 Xmas tree
8 moving end
9 wellbay
10 grated deck
11 tree deck
12 rigid riser
13 manifold
14 wellheads

Figure 5 — Examples of flexible-pipe jumper-line applications

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4.3 Flexible pipe description

4.3.1 General

4.3.1.1 This part of ISO 13628 does not apply to flexible pipes for use in choke and kill line or umbilical applications.

4.3.1.2 A flexible pipe generally combines low bending stiffness with high axial tensile stiffness, which is achieved by a composite pipe wall construction. This is more applicable to unbonded flexible pipes than to bonded flexible pipes. The two basic components are helical armouring layers and polymer sealing layers, which allow a much smaller radius of curvature than for a steel pipe with the same pressure capacity. Generally, a flexible pipe is designed specifically for each application and is not an off-the-shelf product, although flexible pipes may be grouped according to specific designs and, hence, applications. This allows the pipe to be optimized for each application.

4.3.2 Unbonded flexible pipe construction

4.3.2.1 Figure 6 shows a typical cross-section of a flexible pipe. The main layers in this cross-section are identified in 4.3.2.2 to 4.3.2.6

4.3.2.2 The carcass is an interlocked metallic layer which provides collapse resistance. Figure 7 illustrates an example of a carcass profile.

4.3.2.3 The internal pressure sheath is an extruded polymer layer which provides internal fluid integrity.

4.3.2.4 The pressure armour is an interlocked metallic layer which supports the internal pressure sheath and system internal-pressure loads in the radial direction. Figure 7 includes some example profiles for the pressure-armour wires. A back-up pressure-armour layer (generally not interlocked) also can be used for higher-pressure applications.

4.3.2.5 The tensile-armour layers typically use flat, round, or shaped metallic wires, in two or four layers crosswound at an angle between 20° and 60°. The lower angles are used for pipe constructions which include a pressure-armour layer. Where no pressure-armour layer is used, the tensile-armour layers are crosswound at an angle close to 55° to obtain a torsionally balanced pipe and to balance hoop and axial loads.

4.3.2.6 The outer sheath is an extruded polymer sheath that provides external fluid integrity.

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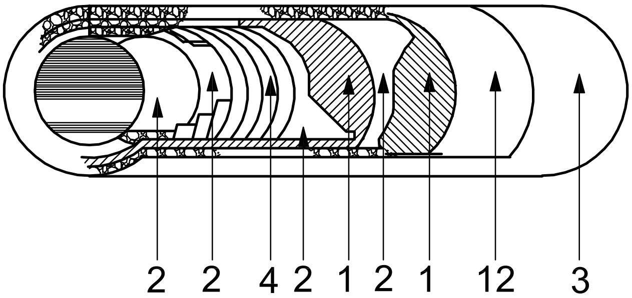
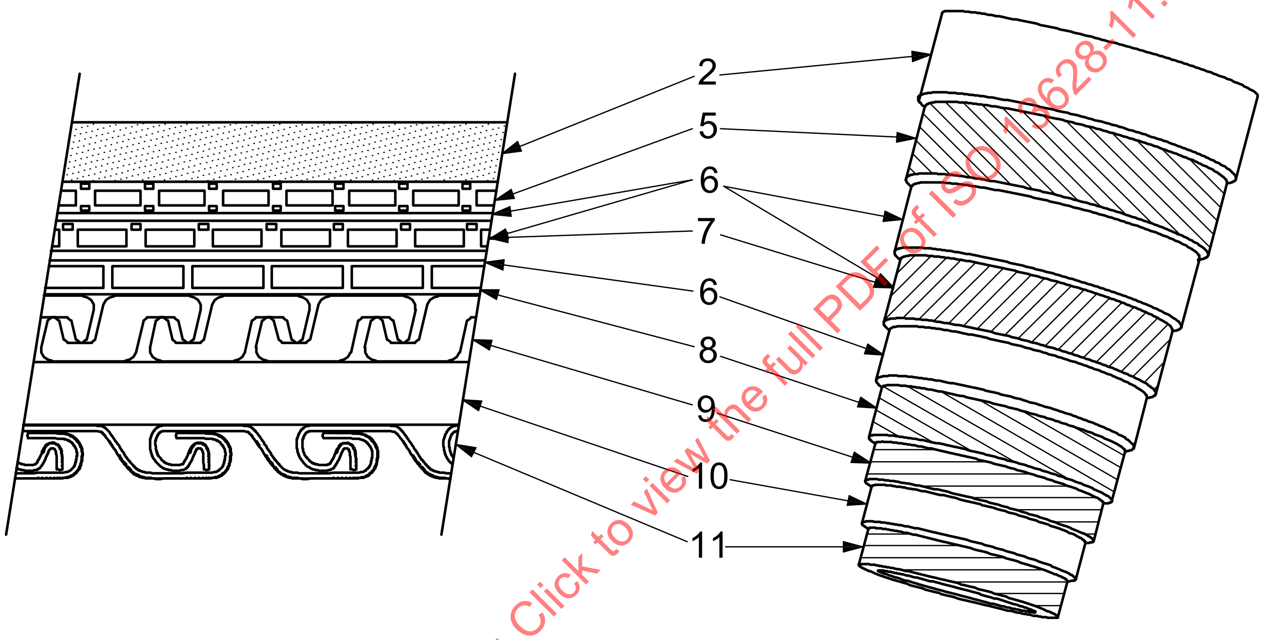


a) Bonded flexible pipe



b) Unbonded flexible pipe

Key

1 tensile layer
2 anti-friction layer
3 outer sheath
4 hoop stress layer
5 outer layer of tensile armour
6 anti-wear layer
7 inner layer of tensile armour
8 back-up pressure armour
9 interlocked pressure armour
10 internal pressure sheath
11 carcass
12 anti-bird-cage layer

Figure 6 — Schematic of typical flexible riser cross-sections

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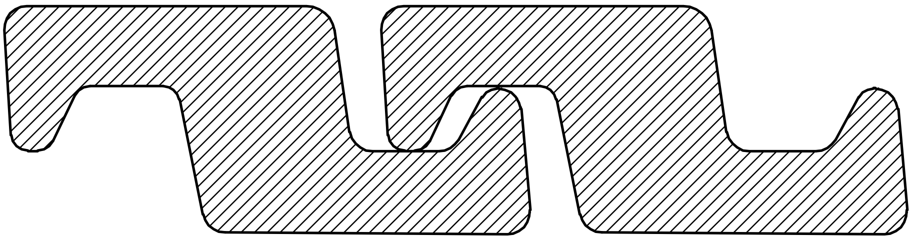
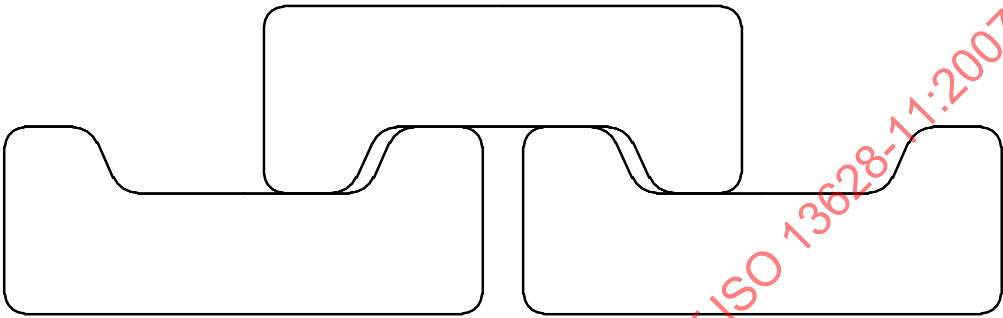
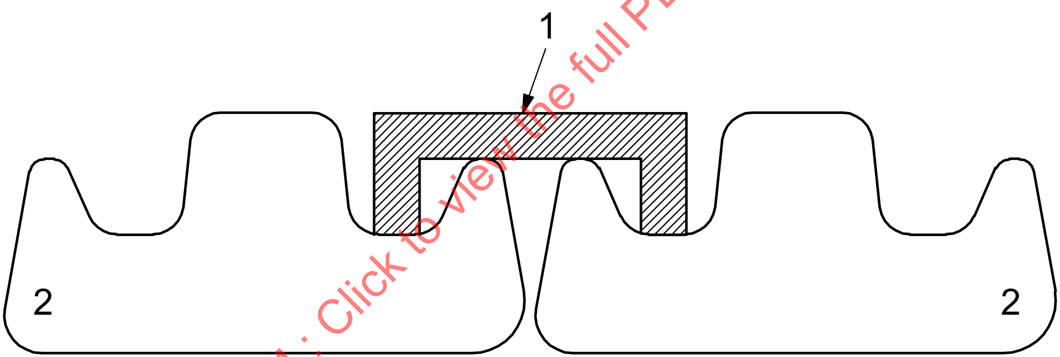


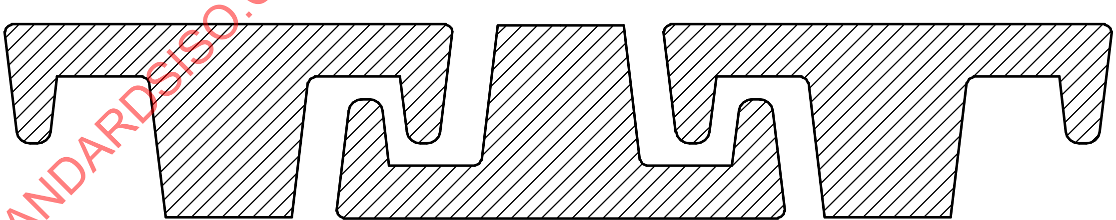
a) **Z-shape (pressure-armour profile)**



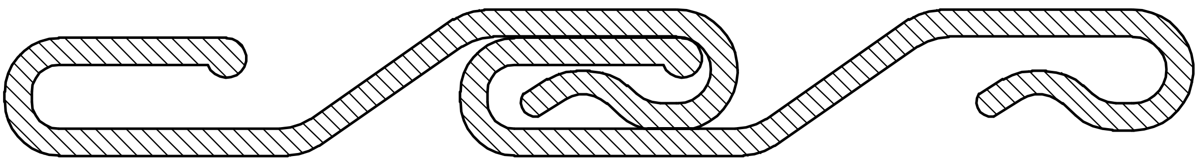
b) **C-shape (pressure-armour profile)**



c) **T-shape 1 (pressure-armour profile)**



d) **T-shape 2 (pressure-armour profile)**



e) **Carcass profile**

Key

1 clip

2 T-wire

Figure 7 — Pressure-armour and carcass interlock profiles

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4.3.3 Bonded flexible pipe construction

4.3.3.1 A typical bonded flexible pipe consists of several layers of elastomer either wrapped or extruded individually and then bonded together through the use of adhesives or by applying heat and/or pressure to fuse the layers into a single construction. Figure 6 shows an example of a bonded pipe construction. The main layers are identified in 4.3.3.2 to 4.3.3.5.

4.3.3.2 The carcass is an interlocked, metallic layer, which provides collapse resistance. Figure 7 shows an example of a carcass profile.

4.3.3.3 The liner is a wrapped or extruded elastomer layer, which provides internal fluid integrity.

4.3.3.4 The reinforcement layer is comprised typically of helically wound, steel cables in an embedding elastomer compound used to sustain tensile and internal pressure load on the pipe. The steel cables are typically laid at an angle of 55° to obtain a torsionally balanced pipe, in addition to equivalent hoop and longitudinal forces in the layer due to pressure. However, this angle may increase or decrease depending on the required strength characteristics of the pipe. For example, a higher angle may be used if increased strength in the hoop direction is required at the expense of tensile capacity and axial stiffness of the pipe.

4.3.3.5 The outer layer is a wrapped or extruded elastomer layer that provides external fluid integrity and protection against external environments, corrosion, abrasion and mechanical damage.

NOTE The concept of separate layers in a bonded pipe construction is notional because the final pipe cross-section is a bonded composite construction.

4.3.4 Classification of flexible pipe

4.3.4.1 Currently, unbonded flexible pipes can generally be classified into three distinct families. These classifications are identified in Table 1. Distinctions exist between pipes for static and dynamic applications within these families, with the main distinction being the use of anti-wear layers for dynamic applications if they are required to achieve service-life criteria.

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Table 1 — Description of standard flexible-pipe families — Unbonded pipe

Layer No.	Layer primary function	Product family I Smooth-bore pipe	Product family II Rough-bore pipe	Product family III Rough-bore, reinforced pipe
1	Prevent collapse	Pressure-armour layer(s)	Carcass	Carcass
2	Internal fluid integrity	Internal pressure sheath	Internal pressure sheath	Internal pressure sheath
3	Hoop stress resistance	Pressure-armour layer(s)	—	Pressure-armour layer(s)
4	External fluid integrity	Intermediate sheath	—	—
5	Tensile-stress resistance	Crosswound tensile armours	Crosswound tensile armours	Crosswound tensile armours
6	External fluid integrity	Outer sheath	Outer sheath	Outer sheath

NOTE 1 All pipe constructions can include various non-structural layers, such as anti-wear layers, tapes, manufacturing aid layers, etc.

NOTE 2 An external carcass can be added for protection purposes.

NOTE 3 The pressure layer can be subdivided into interlocked layer(s) and back-up layer(s).

NOTE 4 The number of crosswound armour layers can vary, though is generally either two or four.

NOTE 5 Thermal insulation can be added to the pipe.

NOTE 6 The internal pressure and outer sheaths can consist of a number of sublayers.

NOTE 7 Product family III is generally used for higher-pressure applications than II.

NOTE 8 The intermediate sheath for smooth-bore pipes is optional if there is no external pressure or the external pressure is less than the collapse pressure of the internal pressure sheath for the given application.

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4.3.4.2 The classifications for bonded flexible pipe are identified in Table 2. Smooth-bore flexible pipes (product family I, unbonded and product family IV, bonded) often are used for water injection or dead crude applications.

Table 2 — Description of standard flexible pipe families — Bonded pipe

Layer No.	Layer primary function	Product family IV Smooth-bore pipe	Product family V Rough-bore pipe
1	Prevent collapse	—	Carcass
2	Internal fluid integrity	Liner	Liner
3	Hoop and tensile-load resistance	Reinforcement layer(s)	Reinforcement layer(s)
4	External fluid integrity and protection	Cover	Cover

NOTE 1 All pipe constructions can include various non-structural layers, such as filler layers and breaker fabrics.

NOTE 2 An external carcass can be added for protection purposes.

NOTE 3 The number of crosswound reinforcement plies can vary, though is, generally, either two, four, or six.

4.3.5 End fittings

4.3.5.1 Figure 8 illustrates a typical unbonded-pipe end fitting. End fittings may be built in during pipe manufacture or installed in the field. The two purposes of a flexible-pipe end fitting are to

a) terminate all the strength members in the pipe's construction, so that axial loads and bending moments can be transmitted into the end connector without adversely affecting the fluid-containing layers, and

b) provide a pressure-tight transition between the pipe body and the connector.

4.3.5.2 End connectors can be an integral part of, or attached to, the end fitting. A variety of end connectors exist, such as bolted flanges, clamp hubs, proprietary connectors and welded joints (two end fittings welded together to join pipe segments into a longer segment). The selection of end connectors depends on operational and service requirements.

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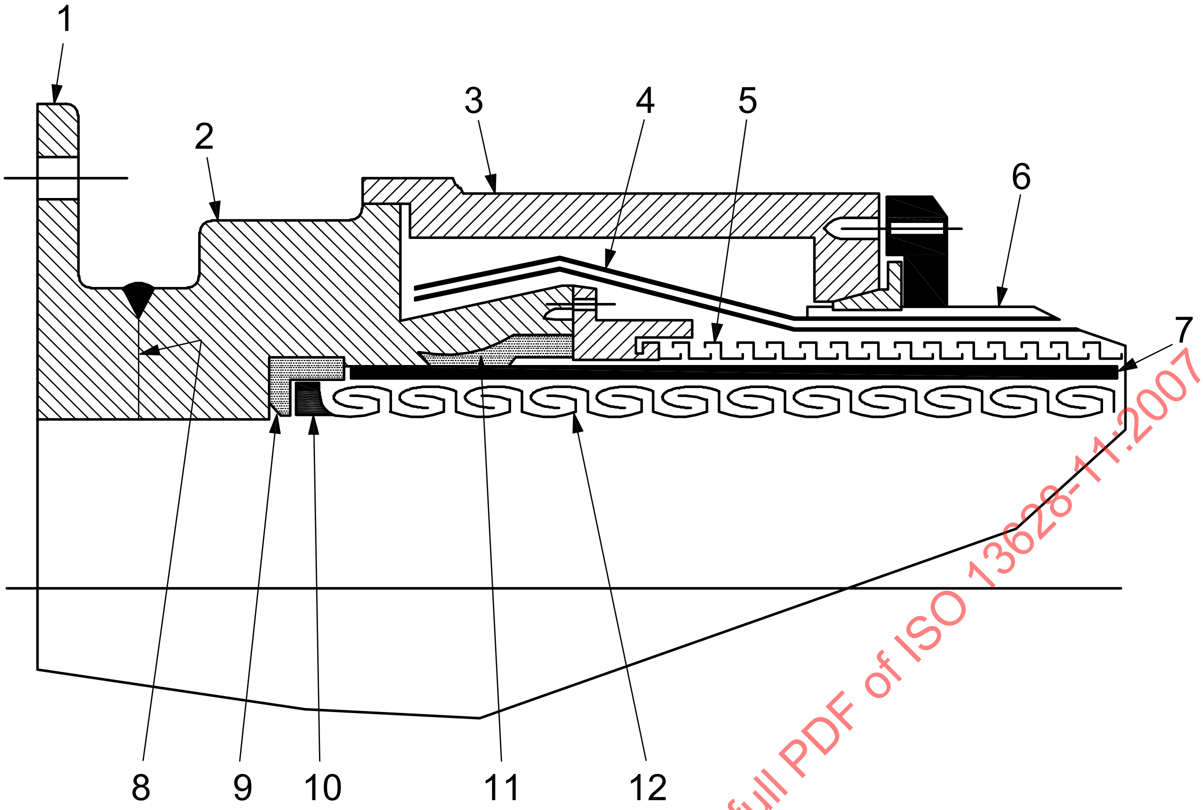

Key

1 mounting flange
2 end-fitting housing (inner casing)
3 end-fitting housing (outer casing)
4 tensile armours (embedded in epoxy)
5 pressure-armour layer
6 outer sheath
7 internal pressure sheath (and sacrificial layers)
8 end-fitting neck
9 insulator
10 carcass end ring
11 seal ring
12 carcass

Figure 8 — Example of an unbonded-flexible-pipe end fitting

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4.3.6 Integrated service umbilicals

4.3.6.1 The functionality of flexible pipes can be combined with umbilicals to form an integrated service umbilical (ISU™)[2]. Figure 9 is a schematic of a typical ISU. The inner core is a standard flexible-pipe construction and provides the axial load-bearing capacity of the structure. The umbilical components (electrical, hydraulic and control lines) are helically (or sinusoidally) wound around the core pipe.

2) ISU is an example of a suitable product available commercially. This information is given for the convenience of users of this part of ISO 13628 and does not constitute an endorsement by ISO of this product.

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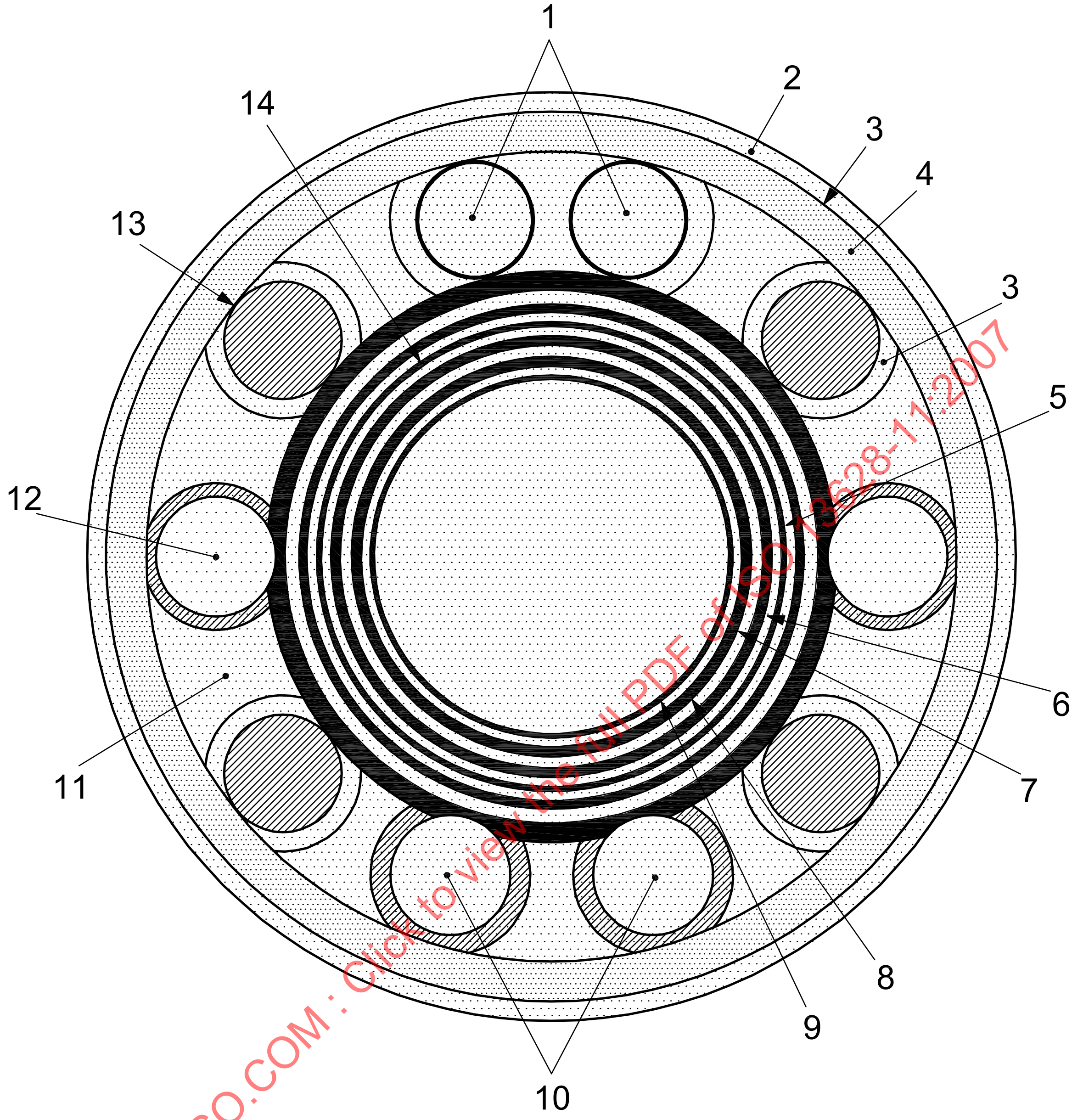

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Key

1 electric power cable
2 outer sheath
3 tape
4 pipe outer sheath
5 tensile-armour layer
6 internal tensile-armour layer
7 pressure-armour layer
8 internal pressure sheath
9 carcass
10 electrical signal cable
11 filler material
12 fibre optical cable
13 hydraulic hose
14 anti-friction tape

Figure 9 — Schematic drawing of an example ISU

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4.3.6.2 Spacers (fillers) are included between the umbilical lines to increase the crushing load resistance of the ISU. The assembly is covered by a protective outer sheath. In some cases, a layer of helical or sinusoidal armouring is applied between the control lines and the outer sheath. This layer increases the mass-to-diameter ratio of the ISU, which reduces the dynamic motions, thereby minimizing the potential for interference with adjacent risers. This layer also protects the control lines against external damage.

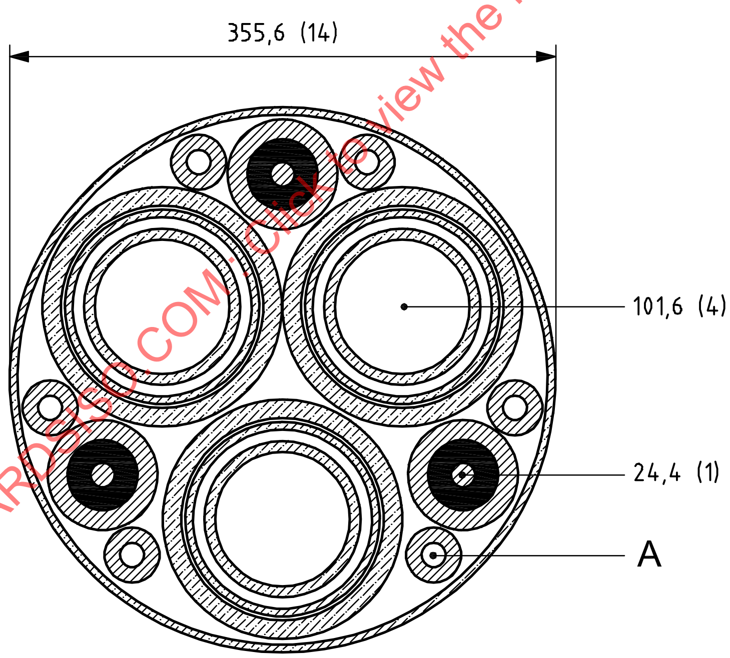
4.3.6.3 The end terminations of an ISU are complex constructions. The core of the termination is the end fitting of the central flexible pipe around which the terminations of the control lines are grouped. This assembly is integrated in a steel housing or frame, which may also carry the bend stiffener and transfer bending loads. The detailed design of the termination is governed by the installation and tie-in strategy.

4.3.6.4 Stainless steel conduits may also be used in the ISU. These overcome the problem of fluid diffusion through the polymer hoses (in particular methanol) and reduce response time in control systems. However, stainless steel conduits can be sensitive to fatigue in dynamic applications and installation loads.

4.3.7 Multibores

4.3.7.1 The multibore concept involves combining multiple flexible pipes and/or umbilical components into a single construction, thus reducing the number of lines in a field development and thereby simplifying the field layout and installation requirements. It can also reduce the number of I-tubes or J-tubes required for some development options. Figure 10 illustrates some examples of multibore constructions. The individual pipes are helically or sinusoidally wound and filler/spacer materials are used to obtain a circular cross-section. External armouring may be applied outside the bundle. A polymer sheath is extruded over the bundle and provides structural integrity and protection.

Dimensions in millimetres (inches)



a) Example 1 [a]

Figure 10 (*continued*)

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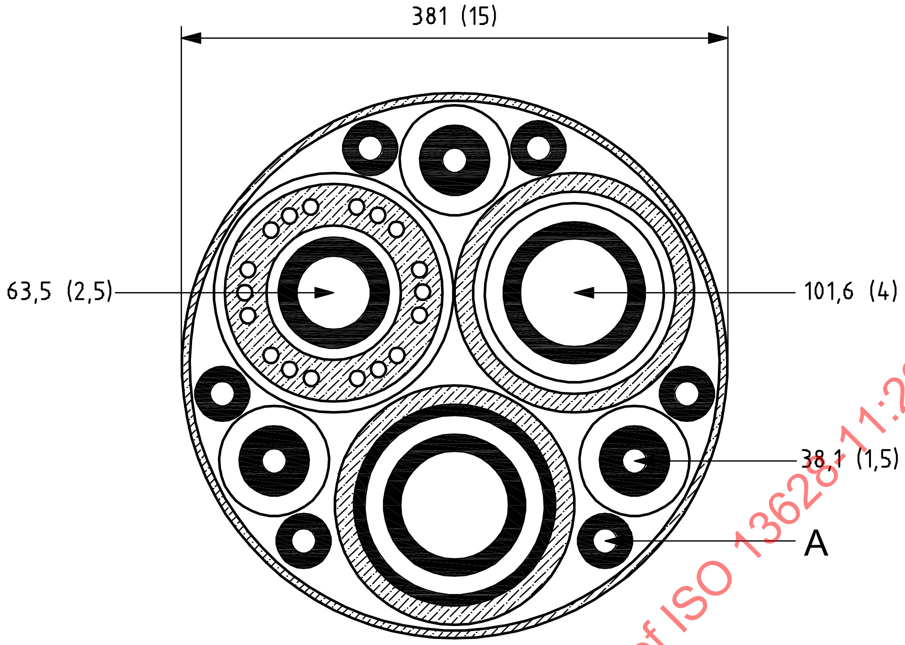
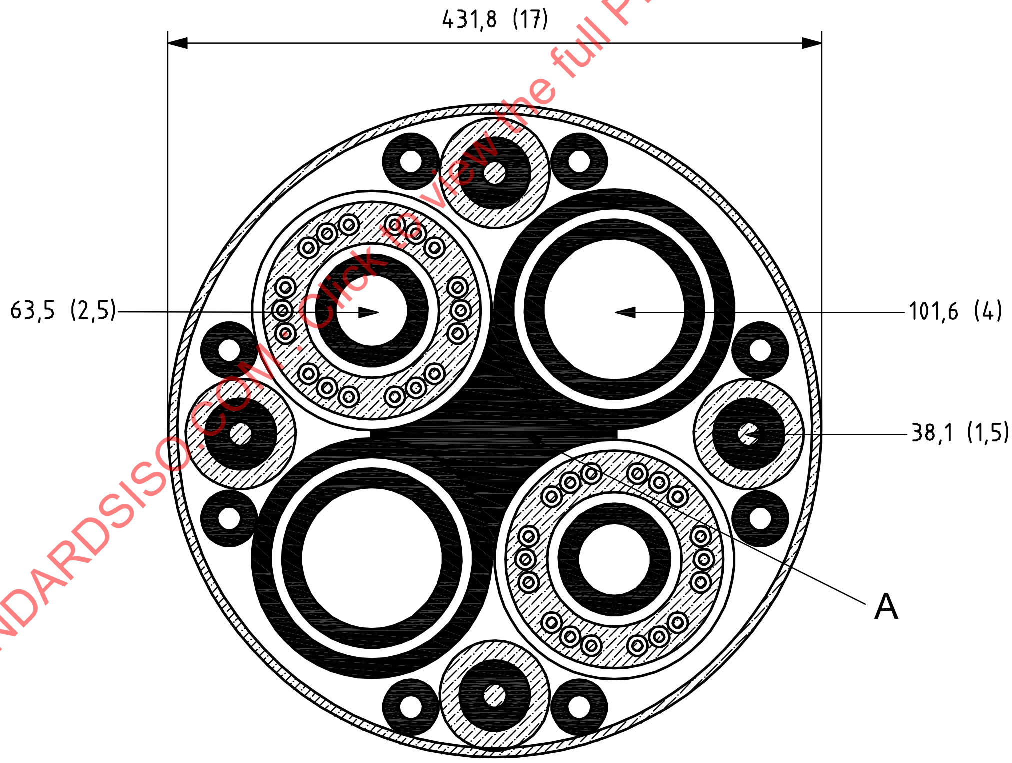
Dimensions in millimetres (inches)



b) Example 2 [b]



c) Example 3 [c, d]

Key

A filler

NOTE Properties given for the three examples are typical.

[a] Linear mass in air, empty, is 181 kg/m (121,63 lb/ft); minimum bending radius is 2,4 m (7,87 ft).

[b] Linear mass in air, empty, is 201 kg/m (135,07 lb/ft); minimum bending radius is 2,5 m (8,2 ft).

[c] Linear mass in air, empty, is 249 kg/m (167,32 lb/ft); minimum bending radius is 2,9 m (9,51 ft).

[d] Umbilical.

Figure 10 — Examples of multibore constructions

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4.3.7.2 The design of a multibore construction is much more complex than a single bore. Important considerations are described in 4.3.7.2.1 to 4.3.7.2.7.

4.3.7.2.1 The most desirable shape in a multibore structure is a circular cross-section, since this results in optimal hydrodynamic performance, efficient space utilization and easy handling during installation and retrieval.

4.3.7.2.2 Standard components (flexible pipes and umbilicals) are recommended for use as much as possible.

4.3.7.2.3 The internal components can possibly provide the axial-load capacity of the structure, depending on the manufacturing process. The axial-load capacity or additional capacity can be provided by armour layers. The structural stability (differing elongations in the components) and torsional balance of the multibore under various loading conditions (unequal pressure levels and bending) should be evaluated.

4.3.7.2.4 The crushing resistance of the multibore shall be large enough to allow for flexibility in installation methods.

4.3.7.2.5 The maximum outer diameter is limited by the extrusion capability of the manufacturer for the outer sheath.

4.3.7.2.6 Care should be taken during winding to minimize torsion loads induced in the individual components.

4.3.7.2.7 A symmetrical construction is recommended to ensure uniform mechanical properties and to prevent structural rearrangement under dynamic loading.

4.3.7.3 The end termination for the multibore construction typically uses standard end fittings contained within a box-type structure.

4.4 Ancillary components

4.4.1 General

Ancillary components commonly used in flexible pipe systems are described in 4.4.2 to 4.4.9.

4.4.2 Bend limiters

4.4.2.1 Figure 11 illustrates two types of bend limiter in common use: bend stiffeners and bellmouths. A third type is a bend restrictor as described in 4.4.3. Bend stiffeners and bellmouths are generally used for dynamic applications. However, they can also be used in static applications. An example of the latter is the use of bend stiffeners on flowlines to prevent overbending at the end fitting during installation.

Bend limiters should be designed to give no bending in the pipe for a length of approximately one OD from the end fitting. Below this, the bending is allowed to increase gradually, with a smooth variation of bending moment within MBR criteria limitations.

4.4.2.2 Bend limiters may be built into the pipe construction in some bonded pipes. This is achieved by extruding or wrapping additional layers of elastomer and then curing the structure to form an integral bend limiter and pipe.

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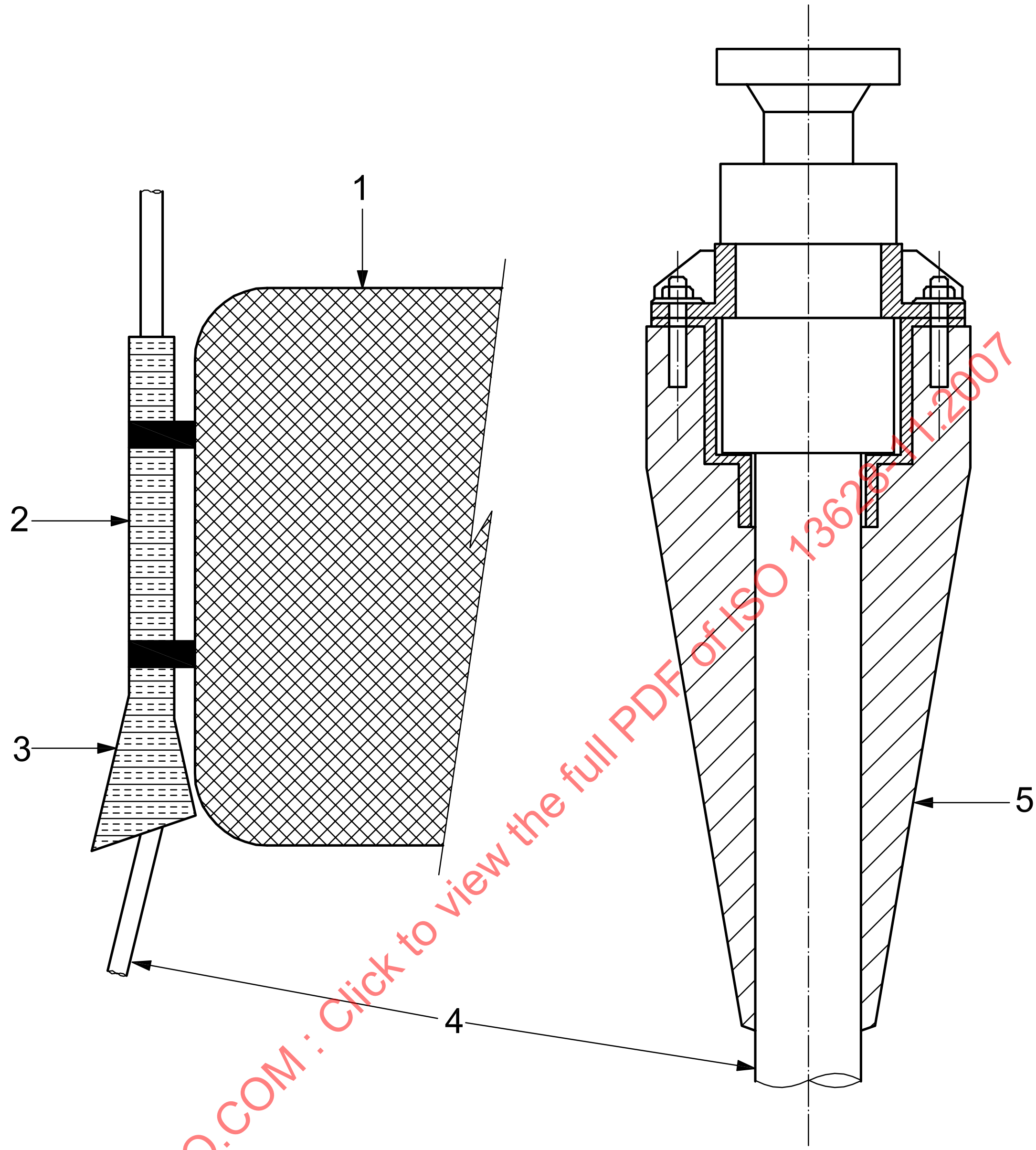

Key

1 pontoon
2 I-tube
3 bellmouth
4 flexible riser
5 bend stiffener

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Figure 11 — Bend limiters

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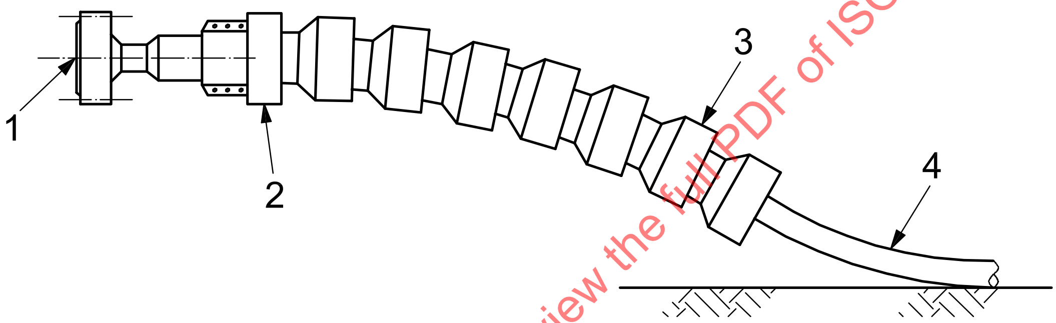
4.4.3 Bend restrictors

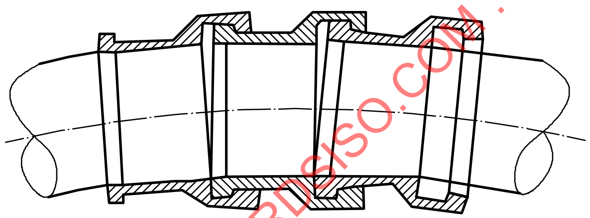
4.4.3.1 Bend restrictors are designed to mechanically restrict the flexible pipe from bending beyond its allowable MBR and are currently only used in static applications. An example of a bend restrictor is shown in Figure 12. Bend restrictors are used to support a flexible pipe over free spans where there is the possibility of damaging the pipe structure because of overbending. Typical applications are at wellhead connections, J-tube exits and rigid-pipe crossovers. Restrictors may also be used to prevent overbending during installation.

4.4.3.2 The restrictor consists of interlocking half rings that fasten together around the pipe so that they do not affect the pipe until a specified bend radius is reached, at which stage they lock. Full rings are permitted if the restrictor is mounted ahead of the end fitting. The locking of the restrictor prevents further bending of the pipe and additional loads are carried by the bend restrictor. Care should be taken that the locking of the rings does not damage the outer sheath of the pipe, i.e. there is smooth support with no sharp edges in the restrictor design.

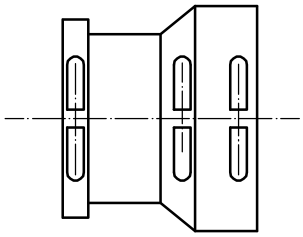
4.4.3.3 The bend restrictor elements may be manufactured from metallic materials, creep-resistant elastomers or glass-fibre-reinforced plastic. All materials should be selected for the specified environment and have sufficient corrosion resistance.



a) Bend restrictors covering flexible pipe



b) Bend restrictor in locked position



c) Side elevation

Key

1 end fitting

2 reaction collar

3 bend restrictor

4 subsea line

Figure 12 — Schematic of a bend restrictor

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4.4.4 Connectors

4.4.4.1 The design of flexible-pipe end fittings allows for the use of a variety of end connectors, such as bolted flanges, clamped hubs and proprietary connectors. The connectors are typically welded to the end fitting prior to connecting to the flexible pipe or they may be integrally machined from the end-fitting body.

4.4.4.2 The flexible pipe and end fitting can also be connected directly to a steel pipe, e.g. by welding. However, welding close to the end fitting [approximately 0,5 m to 0,8 m (1,64 ft to 2,62 ft)] should not be performed when the end fitting is already connected to the flexible pipe because overheating of the end fitting can adversely affect the layer terminations or seals.

4.4.4.3 Quick-disconnect and quick-connect/disconnect systems may be used as connectors where emergency release is an operational requirement for dynamic-riser applications. Figure 13 illustrates an example of a quick-disconnect system. The main features of emergency release systems are typically as follows:

a) isolation ball valve in upper and lower halves of the structure;

b) ability to disconnect under full design loads and internal pressure;

c) minimal size and mass for structure;

d) full-bore throughout to allow for pigging;

e) pressure-tight connection with face-to-face type primary seals to avoid damage to seals during disconnect/reconnect and dynamic loading;

f) ball valves are interlocked with release mechanism to ensure closure on disconnection (might not be required for all applications);

g) simplified support structure (guide-post funnels) to allow easy and safe reconnection;

h) capability to periodically test release mechanism without releasing the riser or breaking primary seals (or, if this is not feasible, an alternative test procedure is required that includes retesting of primary seals after reconnection).

4.4.4.4 Disconnect systems can have emergency shutdown valves on one or both sides of the interface. There can be cases where no valve is required. Important considerations in this decision include

a) risk of disconnection,

b) transported fluid,

c) environmental concerns, and

d) topsides valving.

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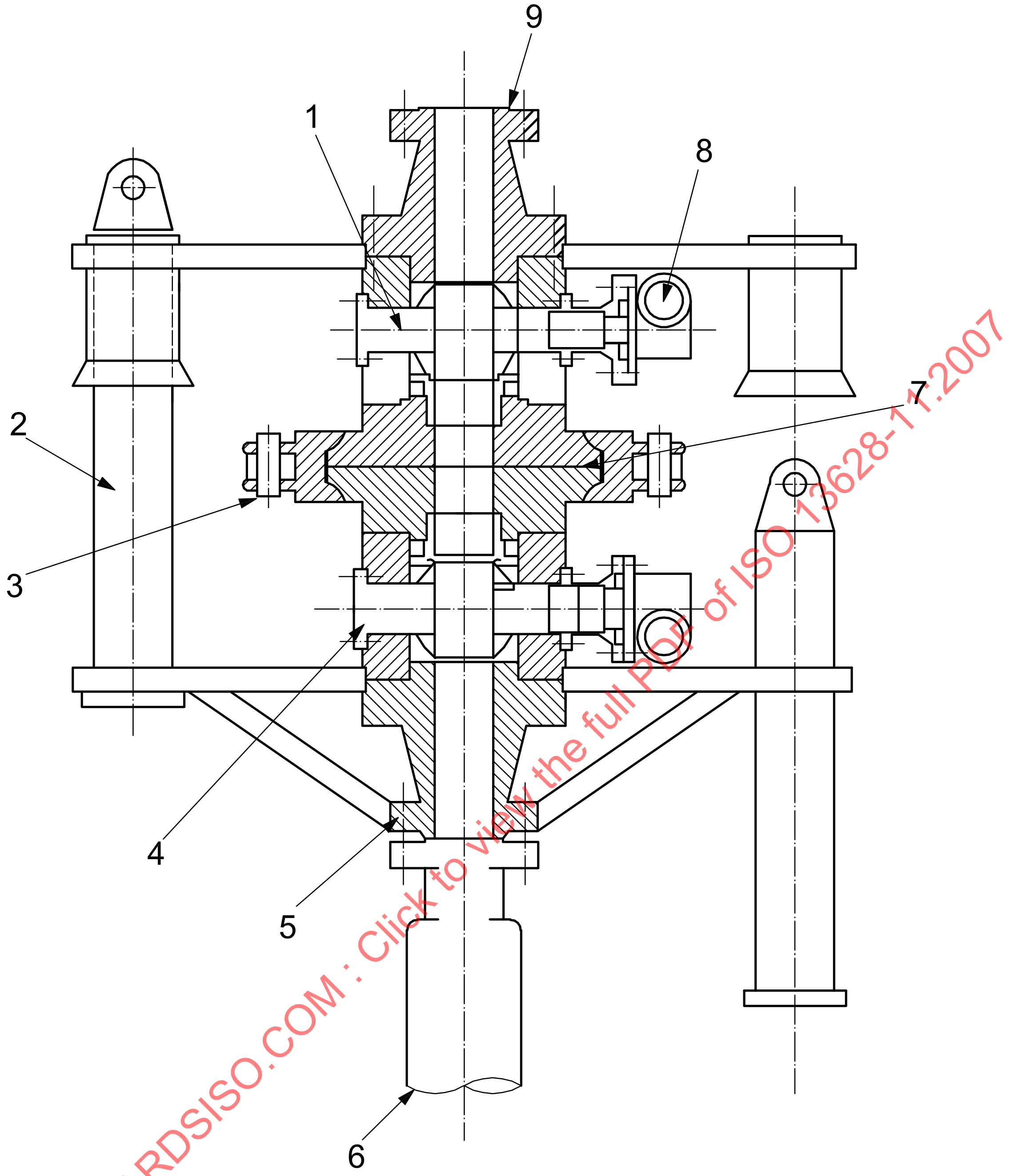

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Key

1 upper ball valve
2 support structure
3 emergency release coupler
4 lower ball valve
5 riser interface flange
6 internal pressure sheath
7 primary seals
8 ball valve actuators
9 hard piping interface flange

Figure 13 — Example of a quick-disconnect system

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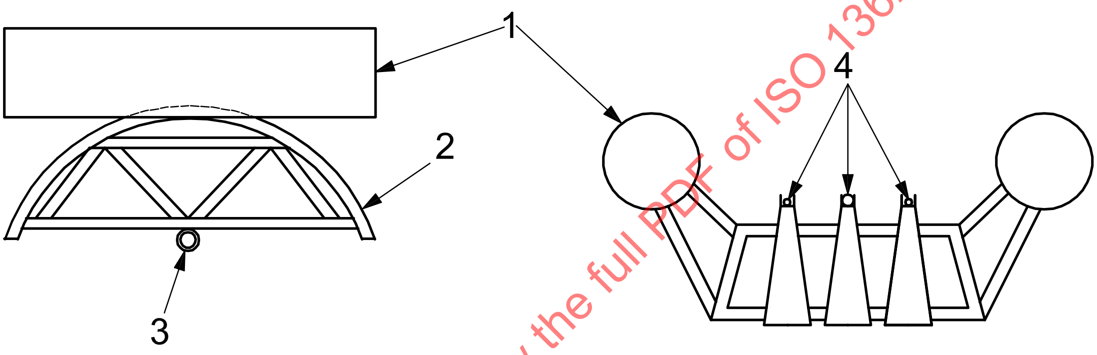
4.4.5 Subsea buoys

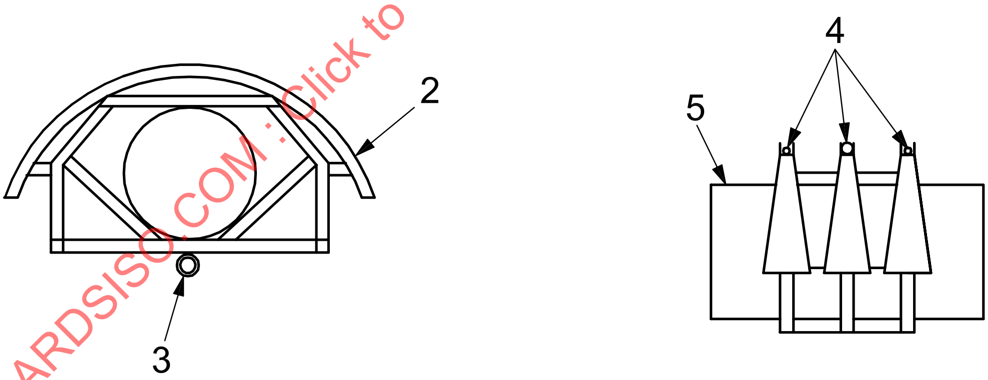
4.4.5.1 Subsea buoy/arch systems are used to achieve S-shaped riser configurations, including lazy, steep, and reverse configurations. (Note that in the reverse configuration, the lower catenary of the riser passes back underneath the buoy.) The systems typically consist of one or more buoyancy tanks supported by a steel structure over which lie individual gutters (arches) for each riser. Figure 14 shows two typical systems. The buoyancy tanks may be constructed from either steel tanks or syntactic foam modules. The tanks can be positioned as shown in Figure 14.

4.4.5.2 The S-shaped riser configuration can alternatively be achieved by using a fixed support instead of a floating buoy (Figure 14). The main disadvantage of this system is the reduction in compliancy of the riser system.

4.4.5.3 The subsea buoy/arch system is held in place by a riser base to which it is connected by tethers (lazy-S) or by flexible risers (steep-S). The subsea buoy/arch systems are typically designed to support two to six risers, though there is no theoretical limit on the number. The risers are held in place on the arch.



a) Option 1 — Twin buoys



b) Option 2 — Single buoy

Figure 14 (*continued*)

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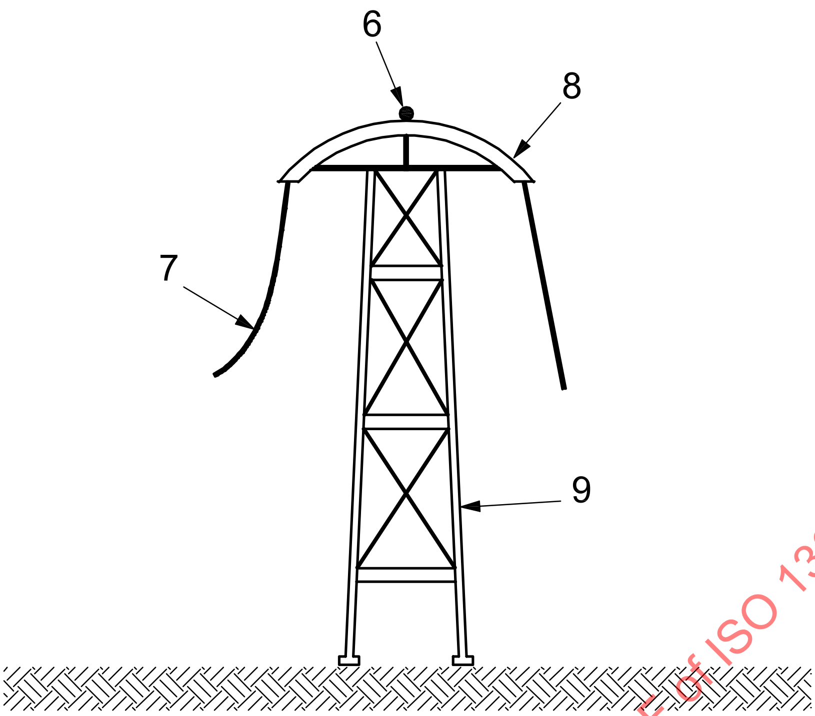

c) Option 3 — Fixed arch

Key

1 buoys
2 gutters
3 tethering point
4 risers
5 buoy
6 riser clamp
7 flexible riser
8 arch/gutters
9 support structure

NOTE The buoys can be steel tanks or syntactic foam structures.

Figure 14 — Subsea buoy/arch systems

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4.4.6 Buoyancy modules

4.4.6.1 Buoyancy modules are used to achieve the wave-shape riser configurations (lazy, steep, and pliant). Figure 15 is a schematic of a typical module. A specific number of modules (such as 30) is required to achieve the wave configuration and are generally sized (both length and diameter) to be about two to three times the pipe OD, though this depends on buoyancy and installation requirements. The number of modules is based largely on riser mass, water depth, offset requirements, and manufacturing/commercial issues. The modules are individually clamped to the riser, so the design should ensure that they do not slide along the pipe or damage it. Some bonded flexible pipes have integral elastomer collars at intervals along the pipe to facilitate the attachment of ancillary devices. These collars are generally built and cured with the pipe.

4.4.6.2 The buoyancy module is comprised, typically, of an internal clamp and a syntactic foam buoyancy element. A polymer casing (polyurethane, for example) provides impact and abrasion resistance. The internal clamp bolts directly onto the flexible pipe, and the buoyancy element fits around the clamp. The buoyancy element is generally in two halves that are securely fastened together. The density of the syntactic foam is selected based on the specified water depth and service life. A typical density is 350 kg/m^3 (21,8 lb/ft^3).

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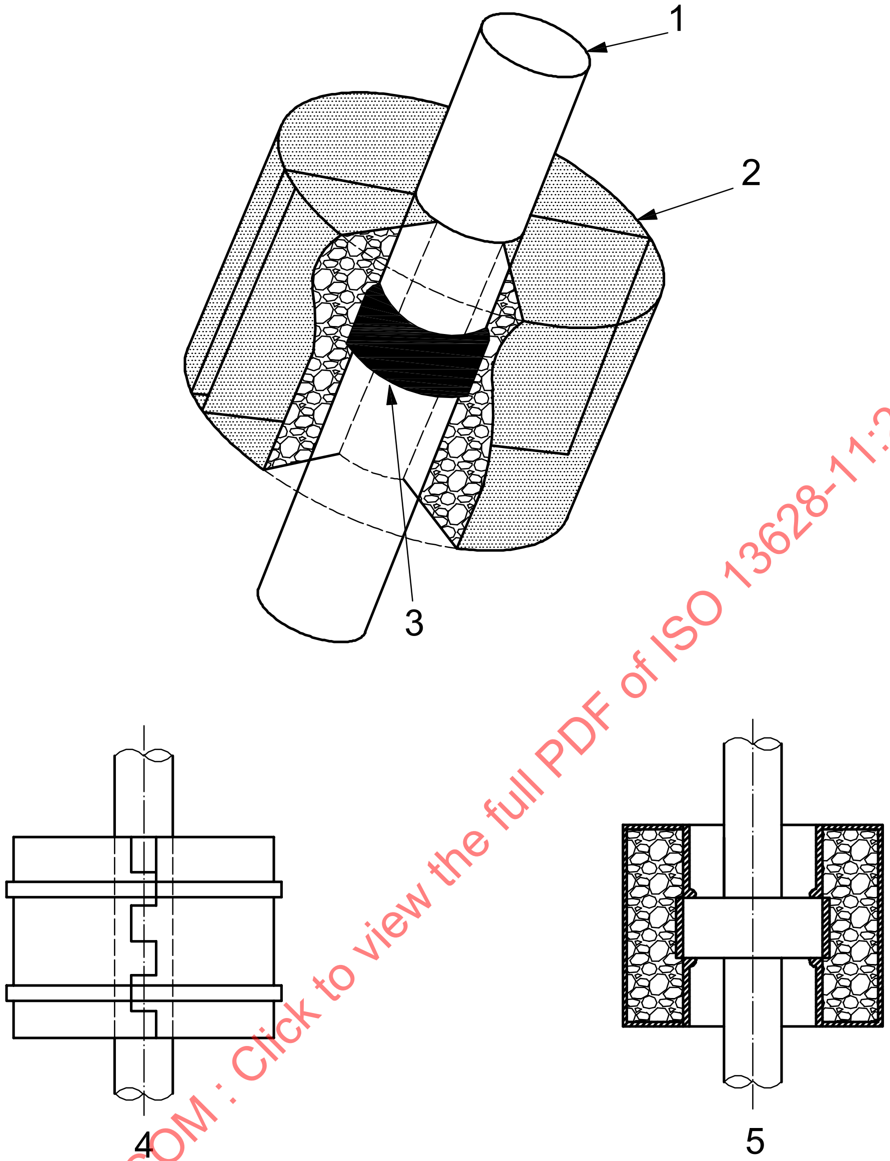

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Key

1 flexible pipe
2 buoyancy module
3 clamp
4 side elevation
5 cross-section

Figure 15 — Example of a buoyancy module for wave configurations

4.4.7 Clamping devices

4.4.7.1 Clamping devices can be used in flexible-pipe applications to connect ancillary components, such as buoyancy modules, subsea arches, tethers and bend restrictors, to the pipe. In addition, bundle clamps can be used to join several pipes together at discrete intervals, such as with piggy-back lines (Figure 16). The main component of bundle and piggy-back clamps is a spacer device or body, which can be in two half sections. The body is provided with cylindrical recesses into which individual lines are fitted. The assembly is joined together with bolts or a set of circumferential straps. Alternatively, band straps may be used for static piggy-back assemblies where they are needed only for installation.

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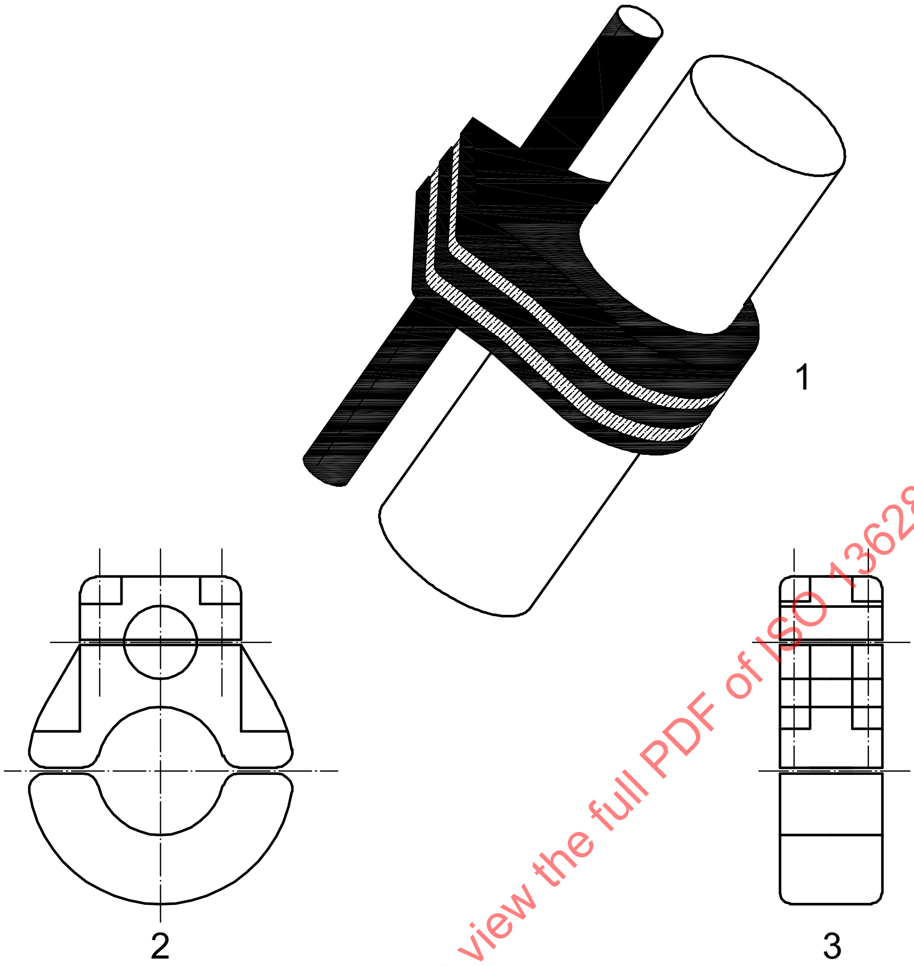

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Key

1 riser clamp

2 front elevation

3 side elevation

Figure 16 — Example of a clamp for piggy-backed flexible risers

4.4.7.2 Avoid excessive contact pressure. If high contact pressure is required, fit some type of protection shell to distribute the applied load. The clamp design should also ensure that there are no sharp edges that can cause local overbending of the pipe.

4.4.8 Riser and tether bases

4.4.8.1 Riser bases are used to connect flexible risers to flowlines and can also be required to support subsea buoy/arch systems (steep-S configuration). Tether bases are used only to anchor subsea buoy/arch systems (lazy-S configuration).

4.4.8.2 The riser base may be a gravity structure, a piled structure or a suction/anchor pad. Selection of a gravity-based or piled structure depends on applied loads and soil conditions. Figure 17 illustrates a typical riser-base structure. As an alternative, the flexible pipe can be connected directly to a manifold or a PLEM, in which case the manifold or PLEM acts as the riser base.

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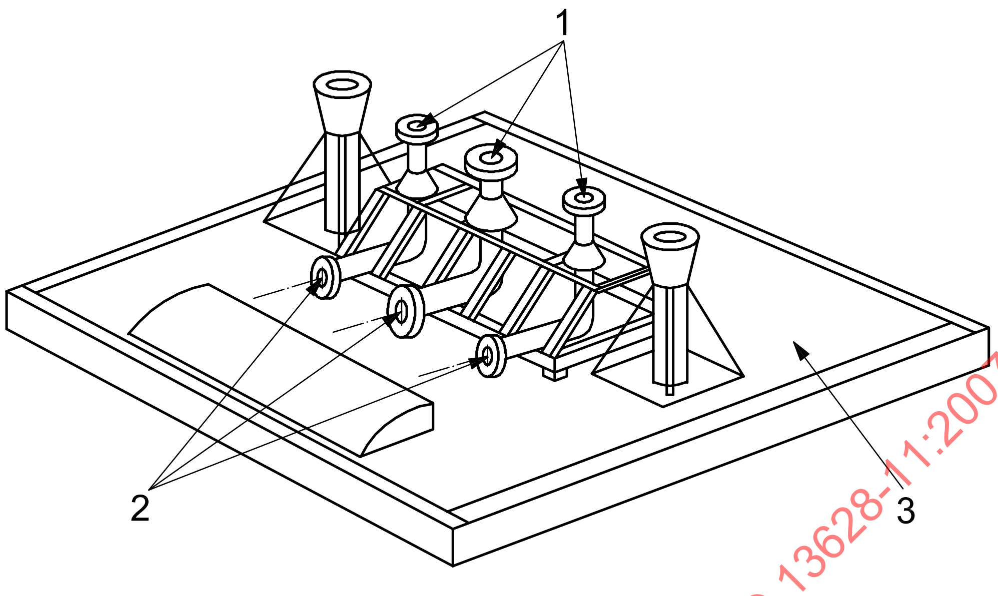

Key

1 flexible riser connections

2 spool pieces to the flowlines

3 concrete slab

Figure 17 — Example of a typical riser base

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4.4.9 Riser hang-off structures

4.4.9.1 The top connection of a flexible riser can be hung off from the support structure (such as a platform, tanker or semi-sub) either externally or internally.

EXAMPLE 1 The riser is connected to topsides piping at pontoon level or hung off at upper-deck level in an external connection.

EXAMPLE 2 The riser is typically pulled through an I-tube and hung off at the top of the I-tube in an internal connection (Figure 18).

The loading on the two hang-off structures is very different, with the internal connection subject only to axial loads while the external connection experiences axial, bending and shear loads.

4.4.9.2 Important considerations in the design of riser hang-off structures are described in 4.4.9.3 to 4.4.9.8.

4.4.9.3 The main constraints in the design of the hang-off structure are load limitations, space limitations, and spool-piece requirements.

4.4.9.4 The design of the hang-off structure for internal connections should account for the weight of the riser within the I-tube.

4.4.9.5 The critical loading for some hang-off structures occurs during installation, when there can be a significant pull-in load (including friction effects).

4.4.9.6 Overbending of the riser at a base of an I-tube is prevented by use of a bend limiter (bend stiffener or bellmouth).

4.4.9.7 The limiter is structurally supported by the I-tube, and can induce substantial loads on the I-tube, which should be designed for all relevant loads. These loads can be significantly increased by the use of short spool pieces (such as between a bend stiffener and the base of an I-tube), and this should be considered during design of the I-tubes.

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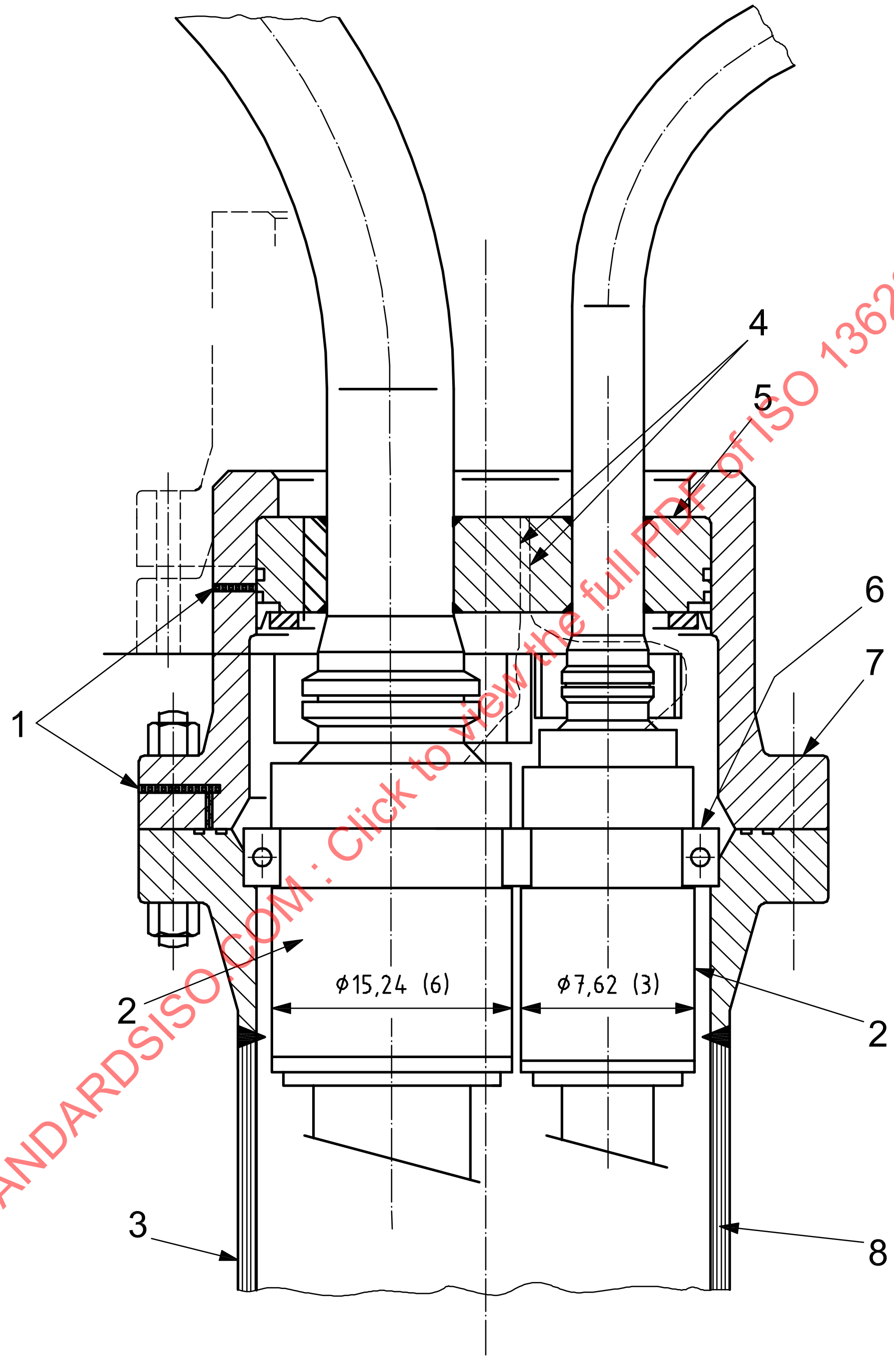
4.4.9.8 Corrosion inhibitors are added, in some cases, to the seawater inside the I-tubes, which requires the bottom of the I-tube to be sealed to prevent loss of inhibitor. If relevant, the design of the riser installation and connection system should account for the requirement for sealing of the I-tube. Compatibility of corrosion inhibitors in the I-tube with materials of the flexible pipe riser shall be verified.

Dimensions in millimetres (inches)



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Key

1 test port
2 flex riser
3 top of deck
4 anunulus bleed line
5 bonnet
6 split plate
7 skirt
8 J-tube

Figure 18 — Example of a typical riser hang-off structure

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5 Pipe design considerations

5.1 General

Clause 5 elaborates and provides guidance on flexible-pipe design consistent with the requirements of ISO 13628-2 and ISO 13628-10. Clause 5 addresses the following specific issues:

a) design process;

b) pipe structural-failure modes;

c) design criteria;

d) design load cases.

5.2 Design overview

5.2.1 General

In 5.2.2 and 5.2.3 a general overview is outlined on the typical design process for flexible-pipe applications. The design process, however, is a function of the pipe application, and a distinction is made between the processes for the design of the following two generic flexible-pipe applications:

a) static (applies to static riser, flowline and jumper applications);

b) dynamic or loading line (applies to dynamic riser, loading-line and jumper applications).

Design of the end fitting is also discussed in 5.2.4. The end fitting is considered an integral part of the pipe.

5.2.2 Static-application design

5.2.2.1 The main design stages for static applications are represented in flowchart form in Figure 19 and are as follows:

a) Stage 1: Materials selection;

b) Stage 2: Cross-section configuration design;

c) Stage 3: System configuration design;

d) Stage 4: Detail and service-life design;

e) Stage 5: Installation design.

5.2.2.2 In Stage 1, the pipe-material selection is made based on internal environment (transported product), functional requirements and material options. Materials compatible with the transported product are selected. Clause 6 contains guidelines for material selection.

5.2.2.3 In Stage 2, the cross-section configuration and dimensions are selected based on the pipe's functional requirements and experience in the selection of the layer structure. Cross-section design calculations and checks are typically carried out by the manufacturer using proprietary software that has been validated with test data.

5.2.2.4 Stage 3 involves selection of the system configuration. This is generally a straightforward task in the case of a flowline, with the only complications typically being the design of the end sections and any requirements to accommodate the relative movement envelope. However, thermal analysis, upheaval buckling and stability analysis can dictate design requirements in certain situations.

5.2.2.5 Stage 4 includes the detailed design of ancillary components, as described in 4.4, and corrosion protection. Service life analysis is also performed at this stage as it applies to the pipe and components.

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5.2.2.6 Stage 5 completes the design process and involves the selection and design of the installation system, including vessel, equipment, methodology and environment conditions. Stage 5 requires detailed global and local analyses to confirm the feasibility of the selected installation system. This stage, in the case of flowlines, is in many cases critical for the pipe design, and it is therefore recommended that preliminary installation analyses be performed at an early stage in the design process.

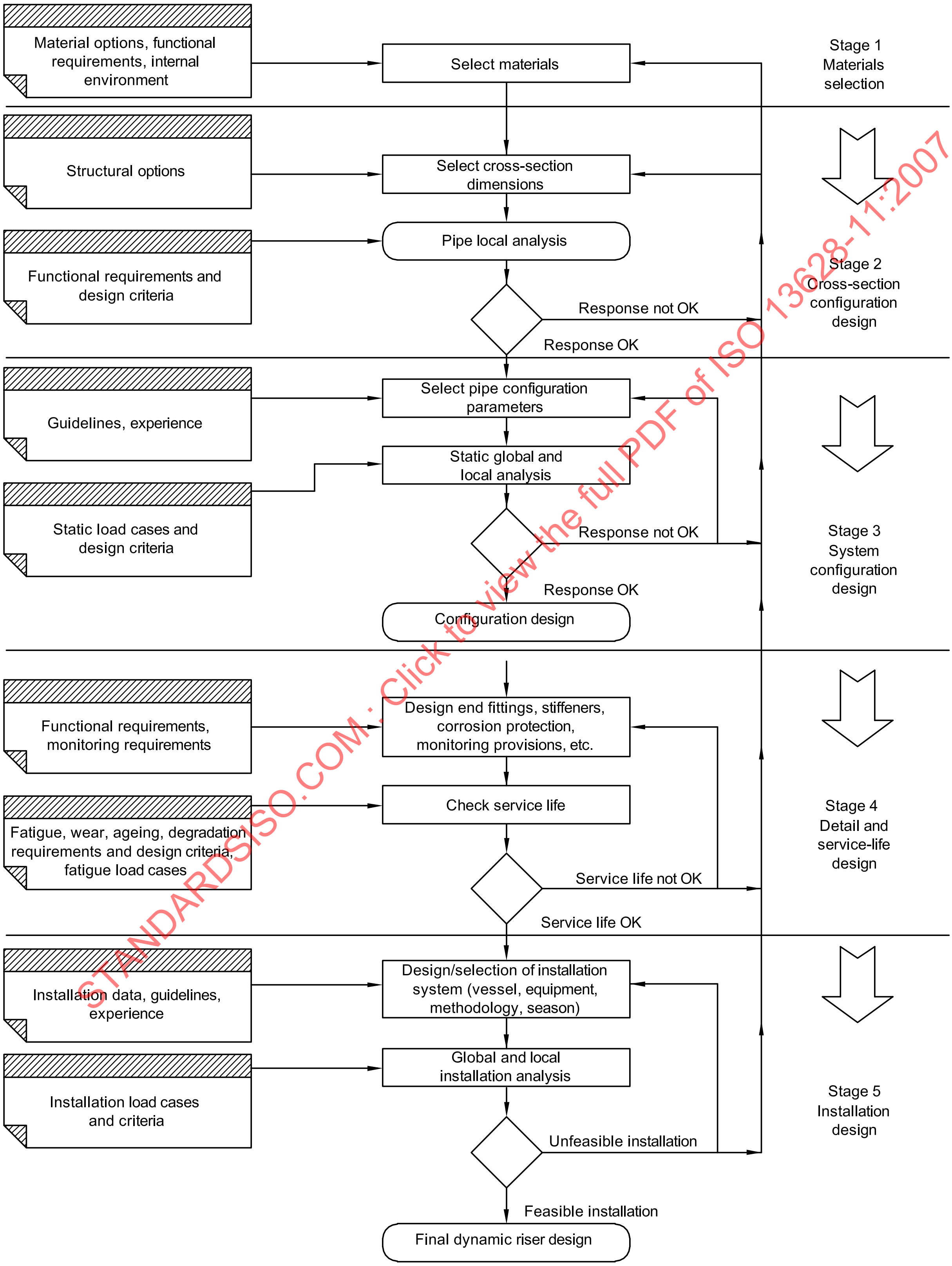

Figure 19 — Static-application design flowchart

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5.2.3 Dynamic-application design

5.2.3.1 The main design stages for dynamic applications are represented in flowchart form in Figure 20, and are as follows:

a) Stage 1: Material selection;

b) Stage 2: Cross-section configuration design;

c) Stage 3: System configuration design;

d) Stage 4: Dynamic analysis and design;

e) Stage 5: Detail and service-life design;

f) Stage 6: Installation design.

5.2.3.2 In Stage 1, the pipe-material selection is made, as for a static flowline, based on internal environment (transported product), functional requirements, and material options. In this case, materials compatible with both the transported product and the dynamic service of the flexible pipe are selected (Clause 6).

5.2.3.3 In Stage 2, the cross-section configuration and dimensions are selected and design calculations and checks are carried out as those for a static flowline.

5.2.3.4 Stage 3 involves selection of the system configuration. This task, for a dynamic riser, involves selecting a pipe configuration from available options, some of which are shown in Figure 4. Some guidelines on the selection of riser configurations are provided in 7.4.1. System configuration design also requires that the effect of ancillary components, such as concentrated or distributed buoyancy, be quantified at this stage.

5.2.3.5 Stage 4 involves the dynamic design of the riser or riser system. Typically, this considers the dynamic response of the riser subject to a series of imposed loading conditions derived from the functional, environmental and accidental loads on the system. Other important issues to be addressed here include possible interference with other system components, top tensions, departure angles and curvatures. Such analysis is typically performed using finite-element dynamic analysis software (8.2.3.3).

5.2.3.6 Stage 5 includes the detailed design of ancillary components, as described in 4.4, and corrosion protection. Service-life analysis is also performed at this stage, as it applies to the pipe and components. Clause 7 gives guidelines on the design of the pipe system and ancillary components.

5.2.3.7 Stage 6, installation design, completes the design process and is largely similar to the equivalent stage in static-flowline design. The complexity of the system installed for risers is generally significantly greater than for a flowline.

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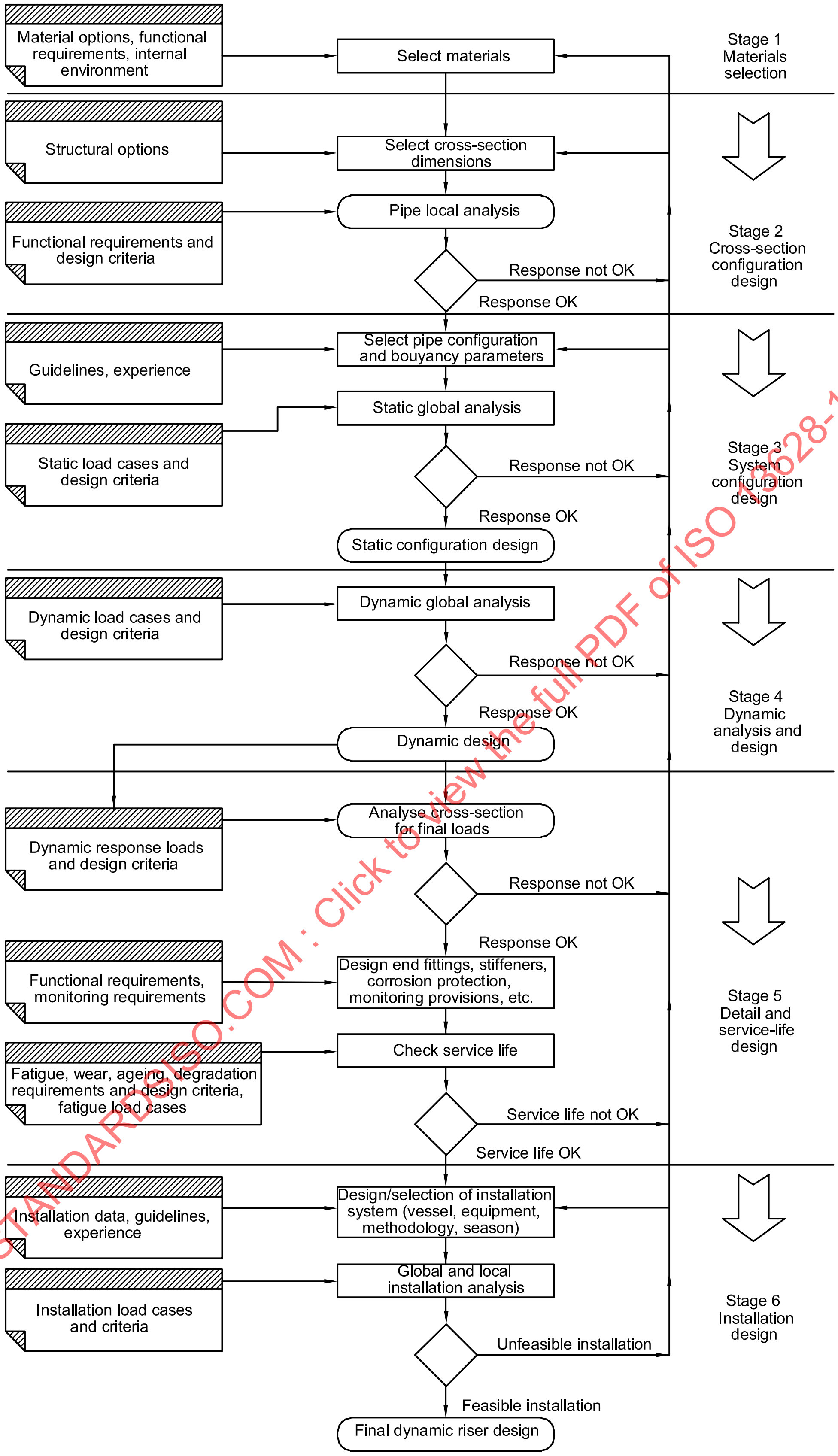

Figure 20 — Dynamic-application design flowchart

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5.2.4 End-fitting design

5.2.4.1 General

The design of the end fitting for flexible pipes is critical. In 4.3.5 the end fittings used for flexible pipes are described, while Figure 8 shows a schematic of a typical unbonded-pipe end fitting. As a minimum, the end fitting design should meet the requirements of ISO 13628-2 and ISO 13628-10.

5.2.4.2 Unbonded pipe

5.2.4.2.1 The end fitting design for unbonded flexible pipes should consider the potential pipe defects identified in 13.3. Of particular relevance are high pressure, deep water and the potential for pull-out of the internal pressure sheath from the inner seal. Critical issues include the following:

a) loss of plasticizer from internal pressure sheath;

b) dimensional changes in sheath because of plasticizer loss and other phenomena;

c) friction coefficient between seal and adjacent layers;

d) creep and stress relaxation in the sheath material;

e) thermal coefficient of expansion for the sheath material;

f) variation of sheath-material properties over service life;

g) requirement for multiple layers in the internal pressure sheath;

h) for vertical risers, potential support of the internal carcass by the internal pressure sheath during periods when pipe is depressurized;

NOTE Decompression results in no support from the pressure armour, as depressurization results in insignificant frictional force between the sheath and the supported pressure armour.

i) number and range of temperature cycles;

j) cool-down rates during temperature cycles of the end fitting and the main pipe body;

k) variations in polymer-material properties with temperature;

l) armour-wire pull-out;

m) epoxy degradation;

n) corrosion;

o) pressure- and tension-retaining capability;

p) resistance to seawater ingress;

q) resistance to external-sheath pull-out during installation.

5.2.4.2.2 The design of the end-fitting internal crimping/sealing mechanism, for PVDF-based pipes in particular, is critical for riser applications. The effectiveness of the seal can be reduced by large temperature cycles, a high thermal-expansion coefficient, plasticizer loss or the use of a multiple-layer construction for a PVDF internal pressure sheath. The end-fitting design should be verified with high-temperature cycling tests (Annex A). These tests should be representative of service conditions, including thermal and dynamic loading, and the effect of plasticizer loss as applicable. For new designs, the prototype tests of Clause 9 should also be considered.

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5.2.4.3 Bonded pipe

The end-fitting design for bonded flexible pipes should consider the potential pipe defects identified in 13.3. Issues of particular relevance include high pressure, deep water, the potential for pull-out of reinforcing cables and loss of fluid-seal integrity. Critical issues include the following:

a) change of pipe body, particularly liner-material properties over service life;

b) dimensional changes in pipe body due to the highly elastic nature of pipe-body elastomer material;

c) bonding of liner-material layers and bonding of liner to remainder of flexible-pipe body;

d) reinforcing-armour pull-out;

e) epoxy degradation;

f) corrosion;

g) pressure- and tension-retaining capability;

h) resistance to seawater ingress;

i) integrated gasket integrity;

j) crimping over-pressure applied;

k) number and range of temperature and pressure cycles;

l) incorporation of integrated bend stiffeners.

5.3 Failure modes

It is important to design a flexible pipe with the knowledge of the potential degradation and failure modes for the intended application. It is important to note that other modes of pipe degradation and failure possibly can be implicitly provided for in design (such as through materials selection, see Clause 6) or are considered, for example, as part of manufacture (Clause 10) or handling, transportation and installation (Clause 11).

Tables 3 and 4 provide lists of pipe-failure modes that are explicitly provided for in typical unbonded- and bonded-pipe design, respectively, and identify relevant failure mechanisms and appropriate design strategies/solutions. The design solutions shall, in all cases, meet the design criteria specified in ISO 13628-2 and ISO 13628-10. A more complete, though not exhaustive, list of potential pipe defects for flowline and riser applications is presented in Tables 30 to 32. Furthermore, some of the modes identified in Table 3, Table 4, Table 30, Table 31 and Table 32 are being addressed by continuing design improvements and are therefore not necessarily relevant to future pipe designs.

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Table 3 — Checklist of failure modes for primary structural design of unbonded flexible pipe

Pipe global failure mode to design against	Potential failure mechanisms	SA or DA	Design solution or variables (ISO 13628-2)
Collapse	1) Collapse of carcass and/or pressure armour due to excessive tension. 2) Collapse of carcass and/or pressure armours due to excess external pressure. 3) Collapse of carcass and/or pressure armour due to installation loads or ovalization due to installation loads. 4) Collapse of internal pressure sheath in smooth-bore pipe.	SA, DA SA, DA SA, DA SA, DA	1) Increase thickness of carcass strip, pressure armour or internal pressure sheath (smooth-bore collapse). 2) Modify configuration or installation design to reduce loads. 3) Add intermediate leak-proof sheath (smooth-bore pipes). 4) Increase the area moment of inertia of carcass or pressure armour.
Burst [a]	1) Rupture of pressure armours because of excess internal pressure. 2) Rupture of tensile armours due to excess internal pressure.	SA, DA SA, DA	1) Modify design, e.g. change lay angle, wire shape, etc. 2) Increase wire thickness or select higher-strength material if feasible. 3) Add additional pressure- or tensile-armour layers.
Tensile failure [a]	1) Rupture of tensile armours due to excess tension. 2) Collapse of carcass and/or pressure armours and/or internal pressure sheath due to excess tension. 3) Snagging by fishing trawl board or anchor, causing overbending or tensile failure.	SA, DA SA, DA SA, DA	1) Increase wire thickness or select higher-strength material if feasible. 2) Modify configuration designs to reduce loads. 3) Add two more armour layers. 4) Bury pipe.
Compressive failure	1) Bird-caging of tensile-armour wires. 2) Compression leading to upheaval buckling and excess bending (see also upheaval buckling failure mode, 7.3.4).	SA, DA SA, DA	1) Avoid riser configurations that cause excessive pipe compression. 2) Provide additional support/restraint for tensile armours, such as tape and/or additional or thicker outer sheath.
Overbending [a]	1) Collapse of carcass and/or pressure armour or internal pressure sheath. 2) Rupture of internal pressure sheath. 3) Unlocking of interlocked pressure or tensile-armour layer. 4) Crack in outer sheath.	SA, DA SA, DA SA, DA SA, DA	Modify configuration designs to reduce loads.
Torsional failure [a]	1) Failure of tensile-armour wires. 2) Collapse of carcass and/or internal pressure sheath. 3) Bird-caging of tensile-armour wires.	SA, DA SA, DA SA, DA	1) Modify system design to reduce torsional loads. 2) Modify cross-section design (e.g. change lay angle of wires, add extra layer outside armour wires, etc.) to increase torsional capacity.
Fatigue failure	1) Tensile-armour-wire fatigue. 2) Pressure-armour-wire fatigue.	DA DA	1) Increase wire thickness or select alternative material, so that fatigue stresses are compatible with service-life requirements. 2) Modify design to reduce fatigue loads.
Erosion	Of internal carcass.	SA, DA	1) Modify material selection. 2) Increase thickness of carcass. 3) Reduce sand content. 4) Increase MBR.
Corrosion	1) Of internal carcass. 2) Of pressure- or tensile-armour exposed to seawater, if applicable. 3) Of pressure- or tensile-armour exposed to diffused product.	SA, DA SA, DA SA, DA	1) Modify material selection. 2) Cathodic protection system design. 3) Increase layer thickness. 4) Add coatings or lubricants.

[a] Burst, tensile, overbending and torsional failure are not considered in isolation for final design of the flexible pipe.

NOTE See Tables 30 to 32 for defects important in end-fitting designs.

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Table 4 — Checklist of failure modes for primary structural design of bonded flexible pipe

Pipe global failure mode to design against	Potential failure mechanisms	SA or DA	Design solution or variables (ISO 13628-10)
Collapse	1) Collapse of carcass due to excessive tension. 2) Collapse of carcass due to excess external pressure. 3) Collapse of carcass and due to installation loads or ovalization due to installation loads. 4) Collapse of pipe in smooth-bore pipe.	SA, DA SA, DA SA, DA	1) Increase thickness of carcass strip or pipe body (smooth-bore collapse). 2) Modify configuration or installation design to reduce loads. 3) Increase the area moment of inertia of carcass.
Burst [a]	1) Rupture of reinforcing armours due to excess internal pressure.	SA, DA	1) Modify design, e.g. change lay angle, cable type, etc. 2) Increase cable thickness or select higher strength material if feasible. 3) Add additional reinforcing-armour layers.
Tensile failure [a]	1) Rupture of reinforcing armours due to excess tension. 2) Collapse of carcass and/or pipe-body sheath due to excess tension. 3) Snagging by fishing trawl board or anchor, causing overbending or tensile failure.	SA, DA SA, DA SA, DA	1) Increase cable thickness or select higher-strength material if feasible. 2) Modify configuration designs to reduce loads. 3) Add two more armour layers. 4) Bury pipe.
Compressive failure	1) Compression leading to upheaval buckling and excess bending (see also upheaval buckling failure mode, 7.3.4).	SA, DA	Avoid riser configurations that cause excessive pipe compression.
Overbending [a]	1) Collapse of carcass or pipe body. 2) Rupture of liner. 3) Crack/tear in outer sheath.	SA, DA SA, DA SA, DA	Modify configuration designs to reduce loads.
Torsional failure [a]	1) Failure of tensile-armour wires. 2) Collapse of carcass and/or liner. 3) Birdcaging of tensile-armour wires.	SA, DA SA, DA SA, DA	1) Modify system design to reduce torsional loads. 2) Modify cross-section design (e.g. change lay angle of wires, add extra layer outside armour wires, etc.) to increase torsional capacity.
Fatigue failure	1) Tensile-armour-wire fatigue. 2) Pressure-armour-wire fatigue.	DA DA	1) Increase wire thickness or select alternative material, so that fatigue stresses are compatible with service-life requirements. 2) Modify design to reduce fatigue loads.
Erosion	1) Of internal carcass or liner.	SA, DA	1) Modify material selection. 2) Increase thickness of carcass. 3) Reduce sand content. 4) Increase MBR.
Corrosion	1) Of internal carcass. 2) Of pressure- or tensile-armour exposed to seawater, if applicable. 3) Of pressure- or tensile-armour exposed to diffused product.	SA, DA SA, DA SA, DA	1) Modify material selection. 2) Modify cathodic protection system design. 3) Increase layer thickness. 4) Add coatings or lubricants.

[a] Burst, tensile, overbending and torsional failure are not considered in isolation for final design of the flexible pipe.

NOTE See Tables 30 to 32 for defects important in end-fitting design.

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5.4 Design criteria

5.4.1 Unbonded flexible pipe

5.4.1.1 Introduction

5.4.1.1.1 The design criteria for unbonded flexible pipes are given in ISO 13628-2 in terms of the following:

a) strain (polymer sheath);

b) creep (internal pressure sheath);

c) stress (metallic layers and end fitting);

d) hydrostatic collapse (buckling load);

e) mechanical collapse (stress induced from armour layers);

f) torsion;

g) crushing collapse and ovalization (during installation);

h) compression (axial and effective);

i) service-life factors.

5.4.1.1.2 These criteria are discussed further in 5.4.1.2 to 5.4.1.10, in which some guidance on their derivation is given. Criteria are also introduced that provide for design against failure in addition to the criteria specified in ISO 13628-2.

5.4.1.1.3 The criteria specified by ISO 13628-2 apply to the materials currently used in flexible-pipe applications. Where new materials are proposed or used, the design criteria for the new materials should give at least the safety level specified in this part of ISO 13628 and in ISO 13628-2. The design criteria should consider all material characteristics, such as susceptibility to such conditions as creep, fatigue, excessive strain and cracking.

5.4.1.1.4 Simplified approaches exist for the approximation of pipe characteristics (axial, bending and torsional stiffness, etc.) and for calculating loads in the individual layers. These simplified methodologies may be used for preliminary comparison of design loads with design criteria. For final design calculations, however, it is necessary to use a verified (with prototype tests) methodology, as defined in ISO 13628-2.

5.4.1.2 Strain

5.4.1.2.1 A critical parameter in the design of the internal pressure and outer sheaths is the allowable strain. ISO 13628-2 specifies allowable-strain values for the most commonly used materials. The allowable strain for materials not explicitly provided for in ISO 13628-2 is specified by the manufacturer.

5.4.1.2.2 Allowable strains have been verified by material tests performed under relevant service and ageing conditions. A safety factor is typically applied to results of such tests to derive the allowable strain of the material over its service life, accounting for material ageing and degradation in the appropriate environment.

5.4.1.2.3 ISO 13628-2 also provides for the calculation of MBR to prevent locking of the interlocked pressure-armour wires.

5.4.1.3 Creep

5.4.1.3.1 Under normal service conditions, the internal pressure sheath creeps into gaps in the pressure- or tensile-armour layer as a result of pressure and temperature effects. If the sheath is too thin or the gap too large, the internal pressure sheath will creep until a failure (leakage) occurs. Creep of the sheath at the end-fitting seal is also an important issue (see Table 5).

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Table 5 — Recommended allowable degradation for unbonded pipes

Component	Degradation mode	Recommendation
Carcass	1) Corrosion 2) Erosion	1) Limited corrosion acceptable provided structural capacity and functional requirements are maintained. 2) Same as for corrosion.
Internal pressure sheath	1) Creep 2) Thermal/chemical degradation 3) Cracking	1) Limited creep acceptable provided — structural capacity to bridge gaps maintained, — no cracks, — no locking of carcass or pressure-armour layers, — no leakage, — sealing maintained at end fittings. 2) Capacity at design life remains within specified usage factors with maximum gaps between layers. No leakage allowed. Increased permeation allowed if system has been designed for the increased level of permeation. Important considerations are increased damage rates (corrosion, HIC, SSC) for armours and limits on gas-venting-system capacity. Strain capacity sufficient to meet the design requirements of ISO 13628-2. 3) No cracking because of dynamic service.
Pressure and tensile armours	1) Corrosion 2) Disorganization or locking of armouring wires 3) Fatigue and wear	1) Only general corrosion accepted; no crack initiation acceptable. 2) No disorganization of armouring wires when bending to minimum bend radius. 3) See 8.2.4.
Anti-wear layer	1) Wear	1) No wear through the thickness of the layer over its service life.
Intermediate sheath	1) Thermal degradation	1) Functional requirements are maintained.
Thermal insulation	1) Thermal degradation	1) Insulation capacity is maintained equal to or above minimum specified value.
Outer sheath	1) General degradation 2) Radial deformation (loosening) 3) Breaching	1) Strain capacity is sufficient to meet the design requirements of ISO 13628-2. 2) No loosening that causes the disorganization of armour wires or strain failure of outer sheath material. 3) No breaching allowed unless pipe design under flooded annulus conditions can be shown to meet the design requirements and remaining service-life requirements.
End fitting and carcass/sheath interface	1) Corrosion	1) No corrosion that results in reduction of capacity, possibility for leakage, or damage to any sealing or locking mechanism is acceptable.

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5.4.1.3.2 The design of the internal pressure sheath (wall thickness) should account for creep. The main factors that require consideration are material properties, layer thickness, pressure- or tensile-armour geometry, temperature and pressure. Two methodologies are currently used to determine the wall thickness required to prevent creep failure:

a) physical tests to determine the required wall thickness;

b) finite-element analyses, calibrated with gap span test data, to determine the required wall thickness.

5.4.1.3.3 The creep design criterion specified in ISO 13628-2 is based on both of these methodologies. This specifies the maximum allowable reduction in wall thickness below the minimum design value under all load conditions.

5.4.1.4 Stress

The design stress criteria (utilization factors) given in ISO 13628-2 were derived to give acceptable factors of safety against failure. These factors prescribe the maximum nominal applied stress as a proportion of the structural capacity of steel materials. The utilization factors make implicit allowance for the presence of residual wire stress.

NOTE The published utilization factors relate to steel materials. No inference can be made about allowable stress in new materials based on these values.

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5.4.1.5 Hydrostatic collapse

5.4.1.5.1 Utilization factors which relate to buckling of the internal carcass under hydrostatic pressure are specified in ISO 13628-2 as a function of water depth, with a higher permissible utilization factor (smaller safety factor) allowed for deep-water applications. The safety factor (the reciprocal of the utilization factor) is related to the absolute, rather than relative, margin between collapse and design depth.

5.4.1.5.2 Hydrostatic collapse calculations should be performed for both an intact outer sheath and a breached outer sheath (such as seawater penetration into the annulus), with the hydrostatic collapse resistance taken as the minimum of the two collapse-pressure values. Analytical methods for calculating collapse resistance should be based on an assumed initial ovalization. This ovalization should be selected by the manufacturer, based on manufacturing tolerance limits and residual ovalization from the installation process. A minimum ovality of 0,2 % should be used if no other data exist.

5.4.1.5.3 The collapse resistance for smooth-bore pipes should also be calculated based on the resistance of the internal pressure sheath only, and standard analytical methods may be used. If the collapse-to-design ratio is below the required value, then it should be specified that sufficient internal pressure be maintained to prevent collapse (such as by ensuring that the line is full of liquid at hydrostatic pressure). Alternatively, an impermeable intermediate sheath should be provided to ensure that the pressure armour provides the required collapse resistance.

5.4.1.5.4 FPS 2000 [23] and Reference [34] contain recommended procedures for calculating the hydrostatic buckling load (collapse pressure) of a carcass. However, these procedures are for the carcass layer alone. In pipe designs that include a pressure-armour layer, this layer assists the carcass and significantly increases the collapse strength of the pipe. When used, methodologies for calculating the collapse strength (design water depth) of a flexible pipe with contribution from the pressure-armour layer should be verified by documented prototype tests.

5.4.1.6 Mechanical collapse

5.4.1.6.1 The utilization factors that relate to mechanical collapse of the internal carcass due to excessive tension are specified in ISO 13628-2 and are identical to the utilization factors for the tensile and pressure armours.

5.4.1.6.2 The contribution of all supporting steel layers may be taken into account when designing against mechanical collapse.

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5.4.1.7 Torsion

5.4.1.7.1 The flexible pipe should have a torsional strength sufficient to withstand torsional loads induced during installation and service conditions without any structural damage. The torsional stiffness indicates the resistance of a flexible pipe to rotation around its axis under a torsional moment and is a performance characteristic of the pipe.

5.4.1.7.2 The maximum acceptable torsion derives from the following two scenarios, depending on the direction of the applied torsion.

5.4.1.7.3 The outer tensile-armour layer is turned inward and presses against the internal layer (in which case the allowable tension causes overstressing of the tensile armour) by inducing a stress corresponding to its structural capacity (defined by ISO 13628-2 and multiplied by the utilization factor specified in ISO 13628-2).

5.4.1.7.4 The inner tensile-armour layer is turned outward and presses against the outer layers, leading to a gap between the two tensile.armour layers, in which case, the damaging torsion induces a gap between tensile-armour layers equal to half the thickness of the tensile-armour wire. The allowable torsion for this case should be calculated from the damaging torsion using a safety factor not less than 1,0.

5.4.1.8 Crushing collapse and ovalization

5.4.1.8.1 During conventional laying operations, the tension in the flexible pipe is generally controlled with a tensioner or with a laying winch. The load applied to the flexible pipe when tightening it in a tensioner or unreeling/reeling the flexible pipe under tension (possibly over a V-shaped sheave) shall be controlled to avoid sudden collapse (or significant ovalization) of the structure or overstressing of the metallic layers. The tension loads and crushing effect on the structure during installation should be accounted for in the design of the flexible pipe.

5.4.1.8.2 The feasibility of installing the flexible pipe with the selected procedure should be evaluated considering the following effects:

a) crushing of the flexible pipe under radial compression in a tensioner;

b) crushing effect on a laying pulley or sheave;

c) damaging pull of the flexible pipe at the top of the catenary.

5.4.1.8.3 The collapse load should be calculated based on the resistance of the internal carcass and supporting pressure layers (pressure armour and flat steel spiral), as applicable. The two following alternative approaches, which have been calibrated against full-scale tests, are recommended for the collapse calculation:

a) finite-element analysis;

b) analytical/empirical equations.

5.4.1.8.4 The following load cases should be investigated, as applicable:

a) reeling/unreeling on a sheave of a flexible pipe subjected to design maximum axial load;

b) radial compression in a tensioner of a flexible pipe subjected to design maximum axial load.

5.4.1.8.5 The minimum of the following two limits should then be taken as the design maximum allowable installation tension.

a) The axial tension or radial compression in the flexible pipe should remain less than that which induces a stress corresponding to the structural capacity of the pressure or tensile armours (defined by ISO 13628-2 and multiplied by the utilization factor for installation, as specified in ISO 13628-2);

b) The effective tension or radial compression in the flexible pipe should be less than that which induces mechanical collapse, multiplied by the utilization factor for installation, as specified in ISO 13628-2.

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5.4.1.8.6 In addition, the maximum permanent ovalization of the pipe for both installation methods should be less than the value of initial ovalization used for hydrostatic collapse calculations (see 5.4.1.5).

5.4.1.9 Compression

5.4.1.9.1 A flexible pipe can be subject to two types of compression: effective compression (negative effective tension) and axial (true wall) compression. Effective compression causes increased deformations in the pipe, while axial compression can potentially cause bird-caging in the tensile-armour layer. The behaviour of flexible pipe under compressive load is based on the pipe temperature.

5.4.1.9.2 The potential for both types of compression to occur should be checked in the design of the flexible pipe system. If effective compression occurs, the following design criteria should be verified.

a) The effective compression should be less than that which causes the MBR criteria to be violated (see ISO 13628-2).

b) Bar buckling of the pipe should not occur.

5.4.1.9.3 The maximum axial compression for an unbonded flexible pipe should be calculated as the value which causes a gap between the tensile-armour wires and the underlying layer equal to half the thickness of the armour wire. The allowable axial compression for stress and stability should be calculated from the maximum axial compression using a safety factor not less than 1,0, and any axial compression experienced by the pipe should be less than the allowable. Tensile wire buckling analysis should also be conducted.

5.4.1.10 Service-life factors

In 8.2.4 is presented a more detailed discussion of service-life analysis, including fatigue calculations. The criteria for fatigue calculations are specified in ISO 13628-2. Furthermore, permissible levels of degradation should be defined for the service-life analysis. Recommendations on these are given in Table 5.

5.4.2 Bonded flexible pipe

5.4.2.1 Introduction

5.4.2.1.1 The design criteria for bonded flexible pipes are shown in ISO 13628-10 in terms of the following:

- strain (elastomer layers);
- stress and load (reinforcement layers, carcass and end fitting);
- hydrostatic collapse (buckling load);
- mechanical collapse (stress induced from reinforcement layers);
- crushing collapse and ovalization (during installation);
- service-life factors.

5.4.2.1.2 These criteria are discussed further in 5.4.2.2 to 5.4.2.9, in which some guidance on their derivation is given. Criteria are also introduced that provide for design against failure additional to the criteria specified in ISO 13628-10.

5.4.2.1.3 The criteria specified by ISO 13628-10 apply to the materials currently used in bonded flexible pipe applications. If new materials are proposed or used, the design criteria for the new materials should give at least the safety level specified in this part of ISO 13628 and in ISO 13628-10. The design criteria should consider all material characteristics, such as ageing, fatigue and excessive strain.

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5.4.2.1.4 Simplified approaches exist for the calculation of pipe characteristics (axial, bending and torsional stiffness, etc.) and for calculating loads in the individual materials of the pipe (reinforcing cables, elastomer body, etc.). These simplified methodologies may be used for preliminary comparison of design loads with design criteria. A verified (with prototype tests) methodology as defined in ISO 13628-10 shall be used for final design calculations.

5.4.2.1.5 Due to the composite nature of bonded flexible pipes, the verified design methodology should account for interaction between metallic and elastomer components, and for load sharing between different layers and components, in particular at and adjacent to the end fitting.

5.4.2.1.6 Two distinctly different types of design methodology are used by bonded-flexible-pipe manufacturers. Some manufacturers use analytical or finite-element methods to account for the load sharing between the various components making up the bonded pipe. Others use standard analytical methods derived from geometrical considerations of the pipe in conjunction with empirical efficiency factors. The efficiency factors are calculated based on prototype tests, for example burst and tensile tests.

5.4.2.2 Strain

5.4.2.2.1 ISO 13628-10 specifies allowable strain values for elastomer layers as a maximum of 50 % of design maximum strain for aged material. Due to the typically large strain capacity of elastomer materials used in the manufacture of bonded flexible pipes, this design criterion is not necessarily as critical as it is for the thermoplastic materials used in the manufacture of unbonded flexible pipe.

5.4.2.2.2 ISO 13628-10 provides for the calculation of MBR to prevent damage to the interlocked inner or outer carcass, if present.

5.4.2.3 Stress/load

The design stress and load criteria (utilization factors) given in ISO 13628-10 were derived to give acceptable factors of safety against failure. These factors prescribe the maximum nominal applied stress or load as a proportion of the structural capacity of steel materials (defined by ISO 13628-10). The utilization factors make implicit allowance for the presence of residual wire stress.

NOTE The published utilization factors relate to steel materials. No inference can be made about allowable stress in new materials based on these values.

5.4.2.4 Hydrostatic collapse

5.4.2.4.1 Utilization factors that relate to buckling of the internal carcass under hydrostatic pressure are specified in ISO 13628-10 as a function of water depth, with a higher permissible utilization factor (smaller safety factor) allowed for deep-water applications. The safety factor (the reciprocal of the utilization factor) is related to the absolute, rather than relative, margin between collapse and design depth.

5.4.2.4.2 Analytical methods, if used for calculating collapse resistance, should be based on an assumed initial ovalization. This ovalization should be selected by the manufacturer, based on manufacturing tolerance limits and residual ovalization from the installation process. A minimum ovality of 0,2 % should be used if no other data exist.

5.4.2.4.3 The collapse resistance for smooth-bore pipes should be calculated based on the resistance of the pipe body, and standard analytical methods may be used. If the collapse-to-design ratio is below the required value and if the pipe is not designed to be collapsible, then it should be specified that sufficient internal pressure be maintained to prevent collapse (such as by ensuring that the line is full of liquid at hydrostatic pressure).

5.4.2.4.4 The hydrostatic buckling load (collapse pressure) of a carcass should be calculated as per FPS 2000 [23] and Reference [34].

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5.4.2.5 Mechanical collapse

See 5.4.1.6.

5.4.2.6 Torsion

See 5.4.1.7.

5.4.2.7 Crushing collapse and ovalization

See 5.4.1.8.

5.4.2.8 Compression

See 5.4.1.9.1 and 5.4.1.9.2.

5.4.2.9 Service-life factors

In 8.2.4 is presented a more detailed discussion of service-life analysis, including fatigue calculations. The criteria for fatigue calculations are specified in ISO 13628-10. Furthermore, permissible levels of degradation (see Table 6) should be defined for the service-life analysis.

Table 6 — Recommended allowable degradation for bonded pipe

Component	Degradation	Recommendation
Carcass	1) Corrosion	1) Limited corrosion is acceptable provided structural capacity and functional requirements are maintained.
	2) Erosion	2) Same as for corrosion.
Liner	1) Blistering, delamination	1) No blistering, delamination or leakage paths because of gas rapid decompression. Damage due to dissection process should be ignored.
	2) Thermal/chemical degradation	2) No leakage is allowed. Increased permeation allowed if system has been designed for the increased level of permeation. Limited degradation acceptable provided sealing is maintained at end fitting in addition to the above.
Reinforced layers	1) Corrosion	1) No corrosion that results in increase in utilization of cables in reinforcing layer to beyond allowable values shown in ISO 13628-10:2005, Table 7, is allowed.
	2) Fatigue and wear	2) See 8.2.4.
Cover	1) General degradation	1) Strain capacity is sufficient to meet the design requirements of ISO 13628-10:2005, Table 7.
End fitting	1) Corrosion	1) No corrosion that results in reduction of capacity, possibilities for leakage, or damage to any sealing or locking mechanism is allowed.

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5.5 Load cases

5.5.1 General

5.5.1.1 The flexible pipe shall be designed to satisfy its functional requirements under loading conditions corresponding to the internal environment, external environment, system requirements and service life defined by the purchaser of the pipe.

5.5.1.2 All potential load cases for the flexible pipe system, including manufacture, storage, transportation, testing, installation, operation, retrieval and accidental events shall be defined by the manufacturer in the design premise specified by ISO 13628-2 and ISO 13628-10. The design premise should specify a load case matrix that defines all normal, abnormal, installation and fatigue loading conditions according to requirements specified by the purchaser in ISO 13628-2:2006, Annex A, and ISO 13628-10:2005, Annex A.

5.5.1.3 Table 7 contains the recommended annual probabilities of occurrence for installation, and normal and abnormal loads for a 20-year service life. These can be changed for different service lives. The following two load combinations should be considered, unless more specific data are available, when combining annual probabilities of waves and currents for 100-year conditions:

a) 100-year wave combined with 10-year current;

b) 10-year wave combined with 100-year current.

Table 7 — Recommendations on annual probabilities for installation, and normal and abnormal operation for a 20-year service life

Type of load [a]	Service condition		
	Installation	Service	
		Normal service [b]	Abnormal service [b]
Functional	Expected, specified or extreme value.	Expected, specified or extreme value.	Expected, specified or extreme value.
External environmental	Probability of exceedance according to season and duration of installation period.	Yearly probability of exceedance > 10^{-2}.	Yearly probability of exceedance between 10^{-2} and 10^{-4}.
Possibility of abandonment	If abandonment is possible, the maximum weather in a period three times the expected installation duration can be used. If abandonment is impossible, a more conservative approach shall be used or the duration of the operation reduced to a period where reliable weather forecast is available (typically hours).	The environmental load may be reduced such that the yearly probability of joint occurrence is > 10^{-2} if combined with an accidental load. —	The environmental load may be reduced such that the yearly probability of joint occurrence is > 10^{-4} if combined with an accidental load. —
Accidental	As appropriate to installation method.	As appropriate to normal operation conditions, i.e. annual probability > 10^{-2}.	Individual considerations. Yearly probability between 10^{-2} and 10^{-4}.

[a] See ISO 13628-2 and ISO 13628-10 for load combination requirements.

[b] Yearly probabilities of 10^{-2} and 10^{-4} are equivalent to return periods of 100 years and 10 000 years, respectively.

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5.5.1.4 The requirement to analyse load cases for an accidental event should be based on an assessment of the probability of the event occurring. The accidental events typically considered for static applications include impact from trawl boards and dropped objects. For dynamic applications, accidental events typically considered include one or more mooring lines broken and partial loss of buoyancy. Furthermore, for dynamic applications, consideration should be given to performing extreme-event load cases (such as events with probabilities of occurrence equal to or less than 10^{-4}) to assess the robustness of the design.

5.5.1.5 The load-case matrix constitutes the full set of loading conditions examined as part of the structural analysis and design process. Specific load cases form inputs to five stages in the overall pipe design, as follows:

a) cross-section configuration design (local analyses);

b) system configuration design (static global and local analyses);

c) dynamic analysis and design (global analyses for dynamic riser design only);

d) detail and service-life design (final local and service-life analyses);

e) installation design (global and local analyses).

5.5.1.6 Figures 19 and 20 illustrate the stages listed in 5.5.1.5 for the static flowline (or static riser) and dynamic riser (or dynamic jumper) design processes, respectively, and are discussed further in 5.5.2 to 5.5.6.

All stages of the design process involve either global or local (cross-section) analyses of the flexible pipe. The primary objectives of the global analyses are to verify that the main design criteria are satisfied (such as MBR, allowable tension and stability of dynamic motions) and to identify critical load combinations. Local analysis is then performed to verify that these critical global load combinations do not exceed the criteria specified in ISO 13628-2 and ISO 13628-10.

5.5.2 Cross-section configuration design

The results of initial local analyses (to determine burst pressure, response to FAT pressure, MBR, collapse depth, damaging tension, thermal properties, weight in seawater, drag-to-weight ratio, etc.) provide information that can be compared with design requirements (such as water depth and design pressure) and experience to arrive at a preliminary cross-section design. This initial cross-section design can be subsequently modified based on the results from the remaining stages in the design process. In particular, it can be necessary to consider installation loads at the start of the design process for deep-water applications.

5.5.3 System configuration design

5.5.3.1 Input to this stage includes all static loads relating to the system design. The pipe is analysed under all functional, environmental and accidental loading combinations deriving from the internal environment (pressure, temperature, fluid composition) and the static components of the external environment defined in ISO 13628-2 and ISO 13628-10. In this context, functional, environmental and accidental loads are defined by ISO 13628-2 and ISO 13628-10.

5.5.3.2 Examples of the global-static-analysis load cases that form an input to this process include thermal analysis, upheaval-buckling load cases (static flowlines only), on-bottom stability load cases (static flowlines only), and/or static global-configuration load cases. Table 8 presents a typical example of the global-static-analysis load cases relating to this stage of design. Local analyses are generally required only for static applications in this phase of the design. The local analyses for dynamic applications are performed in Stage 4 of Figure 20. Local analysis load cases for static applications should include all relevant test, installation and operational load cases.

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EXAMPLES

Case A Design pressure, mean tension, bending to maximum expected curvature.

Case B No internal fluid, external hydrostatic pressure at maximum water depth, damaged outer sheath.

Case C Maximum axial compression.

Table 8 — Typical static global-analysis load cases — Operating conditions

Load case	Description	Application
A	Global static analysis at design pressure, operating internal fluid, mean vessel offset, no current.	DA
B	Global static analysis at design pressure, operating internal fluid, 100-year return inline near current, 100-year near-vessel offset.	DA
C	Global static analysis at design pressure, operating internal fluid, 100-year return far current, 100-year far-vessel offset.	DA
D	Global static analysis at design pressure, operating internal fluid, 100-year return cross-current, 100-year cross-vessel offset.	DA
E	Thermal analysis.	SA, DA
F	On-bottom stability analysis.	SA
G	Upheaval-buckling analysis.	SA

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5.5.4 Dynamic analysis and design

5.5.4.1 Load cases for this stage relate only to dynamic riser (or jumper) applications and include all dynamic loads for the global system design. The pipe is again analysed under all functional, environmental, and accidental loading combinations deriving from the internal and external environment. For static design, the functional, environmental and accidental loads are defined by ISO 13628-2 and ISO 13628-10.

5.5.4.2 All dynamic operational and accidental load cases typically combining static internal with dynamic external environmental conditions (such as wave, current and riser top motions) are considered as part of the dynamic analysis. Sufficient load cases should be analysed to cover the complete envelope of response in terms of motions and forces. Sensitivity studies should be performed to evaluate the effect of variations in critical parameters, including internal fluid, marine growth, wave periods, VIV effects, etc. The load-case matrix depends largely on site-specific conditions.

5.5.4.3 Tables 9 and 10 illustrate elements of the recommended approach.

5.5.4.3.1 Table 9 contains an example sub-set of load cases for an FPSO/FPS application. Each of the defined load cases would be analysed for different combinations of environmental conditions. Table 10 contains a typical example of a global-dynamic-analysis load matrix for a set of “functional and environmental” operational load cases.

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Table 9 — Example of dynamic load cases for FPSO/FPS applications

Load case	Load condition [a]	Load type	Stress criterion [b]	MBR criterion [c]	Description
A	Normal operation	Functional and environmental	0,55 Pressure armour	1,5	Operating internal fluid conditions, intact mooring system and 100-year environmental conditions.
			0,67 Tensile armour	—	—
B	Normal operation	Functional, environmental and accidental	0,85	1,25	No internal fluid, one mooring line broken and 100-year environmental conditions.
C	Abnormal operation	Functional, environmental and accidental	0,85	1,25	No internal fluid, two mooring lines broken and 10-year environmental conditions.

[a] Regulatory or contractual requirements should define actual “normal” or “abnormal” operations.

[b] The stress criterion is permissible utilization as a function of structural capacity.

[c] The MBR criterion is a factor of safety on storage MBR.

5.5.4.3.2 Table 10 shows the use of regular wave analyses. Consideration can be given to also using irregular sea analyses for complete design or design verification. Generally, vessel-offset data is given as maximum values. If significant values are available, then these may be used for regular wave analyses. Maximum values should be used for irregular sea analyses. See 8.4.1 for guidance on analysis types.

Table 10 — Example of a dynamic load-case matrix — Normal operation — Functional and environmental loads

Parameter	Load-case matrix [a, b]					
	Near [c]	**Near**	**Far [d]**	**Far**	**Cross [e]**	**Cross**
Water depth	Min. MWL	Min. MWL	Max. MWL	Max. MWL	Max. MWL	Max. MWL
Internal pressure	Operating	Operating	Operating	Operating	Operating	Operating
Vessel draft	Loaded	Loaded	Ballasted	Ballasted	Ballasted	Ballasted
Vessel offset [f]	Near intact	Near intact	Far intact	Far intact	Cross intact	Cross intact
Current	Near 10-year	Near 10-year	Far 10-year	Far 10-year	Cross 10-year	Cross 10-year
Regular wave height	Near 100-year	Near 100-year	Far 100-year	Far 100-year	Cross 100-year	Cross 100-year
Regular wave height [g]	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum

[a] Appropriate vessel motions shall be included in the load cases.

[b] Similar matrices shall also be prepared for the load cases B and C in Table 9.

[c] Near case has the environment and offset orientated along the plane of the riser toward the riser-seabed connection.

[d] Far case has the environment and offset orientated along the plane of the riser away from the riser-seabed connection.

[e] Cross case has the environment and offset orientated perpendicular to the plane of the riser.

[f] Vessel offset includes installation tolerances. Intact refers to the mooring system condition.

[g] The associated regular wave periods should be selected to capture peak riser response within the range of possible periods.

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5.5.4.3.3 A set of load cases should be performed to evaluate potential interference between different system components. Guidance on the issue of interference is shown in 7.4.2 and API RP 2RD [4]. The load cases should include normal operation (1-year and 100-year conditions) with relevant accidental loading conditions.

5.5.5 Detail and service-life design

5.5.5.1 The final local-analysis load cases, for dynamic applications, are checked at this stage of the design using loads that have been derived from previous global dynamic analyses. Local analyses should be performed for all critical locations in the pipe considering loads calculated in the global analyses for all relevant conditions during the life of the pipe (such as FAT, installation and normal and abnormal operation). Typical examples of the local-analysis load cases relating to this stage of design are as follows:

EXAMPLE

Case A Design pressure, maximum top tension from 10-year storm, pipe bent to operational MBR.

Case B No internal pressure, maximum top tension from 100-year wave, pipe bent to operational MBR.

Case C Design minimum pressure, maximum axial compression.

5.5.5.2 Service-life calculations to be performed relate to the polymer degradation, to the corrosion of metallic layers and to fatigue analysis (see Clauses 6 and 8). Unless the stresses in the pressure and tensile armours (unbonded) and reinforcing cables (bonded) are below the endurance limit for all load cases, a fatigue analysis is required. For the fatigue analysis, the pipe is analysed under all fatigue-loading combinations that are specified in the design premise. The combinations are derived from the internal environment and the fatigue (typically sea-state) components of the external environment.

5.5.5.3 The number of sea-states analysed should be shown to be conservative. The selected sea-states should represent the wave-scatter diagram for the location. The wave-scatter diagram is generally divided into a minimum of five blocks, with the maximum sea-state from each block being used. Also, it can be necessary to perform the analyses for a number of directions, e.g. near, far and cross-loading.

5.5.6 Installation design

5.5.6.1 In this stage of the design process, the flexible pipe is analysed to check the feasibility of the proposed installation method. The load cases should account for all relevant functional, environmental and accidental loads as applicable to the installation method, vessel, season, test pressure, etc. Table 11 shows a typical set of installation load cases.

Table 11 — Example global-analysis load cases for installation conditions

Load cases	Description
A	Static analysis, field hydrotest pressure.
B [a]	Static analysis, installation internal-fluid conditions, maximum installation current, equivalent vessel offset.
C [a]	Dynamic analysis, installation internal-fluid conditions, maximum installation current and extreme wave, equivalent vessel offset.
D [a]	Dynamic analysis, hydrotest pressure, maximum current and extreme wave at hydrotest conditions, equivalent vessel offset.
E	Static analysis, post-installation plough operation.

[a] Typically performed for a number of loading directions, such as 0°, 45°, 90°, 135° and 180°.

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5.5.6.2 The load cases for riser systems should cover all phases in the installation process. For example, in the case of a wave configuration, this can include analyses of the initial bare riser section, after buoyancy modules paid out, and during final connection. The installation internal-fluid conditions should be in agreement with the purchaser and defined in the design premise. Consideration may be given to flushing the lines with seawater for normal or extreme environment installation conditions if the material of the innermost layer is suitable.

5.5.6.3 A critical set of local installation load cases based on the results of the global analyses should be selected. Table 12 shows an example set of local load cases. The results of these analyses should be compared with the design criteria specified in ISO 13628-2 and ISO 13628-10 for installation conditions. Additional criteria given in 5.4.1.8 and 5.4.2 of this part of ISO 13628 for crushing collapse and ovalization should also be checked.

Table 12 — Example local-analysis load cases for installation conditions

Load cases	Description
A	Field hydrotest pressure, maximum top tension at hydrotest conditions
B	Installation internal-fluid conditions, maximum installation top tension, installation MBR
C [a, b]	Maximum top tension, maximum radial compression over chute or at tensioners
D [a, c]	Maximum top tension, minimum radial compression from tensioners

[a] Load cases C and D are used to check two critical load conditions for vertical installation with tensioners.

[b] Checks for potential collapse of the carcass.

[c] Checks for slippage of the pipe due to insufficient friction between the outer sheath and the outer tensile-armour layer (unbonded pipe only).

6 Materials

6.1 Scope

Clause 6 provides support for the material requirements specified in ISO 13628-2 and ISO 13628-10 and gives general guidance on material selection for flexible-pipe applications. Commonly used flexible-pipe materials are identified and their performance characteristics are given. Alternative materials, including composites, are discussed. Recommendations are given for fluid compatibility and ageing resistance testing of polymer/elastomer and metallic materials.

Due to the complexity of the applications for flexible pipes, the guidelines in Clause 6 should be used only as a basis for discussions between the purchaser and the manufacturer for each specific application. These discussions should also be based on the requirements in ISO 13628-2 and ISO 13628-10, which define detailed requirements for the qualification and use of polymer/elastomer materials in flexible-pipe applications and the minimum property requirements for the materials.

6.2 Materials — Unbonded pipe

6.2.1 General

6.2.1.1 In 6.2, the materials commonly used in the unbonded flexible pipe industry are identified and the performance characteristics of these materials, such as allowable temperature ranges and fluid compatibility, are presented in general terms.

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6.2.1.2 The characteristics identified for the various materials are possibly not appropriate for specific applications because the suitability of a particular material is based several factors, including transported fluid components, temperature, pressure and parameter variations over the service life (see ISO 13628-2:2006, Annex A, for a detailed listing of relevant parameters). The purchaser should, therefore, specify to the manufacturer the design and operating values of all relevant parameters, including variations over the service life, with reference to the requirements of ISO 13628-2.

6.2.1.3 The materials and their properties should be reviewed against potential failure modes so as to identify the critical requirements of the materials in each layer of the pipe. A detailed list of potential failure modes is given in Clause 13.

6.2.2 Polymer materials

6.2.2.1 General

Table 13 lists the polymer materials typically used in unbonded flexible pipes. Typical thermoplastics used in pressure sheaths are HDPE, XLPE, PA-11 and PVDF. Other polymers, such as PA-12, have been used occasionally. The manufacturer shall provide sufficient evidence that the use of alternative polymers complies with this part of ISO 13628 and with ISO 13628-2. PA-11 can be more suitable than HDPE for the outer sheath in the case of higher-temperature or dynamic applications because of its better abrasion and fatigue characteristics.

Table 13 — Typical polymer materials for unbonded flexible pipe applications

Layer	Material type [a, b]
Internal pressure sheath	HDPE, XLPE, PA-11, PVDF
Intermediate sheaths	HDPE, XLPE, PA-11, PVDF
Outer sheath	HDPE, PA-11
Insulation [c]	PP, PVC, PU

[a] MDPE may be used instead of HDPE.

[b] Designation systems for PA-11 and PVDF are shown in DIN 73378, ISO 1874-1, ISO 12086-1, and ISO 10931-1.

[c] The insulation may be solid material, foam or synthetic foam.

XLPE, a special grade of PE, is achieved by a crosslinking process so as to improve the base material characteristics. The crosslinking can be achieved by several proprietary methods. The products of any of these methods shall be qualified by the flexible pipe manufacturers prior to use in the flexible-pipe products.

PVDF is a thermoplastic material with a rather high modulus compared to HDPE and to plasticized PA-11. In addition, its elasticity is considerably lower than that of PA-11. Several ways exist to improve flexibility and elasticity such as addition of plasticizer, addition of a polymer modifier, addition of a PVDF copolymer, use of a copolymer or a combination of any of these. It is necessary to take the specific issues of plastification, loss of plasticizer and lower flexibility into account in the pipe design. A critical issue with the use of PVDF is sealing of the layer in the end fitting. In 5.2.4, guidelines are given for this issue.

Typical properties (operating temperature range, fluid compatibility and blistering characteristics) for the main polymer-sheath materials (HDPE, XLPE, PA-11 and PVDF) are found in 6.2.2.2 to 6.2.2.4. The polymer material properties and characteristics for many applications are interdependent. For example, the allowable temperature range can be a function of the transported fluid or the blistering characteristics can be a function of temperature and pressure.

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6.2.2.2 Temperature

Table 14 shows guidelines for selection of polymers for flexible pipe applications based on a 20-year service life. For detailed engineering, a validated ageing model is required to confirm the polymer service-life requirements (see 6.5.3 and ISO 13628-2).

Table 14 — Guidance on temperature limits for thermoplastic polymers in flexible-pipe internal pressure sheath applications based on 20-year service life

Polymer material	Minimum exposure temperature [a] °C	Maximum operating temperature [a] °C	Water cut limits [a] %	Comments
HDPE	− 50	+ 60	0 to 100	High tensile and impact resistance at low temperature.
XLPE	− 50	+ 90	0 to 100	May be used for high water-cut applications. Maximum temperature is a function of operating pressure, with a reduction in temperature for pressures above 13,8 MPa (2 000 psi).
PA-11	− 20 − 20	—	0 0 to 100	See API 17 TR2 for further guidance.
PVDF	− 20	+ 130	0 to 100	The material can be susceptible to crack growth depending on the initial defect size and stress level.

[a] This table shows only general limits and does not necessarily apply for specific applications. The temperature ranges for each of the materials also depend on the components of the conveyed fluids. For example, the maximum temperature for PA-11 is significantly lower with water cuts. Also, higher operating temperatures can be feasible for many polymers when the required design life is shorter than 20 years because higher temperatures typically accelerate ageing. This point is not valid for all polymer materials, and the ageing characteristics should be based on test data. Temperature excursions above the maximum stated values may also be acceptable for relatively short durations with supplier acceptance.

6.2.2.3 Fluid compatibility

Table 15 lists typical fluid compatibility characteristics for flexible-pipe polymer materials. Note that fluid compatibility is highly dependent on temperature.

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Table 15 — Typical fluid compatibility and blistering characteristics for flexible-thermoplastic-pipe polymer materials

Polymer material	General compatibility characteristics [a]	Blistering characteristics [b, c]
HDPE	Good ageing behaviour and resistance to acids, seawater and oil. Weak resistance to amines and sensitive to oxidation. Susceptible to environmental stress cracking (environments include alcohols and liquid hydrocarbons).	Good blistering resistance at low temperatures and pressures only.
XLPE	Good ageing behaviour and resistance to seawater, weak acids (dependent on concentrations and dosage frequency) and production fluid with high water cuts. Weak resistance to amines and strong acids (dependent on concentrations and dosage frequency) and sensitive to oxidation. Less susceptible to environmental stress cracking than HDPE (environments include alcohols and liquid hydrocarbons).	Better blistering resistance than HDPE, with positive results obtained in excess of 20,68 MPa (3 000 psi) and 60 °C (140 °F).
PA-11	Good ageing behaviour and resistance to crude oil. Good resistance to environmental stress cracking. Limited resistance to acids at high temperatures; limited resistance to bromides. Weak resistance to high temperatures when any liquid water is present.	Good blistering resistance up to 68,95 MPa (10 000 psi) and 100 °C (212 °F). Limited resistance against water, even in small quantities. The resistance drops with dropping pH. See 6.5.3.5 for service life against temperature.
PVDF	High resistance to ageing and environmental stress cracking.	Good blistering resistance up to 68,95 MPa (10 000 psi) and 130 °C (266 °F).
	Compatible with most produced or injected well fluids at high temperatures including alcohols, acids, chloride solvents, aliphatic and aromatic hydrocarbons and crude oil.	—
	Weak resistance to strong amines, concentrated sulfuric and nitric acids and sodium hydroxide (recommend pH < 8,5).	—

[a] The suitability of a material for a particular application should be verified by the manufacturer.

[b] Blistering characteristics are a function of transported fluid, pressure, depressurization rate, temperature, and material grade. Generally, lower pressure values allow higher temperature values and vice versa.

[c] Provided values are for reference use only. Actual values should be confirmed by testing.

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6.2.2.4 Gas exposure

6.2.2.4.1 Gas in the transported fluid is an important consideration in material selection for the polymer layers. The main issues relate to blistering resistance and permeability of the material of the internal pressure sheath; permeability characteristics of the outer sheath, however, will also be required. Table 15 lists typical blistering resistance characteristics for the internal pressure sheath polymer materials.

6.2.2.4.2 The gas-permeation rate depends on many factors (see 8.2.2). The main issues to be considered in relation to gas permeation are the transported fluid components to be evaluated (the main components being CH_4, CO_2, H_2S, and water vapour), their effect on the steel layers in the annulus (see 6.6), and the gas-venting-system capacity.

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6.2.3 Metallic materials

6.2.3.1 General

Property requirements for metallic materials are listed in ISO 13628-2. These properties should be compared with the requirements of each application, with reference to the critical failure modes identified in 13.3.

6.2.3.2 Carcass

6.2.3.2.1 Materials typically used for the carcass layer are as follows:

a) carbon steel;

b) ferritic stainless steel (AISI 409 and AISI 430);

c) austenitic stainless steel (AISI 304, AISI 304L, AISI 316 and AISI 316L);

d) high-alloyed stainless steel (Duplex UNS S31803);

e) nickel-based alloys (such as N08825).

6.2.3.2.2 Material selection for the carcass is based on the internal fluid components and expected use of the flexible pipe. Important parameters to be considered are identified in ISO 13628-2.

6.2.3.2.3 The material selected for the carcass shifts from 6.2.3.2.1 a) to 6.2.3.1.2 e) (carbon steel is used for non-corrosive environments while high-alloyed stainless steels are used for corrosive applications) as the severity of the internal fluid environment increases. The most commonly used materials are 304L and 316L austenitic stainless steel. A high molybdenum content (2,7 mass % to 3,0 mass %) can be specified for AISI 316L material to improve its corrosion resistance characteristics.

6.2.3.2.4 The main parameters to be considered in the material selection for the carcass are fluid temperature, CO_2, H_2S, chloride and oxygen content. Other parameters that should be considered include pH, water, free sulfur and mercury content of internal fluid. The carcass material in sour-service environments should be resistant to HIC and SSC with reference to ISO 15156-1[25], as applicable.

6.2.3.2.5 If the transported fluid is oxygenated (aerated) (e.g. seawater injection) and a carcass is required, consideration can be given to using non-metallic material (e.g. polymers, composites) for the carcass. However, it is necessary to validate this unproven technology by testing.

6.2.3.2.6 It is important that the hydrotest fluid be benign to the carcass material. As a minimum for carbon steel carcasses, dissolved oxygen should be removed from the hydrotest water, even for potable waters. In addition, it can be necessary to consider the use of a biocide and, for particularly aggressive cases, a corrosion inhibitor.

6.2.3.3 Pressure- and tensile-armour layers

6.2.3.3.1 The typical material used for the pressure- and tensile-armour layers is carbon steel, with the carbon content dependent on the design requirements. High-carbon content steel is used where the design requires very high strength and where the environment permits. Low- or medium-carbon-content steels are used for sour-service environments. Not all wires, however, meet ISO 15156-1 sour-service requirements. For sour-service environments, the steels may also be heat-treated (quenched and tempered).

6.2.3.3.2 Chemical composition of the steel material for both the pressure and tensile armours should be reviewed to confirm suitability for the specified application. Other important issues are manufacturability, weldability, sour-service requirements, conformance to specified structural capacity and compliance with ISO 13628-2 requirements. Important components for specification and control include carbon, manganese, phosphorus, sulfur, silicon and copper. The manufacturer's material specifications should define content limits for these components and distinguish between sweet- and sour-service applications. For some applications, consideration should also be given to minimizing the manganese content and performing calcium treatment of the melt.

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6.2.3.3.3 Wire weldability should be verified by conducting tests with defined and documented acceptance criteria. For evaluation of material weldability, the maximum carbon equivalent content should be specified when no post-weld heat treatments are performed. The maximum carbon equivalent, CE, expressed in mass percent, may be defined by equations similar to Equation (1):

$$\mathrm{CE} = \mathrm{C} + \frac{\mathrm{Mn}}{6} + \left(\frac{\mathrm{Cr} + \mathrm{Mo} + \mathrm{V}}{5}\right) + \left(\frac{\mathrm{Cu} + \mathrm{Ni}}{15}\right) \quad (1)$$

where the symbols for the chemical elements represent the mass fraction expressed in percent.

NOTE A derogation from the ISO rules for the presentation of chemical equations has been granted for Equation (1) in deference to the longstanding use of this formulation in the industry.

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6.2.4 End fittings

6.2.4.1 The materials typically used for the primary metallic end-fitting components are AISI 4130 steel or alloyed stainless steel (Duplex or 6Mo). The corrosion-resistant coatings typically used for the end fittings include the following:

a) electrolysis nickel plating, thickness at least 75 µm (0,002 9 in);

b) Inconel 625[3)] inlay, thickness at least 3 mm (0,12 in);

c) epoxy coating systems;

d) fluoropolymer coatings.

6.2.4.2 The material and corrosion-coating selection for the end fitting is a function of the application, in particular, the internal and external environmental conditions. End-fitting materials and coatings should meet the requirements of ISO 13628-2.

6.3 Materials — Bonded pipe

6.3.1 General

6.3.1.1 In 6.3, the commonly used materials in the bonded-flexible-pipe industry are identified and the performance characteristics of these materials, such as allowable temperature range and fluid permeability, are presented in general terms. The elastomer materials are identified by their primary elastomeric component, for example, NBR. While the primary component is given, the recipe or mix used is, in general, specific to each company and not usually released to second parties.

6.3.1.2 The characteristics identified for the various materials for specific applications are perhaps not appropriate because the suitability of a particular material is dependent on a large number of factors, including transported fluid components, temperature, pressure, compound mix and parameter variations over the service life (see ISO 13628-10:2005, Annex A). The purchaser should, therefore, specify to the manufacturer the design and operating values of all relevant parameters, including variations over the service life, with reference to the requirements of ISO 13628-10.

6.3.1.3 The materials and their properties should be reviewed against potential failure modes so as to identify the critical requirements of the materials in each layer of the pipe. A detailed list of failure modes is given in Clause 13.

3) Inconel is an example of a suitable product available commercially. This information is given for the convenience of users of this part of ISO 13628 and does not constitute an endorsement by ISO of this product.

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6.3.2 Elastomer materials

6.3.2.1 General

Table 16 lists the elastomer materials typically used in bonded flexible pipes. These elastomer materials constitute approximately 40 % to 65 % of the final compound mix, with carbon black, antioxidants, activators, plasticizers and curing agents making up the remainder amongst other ingredients. The final properties of the rubber compound are dependent on the final mix of all ingredients. For example, the higher the carbon black content in a compound mix, the lower the electrical resistance will be in addition to a generally higher tensile strength (although the structure and size of the carbon black particles also play a significant role). NBR is extensively used as a liner material because of its low permeability to gas, such as N_2 and O_2. However, NBR is itself dependent on the percentage of acrylonitrite in the elastomer. This is usually 17 % to 50 %. The higher the acrylonitrite content in the NBR, the higher the heat- and oil-resistance and the lower the elasticity of the material at low temperature.

CPE is a typical elastomer used for bonded-pipe covers. Its characteristics make it suitable for a relatively highly abrasive environment where it can be exposed to both seawater and ozone.

Typical properties (operating temperature range, fluid compatibility and fluid permeability) for the main elastomer materials are found in 6.3.2.2 to 6.3.2.4. As each rubber compound material is made up of an elastomer material and several other materials, the properties, therefore, vary with mix type. In addition, for most applications, the elastomer-material properties/characteristics are interdependent. For example, the allowable maximum operating temperature can be a function of the transported fluid.

An API Technical Bulletin [9] has been developed by a joint industry project. The document describes development of test plans to evaluate the suitability of candidate polymers for high-temperature service. Also defined is a set of evaluation criteria for material qualification.

Table 16 — Typical elastomer materials for bonded-flexible-pipe applications

Application	Material
Liner	NBR, HNBR, CR, NR, EPDM
Cover	CR, CPE
Filler	Various
Insulation	PVC, PE, closed-cell foam, glass fibre

6.3.2.2 Temperature

6.3.2.2.1 Table 17 contains guidelines for the selection of elastomers for bonded-flexible-pipe applications. These guidelines consider a relatively benign transported fluid.

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Table 17 — Temperature limits for thermosetting elastomers in a bonded-flexible-pipe-liner application

Elastomer	Brittleness temperature °C (°F) [a]	Maximum continuous operating temperature °C (°F) [a]	Comments
NBR	– 20 to + 40 (– 4 to + 104)	125 (257)	Properties dependent on acrylonitrile content. Excellent resistance to hydrocarbons. Very good tensile strength and dynamic properties. Good impermeability and heat resistance. Poor resistance to weather and ozone.
HNBR	– 40 to + 50 (– 40 to + 122)	150 (302)	Good resistance to hydrocarbons. Very good tensile strength and dynamic properties. Good impermeability and very good resistance to weather and ozone.
CR	– 30 to + 40 (– 22 to + 104)	100 (212)	Reasonable resistance to hydrocarbons. Good tensile strength and reasonable dynamic properties. Good impermeability and heat resistance. Very good resistance to weather and ozone.

[a] This table shows only general limits and may not apply for specific applications. The temperature ranges for each of the materials also depend on the components of the conveyed fluid. For example, the maximum operating temperature for NBR may be reduced by as much as 20 °C (68 °F) if the transported fluid contains a relatively large percentage of aromatics. Temperature excursions above the maximum stated values may also be acceptable for relatively short durations with supplier acceptance.

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6.3.2.2.2 A validated ageing model is required to confirm the elastomer service-life requirements for detailed engineering; see 6.5.3 and ISO 13628-10.

6.3.2.3 Fluid compatibility

Table 17 lists typical fluid-compatibility characteristics for bonded-flexible-pipe elastomer materials.

NOTE Fluid compatibility is highly dependent on temperature.

6.3.2.4 Gas exposure

6.3.2.4.1 It is necessary to take gas exposure into consideration in material selection for the elastomer layers if the bonded flexible pipe is used for service in which the transported fluid contains gas. The main issues relate to the blistering resistance and continuing curing of both the pipe liner and the remainder of the pipe body. In general, elastomer materials are more susceptible to blistering than thermoplastic materials used in unbonded pipe applications. This is attributed to the relatively higher permeability to gas and lower tearing resistance of elastomer materials over thermoplastic materials. A mitigating factor used by the industry is that the bonded flexible pipe, made up of elastomeric materials, is supported by an internal steel stripwound carcass and so the liner is not quite as susceptible to blistering as small-scale test results on the elastomer alone suggest. Bonded-pipe bodies exposed to H_2S can experience continuing curing in field applications, because sulfur is a cross-linking agent for many elastomers. This can result in reduced local flexibility and increased global riser stiffness.

6.3.2.4.2 The gas permeation rate through the elastomer material is dependent on many factors including internal and external pressure, surface area, liner thickness and permeability coefficient. The main issues for consideration in relation to gas permeation are the propensity for blistering to occur under rapid decompression, the likelihood of the permeation of the transported fluid components through the body of the pipe and their effect on the elastomer and steel reinforcing layers.

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6.3.3 Metallic materials

6.3.3.1 General

Property requirements for metallic materials are listed ISO 13628-10. These properties should be compared with the requirements of each application, with reference to the critical failure modes identified in 13.3.

6.3.3.2 Carcass

6.3.3.2.1 Materials typically used for the carcass layer are as follows:

a) carbon steel;

b) ferritic stainless steel (AISI 409 and AISI 430);

c) austenitic stainless steel (AISI 304, AISI 304L, AISI 316, AISI 316L);

d) high-alloyed stainless steel (such as Duplex UNS S31803);

e) nickel-based alloys (such as N08825).

6.3.3.2.2 The selection of the material for the carcass is dependent on the internal fluid components and expected use of the flexible pipe. Important parameters to be considered are identified in ISO 13628-10.

6.3.3.2.3 As the severity of the internal fluid environment increases, the material selected for the carcass shifts from 6.3.3.2.1 a) to 6.3.3.2.1 e), i.e. carbon steel is used for non-corrosive environments while high-alloyed stainless steels are used for corrosive applications. The most commonly used materials are AISI 304L and AISI 316L austenitic stainless steel. A high molybdenum content (2,7 % to 3,0 %) may be specified for AISI 316L material to improve its corrosion-resistance characteristics.

6.3.3.2.4 The main parameters to be considered in the selection of the carcass material are fluid temperature, and CO_2, H_2S, chloride and oxygen content. Other parameters that should be considered include pH, water, free sulfur and mercury content of internal fluid. In sour-service environments, the carcass material should meet the requirements of ISO 15156-1 [25].

6.3.3.2.5 If the transported fluid is oxygenated (aerated), for example by seawater injection, and a carcass is required, consideration can be given to using non-metallic material (such as polymers or composites) for the carcass. However, this is unproven technology and requires validation by testing.

6.3.3.2.6 The hydrotest fluid should be benign to the carcass material. As a minimum for carbon-steel carcasses, dissolved oxygen should be removed from the hydrotest water, even for potable waters. In addition, consideration can be required to use a biocide and, for particularly aggressive cases, a corrosion inhibitor.

6.3.3.3 Reinforcing layers

6.3.3.3.1 The typical material used for the cables of the primary reinforcing layers is carbon steel. High-carbon-content steel is used to give a high-strength cable.

6.3.3.3.2 Chemical composition of the steel material for the reinforcing layers should be reviewed to confirm suitability for the specified environment. Other important issues are sour-service requirements, conformance to specified structural capacity and compliance to ISO 13628-10 requirements. The effect of the enclosing rubber should be considered in determining suitability.

6.3.3.3.3 Important components for specification and control include carbon, manganese, phosphorus, sulfur, silicon and copper. The manufacturers' material specifications should define content limits for these components. Consideration to minimizing the manganese content and performing calcium treatment of the melt is recommended for some applications.

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6.3.4 End fittings

6.3.4.1 The materials typically used for the primary metallic end-fitting components are AISI 4130 steel or alloyed stainless steel (such as duplex, 6Mo). The corrosion-resistant coatings typically used for the end fittings include the following:

a) electrolysis nickel plating, thickness at least 75 µm (0,002 9 in);

b) Inconel 625 inlay, thickness at least 3 mm (0,12 in);

c) epoxy coating systems;

d) fluoropolymer coatings;

e) zinc coating.

6.3.4.2 The material and corrosion-coating selection for the end fitting is a function of the application, in particular, the internal and external environmental conditions. End-fitting materials and coatings should meet the requirements of ISO 13628-10.

6.4 Alternative materials

6.4.1 Aluminium

6.4.1.1 Aluminium material may be used to replace steel in any of the structural layers of the flexible pipe, including carcass, pressure-armour and tensile-armour layers. Aluminium's main advantage is that, compared to steel, it gives a mass saving of between 30 % and 60 % for the same strength characteristics.

6.4.1.2 The corrosion behaviour of aluminium shall be evaluated carefully prior to its use for flexible-pipe applications. Other important issues to be addressed include abrasion and wear resistance, SSC and HIC resistance, fatigue and welding.

6.4.2 Composite materials

6.4.2.1 Composites are materials in which a reinforcing fibre is combined in a resin matrix and cured. For flexible pipes, composite materials are currently only used for the replacement of carbon steel in the tensile-armour layers. Consequently, in 6.4.2.2 to 6.4.2.13, only this particular use of composites in flexible-pipe applications is considered.

6.4.2.2 The steel tensile-armour wires used in unbonded flexibles are typically 3 mm to 6 mm (0,12 in to 0,24 in) thick and are mechanically preformed to a helical structure. The composite armour wires may be 1 mm to 2 mm (0,04 in to 0,08 in) thick and helically wound in several layers per equivalent steel layer. Alternatively, they may be the same thickness as the equivalent steel armour layer [up to 8 mm (0,31 in)].

6.4.2.3 Composites offer a range of beneficial properties for the tensile-armour wires when compared to steel, including the following:

a) high strength-to-mass ratio;

b) good fatigue resistance (not notch sensitive);

c) good impact resistance and toughness (material dependent);

d) immunity to corrosion and degradation by most oil field chemicals and seawater;

e) high stiffness or modulus (in one direction).

NOTE These characteristics are highly dependent on the composite resin and reinforcing fibres.

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6.4.2.4 The main potential for use of composite-based tensile-armour flexible pipes is in deep-water applications, where the mass reduction can be significant compared to steel-based tensile-armour pipes (density of composites is approximately 25 % that of steel). In addition, there is potential for use of composites in high-pressure, sour-service applications. Service-life determination is an evolving technology for composites and currently limits their application.

6.4.2.5 The reinforcing fibres used in composites include E-glass, carbon and aramide fibres. The glass-fibre composite is more economical than the carbon fibre material. The carbon-fibre material, however, has more favourable strength properties and characteristics. For both glass and carbon-fibre composites, the reinforcing fibres are orientated parallel to the wire longitudinal axis. The matrix materials used include epoxy and vinyl-ester resins, and thermoplastic polymers.

6.4.2.6 Some of the main considerations when using composites are described in 6.4.2.7 to 6.4.2.13.

6.4.2.7 Potential wear problems between armour layers and between individual armour wires, which are subject to relative motion and high contact pressure, should be addressed.

6.4.2.8 Influence of defects on composite wire performance should be assessed. It is necessary to identify and access failure mechanisms.

6.4.2.9 Effective anchoring of the composites in the pipe end fitting should be confirmed with suitable tests. Join-up procedures for the individual composite wires should be evaluated carefully.

6.4.2.10 Experiments should be performed to characterize the effects of permeated fluids upon fibre-matrix interfaces in the composites. The susceptibility of glass-fibre composites to stress-corrosion cracking in seawater should be investigated. The potential for galvanic corrosion in carbon-fibre composites should be determined. The use of glass-fibre composites in water at high temperatures is limited and should be verified by testing.

6.4.2.11 The structure of the composite after having been subjected to relevant loads and environmental conditions should be determined by scanning electron microscopy, which can be used to determine microcracking and delamination.

6.4.2.12 Normally, composite wires are preformed during wire fabrication rather than during winding on to the pipe. This process can induce reduction of performance properties (e.g. σ_y) compared to the non-formed wire properties, and should be checked by testing. Bending stresses are induced when the material is wound on to the pipe if the composite wire is not preformed. The reduction in performance should be evaluated by analysis and testing because of these additional bending stresses.

6.4.2.13 Composite materials should be qualified in the final processed state, under test conditions representative of the actual operational conditions. The manufacturer and purchaser should agree on the test procedures, with reference to applicable International Standards. The following properties and characteristics should be determined for composite materials in flexible-pipe applications:

a) tensile strength and elongation;

b) modulus of elasticity;

c) density;

d) fatigue properties, including endurance limit (tensile, flexural, and fretting fatigue);

e) creep characteristics;

f) fracture resistance;

g) ageing characteristics (reduction of material properties with time);

h) microbial (bacterial) degradation;

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i) Poisson's ratio;

j) wear and abrasion resistance;

k) chemical resistance (to corrosion inhibitors, etc.).

6.4.3 Aramide fibres

6.4.3.1 A potential alternative material for flexible pipes is synthetic fibres, such as aramide. These fibres can be used to replace the steel armour layers, giving significant mass reduction and potentially improved performance in sour-service applications. In addition, aramide fibres have the following positive characteristics for flexible-pipe applications:

a) no corrosion;

b) good chemical resistance to most production fluids;

c) good fatigue properties;

d) good creep properties;

e) low temperature sensitivity.

6.4.3.2 Areas of concern for the use of aramide fibres include the following:

a) time and temperature dependency of mechanical properties;

b) termination in the end fittings;

c) ageing characteristics (UV sensitivity);

d) non-isotropic behaviour;

e) static and dynamic bending flexibility requirements;

f) notch sensitivity;

g) environmental-stress-cracking resistance.

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6.5 Polymer/elastomer test procedures

6.5.1 General

ISO 13628-2 and ISO 13628-10 specify material property requirements and test procedures. Standard procedures are unavailable for polymer/elastomer fluid-compatibility and ageing-resistance tests. Therefore, procedures are not given in ISO 13628-2 and ISO 13628-10. In 6.5.2 to 6.5.4, guidelines and recommendations for performing these tests are given.

6.5.2 Fluid compatibility

6.5.2.1 ISO 13628-2 and ISO 13628-10 contain general requirements for the performance of fluid compatibility tests and identify critical parameters for evaluating compatibility. In 6.5.2.2 and 6.5.2.3, recommendations on the test procedures are given.

6.5.2.2 Laboratory tests with extruded samples of the polymer or calenderized or extruded samples of the elastomer can be used to determine gross incompatibility. Tests should be based on the design conditions, subject to the following recommendations:

— test fluid contains components of design internal fluid that possibly have adverse effects on the polymer, in particular seawater, production fluid, H_2S, CO_2 and injection chemicals, and it is necessary that the pH of the fluid be controlled to design conditions;

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- maximum operating temperature as a minimum;
- ambient pressure for liquids and design pressure or greater for gases;
- stress conditions zero, and if there is potential for stress cracking, also a test at maximum design strain;
- minimum exposure time of 300 h for accelerated tests (increased temperature);
- sample thickness should be at least 3 mm (0,12 in), sample length should be based on the test equipment, and the sample should be immersed in all phases if the test fluid is multi-phase;
- critical parameters and acceptance criteria should be established based on the polymer/elastomer being evaluated and the particular application; tensile strength, elongation, visual appearance and fluid absorption (mass gain) and desorption (mass loss) parameters should be considered for evaluation/measurement.

A 2 000 h test at operating temperature can give an idea of whether there are any crucial incompatibility issues, but might not be sufficient for a qualification of a thermoplastic material with a required lifetime of 20 years or more.

6.5.2.3 Sulfur can be liberated from H_2S reacting with steel components or the elastomer compounds in the bonded pipe to cause cross-linking and hardening. The effects of the released sulfur on either metallic or elastomeric components should be evaluated.

6.5.3 Ageing test

6.5.3.1 Ageing of elastomer/polymer material is an irreversible process that occurs when the material is exposed to particular environmental conditions. Polymer/elastomer ageing is dependent on the fluid transported in flexible pipes, on temperature, pressure and external conditions, such as UV radiation. The ageing process is characterized by a change in properties, such as a reduction in strength or ductility, and embrittlement or softening. In addition, the physical properties of the polymer/elastomer can be significantly altered by the migration of plasticizers.

6.5.3.2 ISO 13628-2, ISO 13628-10, and API Technical Reports 17 TR1 and 17 TR2 contain general requirements for the performance of ageing tests and identify critical parameters for the most commonly used polymers. The objective in performing ageing tests is to develop satisfactory ageing prediction and monitoring models, which may include Arrhenius plots. This gives the material service life as a function of the inverse of temperature, plotted on a log-linear scale. Some materials (such as PA-11) have been found to be more amenable to the development of Arrhenius plots than other materials (such as PVDF). Arrhenius plots are useful to extrapolate accelerated high-temperature ageing tests to lower temperatures and longer times. This is particularly true when there is no change in ageing mechanism or any kind of phase transition over the temperature range considered.

6.5.3.3 An Arrhenius plot defines an exponential decay mechanism for the critical exposure time, t_{crit}, at a given value of temperature, T, using Equation (2):

$$t_{crit} = A e^{\frac{E_a}{RT}} \qquad (2)$$

where

A is a constant;

e is the Neper number, equal to 2,7182;

E_a is a constant reflecting the activation energy for the chemical process underlying degradation;

T is the temperature;

R is the universal gas constant.

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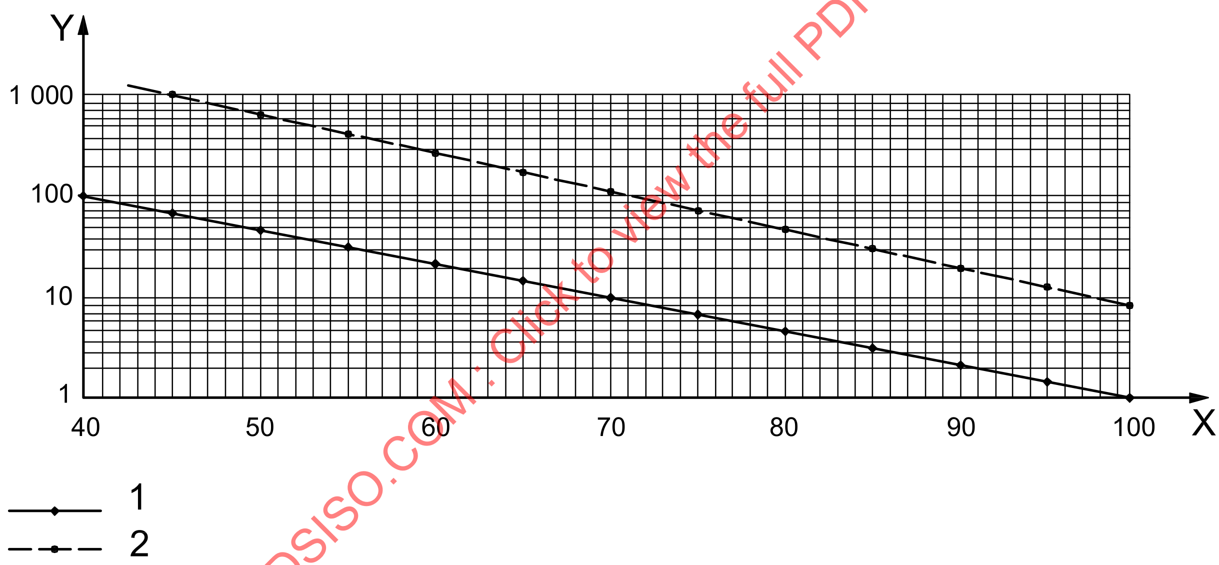
6.5.3.4 The ageing criteria should be established prior to test start-up. The ageing criteria should be based on measurable performance properties at the end of the pipe's service life.

6.5.3.5 Figure 21 illustrates a plot of estimated PA-11 lifetimes in hydrocarbon/water exposure. The plot is based on data measured at temperatures above 100 °C (212 °F) and extrapolated down into the application temperature range. For PA-11 in dynamic flexible-pipe applications, the flowing fluid temperature has been used for ageing evaluations. In some static applications where the pipe is not expected to be subjected to significant alternating strains, the mean temperature of the internal pressure sheath, based on the radial temperature distribution, has been used.

6.5.3.6 The ageing process for PA-11 is strongly influenced by the water content and pH of the transported fluid. Figure 21 shows two curves, one for hydrocarbon saturated with water and the other for hydrocarbon unsaturated with water. Current experience indicates that ageing in hydrocarbon/water exposure above saturation is very similar to the "saturated" curve and, therefore, this curve may be used for all water-cut values that reach saturation of the hydrocarbon at the production conditions. Similarly, the "unsaturated" curve may be used for all water-cut values that do not reach saturation at the production conditions. It has been suggested that the transition can occur at about 80 % saturation.

6.5.3.7 The design life can be read directly from Figure 21 where the transported fluid temperature is constant over the service life of the pipe, unless API 17 TR2 recommends more appropriate ageing curves. The degradation over the total service life for varying temperatures and water cuts should be calculated by an integration of the exposure periods at the different temperatures and water cuts.



Key

X temperature, expressed in degrees Celsius

Y design life, expressed in years

1 hydrocarbon saturated with water

2 hydrocarbon unsaturated with water

Figure 21 — PA-11 service life in hydrocarbon/water exposure versus temperature
(extrapolated data at a pH of 7)

6.5.3.8 This Palmgren-Miner cumulative damage type approach is believed to give a conservative estimate of design life.

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6.5.4 Epoxy shear-strength test

6.5.4.1 The epoxy shear-strength test is intended as an alternative to the ASTM D695 or ISO 604 compressive-strength test in determining the shear capacity of the epoxy resin used for anchoring the reinforcing cables in some bonded-pipe end fittings.

6.5.4.2 ISO 13628-10 contains general requirements for the performance of epoxy shear-strength tests. In 6.5.4.3, recommendations on the test procedures are provided.

6.5.4.3 The epoxy shear-strength test involves testing cured epoxy samples by shearing the sample at different temperatures, thereby obtaining the temperature-dependent shear capacity of the material. Tests should be based on operating conditions, subject to the following recommendations.

a) Sample size should be based on the test equipment and a minimum of three samples per temperature should be tested.

b) Sample should be tested at both minimum and maximum operating temperature and at sufficient close temperature intervals in between to satisfactorily define the shear-strength/temperature relationship of the material.

c) Samples should be moulded and cured under the same temperature and humidity conditions as those prevailing when filling the end fitting.

d) The epoxy resin should be mixed according to the manufacturer's specification and poured slowly into the prepared mould to ensure no air bubbles are enclosed.

e) The epoxy samples should be taken from the batch used to fill the end fitting if the shear-strength test is required as part of the pipe-manufacture quality process.

6.6 Metallic-material test requirements

6.6.1 General

6.6.1.1 In 6.6.2 to 6.6.6, the qualification test requirements for flexible-pipe metallic materials are discussed and recommendations on the performance of the tests and interpretation of results are given. ISO 13628-2 specifies qualification of materials for the carcass, pressure armour (unbonded pipe), tensile-armour layers (unbonded pipe) and reinforcing layers (bonded pipe), and ISO 13628-10 specifies test requirements. The following required tests do not have standard (such as ASTM) test procedures for their performance:

a) SSC and HIC resistance;

b) corrosion resistance;

c) erosion resistance;

d) fatigue resistance;

e) hydrogen-embrittlement resistance;

f) chemical resistance.

6.6.1.2 These tests are discussed in detail below and also supplement requirements in ISO 13628-2 and ISO 13628-10.

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6.6.2 SSC and HIC resistance

6.6.2.1 Hydrogen enters steel components at the corroding surface in wet H_2S environments. Depending on the type of steel, its microstructure and the inclusion distribution, the hydrogen can give rise to internal decohesion resulting in HIC or brittle fracture, termed SSC. ISO 13628-2 and ISO 13628-10 specify SSC and HIC test procedures for steel-wire-cable materials used in flexible-pipe applications.

6.6.2.2 Two types of SSC tests are required by ISO 13628-2 and ISO 13628-10:

a) use of NACE TM0177 environment at constant pH between 3,5 and 3,8 to determine stress threshold levels for the occurrence of SSC;

b) SSC test with actual service conditions, with the samples stressed to 0,9 times the actual yield stress of the sample, as defined in ISO 13628-2 or design stress levels as defined in ISO 13628-10.

6.6.2.3 Results from both of these tests are used to determine suitability of the steel material for the proposed application. Important considerations in the performance of these tests include the following.

a) Recommended test procedures for both SSC tests described above are as follows.

   1) For pressure-armour wires of unbonded pipe (including interlock and back-up flat wires), ring tests should be used where practical for pipe diameters less than 15,24 cm (6 in); otherwise, four-point bend tests from ring samples should be used.

   2) For tensile-armour wires of unbonded pipe, depending on the wire size, Method A of ASTM A370-07 [11] or four-point bend tests should be used;

   3) For reinforcing-layer cables, a coating of embedding compound should be applied, the maximum thickness of which should not be greater than the minimum design thickness of the embedding compound in the pipe construction.

b) SSC tests in the actual service conditions probably do not highlight any susceptibility of the material to HIC and/or stress-oriented HIC, and, therefore, examination procedures should check for both of these characteristics, and require that a check be made for the HIC during the NACE TM0177 SSC tests described in 6.6.2.2.

c) All samples should represent, as closely as possible, the as-manufactured wires and cables and should be tested on a statistical basis to verify resistance. Welded samples should be tested to qualify welding procedures for wires used in unbonded pipe.

d) Test procedures should ensure that the important test parameters are kept largely constant, including stress and strain levels, pH, temperature and H_2S partial pressure.

e) The material is considered to have failed the test if there is evidence of cracking from visual, microscopic or magnetic-particle inspection, other than surface blisters.

f) A 20 °C ± 3 °C (68 °F ± 5,4 °F) test temperature is recommended because this is considered the worst-case temperature for hydrogen effects.

g) Consideration should be given to using the NACE TM02-84 [28] test method to determine the HIC resistance of the steel-wire materials of unbonded flexible pipe. This is much shorter than the NACE TM0177 test and can be used as a quality-control test on the wire material.

6.6.2.4 The specified tests apply to pipes for both static and dynamic applications. In addition, for dynamic applications, fatigue and corrosion-fatigue tests are required, as discussed in 6.6.5.

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6.6.3 Corrosion

6.6.3.1 In 6.6.3, uniform or pitting corrosion is addressed. This is particularly relevant for unbonded-pipe armour-wire corrosion. Corrosion problems in the carcass are generally avoided by proper material selection, as discussed in 6.2.3.1. Though the pressure and tensile armours are not directly in contact with the transported fluid, they are exposed to permeated fluids, such as CO_2 and H_2S gas, and seawater if there is a breach in the integrity of the outer sheath.

6.6.3.2 Uniform corrosion is caused by CO_2 in the presence of deoxygenated seawater. This uniform corrosion should be accounted for in the selection of the armour-wire thickness. Corrosion from oxygenated water, in the immediate vicinity of tears in the outer sheath, should be controlled by appropriate design of the cathodic protection system. No pitting corrosion should occur under design environmental and stress conditions that can cause utilization factors to exceed design criteria or to affect the service-life requirements.

6.6.4 Erosion

6.6.4.1 The production of reservoir sand can cause erosion in the carcass layer of flexible pipes. In addition, the sand can remove any protective films on the carcass, thereby increasing corrosion. Therefore, the erosion and the rates of erosion and corrosion should be calculated, with the calculations based on test data (see 9.7.7 for guidelines on erosion tests). Calculations should confirm the following.

a) The hydrostatic collapse resistance of the eroded and corroded pipe is not lower than the design requirements for the specified service life.

b) The tensile load capacity with the eroded and corroded pipe is not less than the design requirements.

6.6.4.2 Erosion rates are most severe at high-curvature areas. Important parameters that influence erosion rates include fluid velocity, amount and size of produced sand, carcass geometry and steel material. The partial pressure of CO_2 and the fluid temperature have a significant effect on the erosion/corrosion characteristics of the carcass.

6.6.5 Fatigue resistance

6.6.5.1 Adequate fatigue resistance of steel-wire materials for dynamic applications is required. Fatigue analysis (see 8.2.4) should show that all stresses are below the material endurance limit. Otherwise, fatigue damage calculations should be performed, such as with Miner's method using design S-N curves and accounting for damage due to cycles with stresses below the endurance limit. The determination of the S-N curves is critical for the fatigue analysis. ISO 13628-2 and ISO 13628-10 specify relevant test requirements, namely that S-N data be developed based on the actual annulus conditions and the design basis for the annulus (such as exposure to air, seawater), or design annulus environment for unbonded pipes and based on rubberized cables and pipe-bore conditions for bonded pipe.

6.6.5.2 The initial objective of the S-N tests should be to identify the endurance limit of the material, accounting for the relevant environment. Data from previous testing in more severe conditions may be used. Note that a reduction in the endurance limit is expected for sour-service applications. Recommendations on S-N testing are given in 6.6.5.3 to 6.6.5.9.

6.6.5.3 Tests should consider variations in the material strength and hardness. Softer material generally gives a lower fatigue limit in air, but this can change for corrosive environments.

6.6.5.4 The standard S-N tests for wires of unbonded pipe are based on un-notched specimens. Consideration should also be given to performing tests with notched specimens or to using the results of full-scale tests for validation when pitting, wear, corrosion or other sources of notches are likely to occur. This gives a lower-bound S-N curve for pitted or worn wires, or wires scratched during manufacture.

6.6.5.5 The recommended notch is a 60° V, with a depth of 0,2 mm and a root radius of 0,025 mm, which represents typical surface anomalies found in full-scale sour-service tests because of corrosion and also represents the worst case for scratches, damage and corrosion experienced during manufacture and service. The notch should be fully circumferential for round-bar specimens. It should be a single-sided notch for flat wires.

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6.6.5.6 The number of samples and stress levels for development of S-N data should be in accordance with ASTM E739 [12]. Strain gauges should generally be used for stress measurements where appropriate. The cyclic-load test frequency should represent the in-service load frequency. A higher test frequency is allowed if the effect of the higher frequency is documented. A recommended maximum frequency is 0,5 Hz.

6.6.5.7 Sufficient S-N data should be available to confidently extrapolate the S-N curve to stress levels below the endurance limit. The S-N curve can have a reduced slope below the endurance limit. Results should be presented in accordance with ASTM E468 [13].

6.6.5.8 The endurance limit should be the stress level at which specimens exceed 1×10^7 cycles with no evidence of fatigue cracks. The endurance-limit stress is relevant only for fatigue-life analyses that do not include any cycles with stresses above the endurance limit.

6.6.5.9 Unbonded flexible risers are designed generally on the basis that the outer sheath is never breached (no flooding of the annulus with seawater). However, service-life analysis for dynamic applications should calculate the length of time to failure of the tensile and pressure armours when the annulus is flooded with seawater from a rupture of the outer sheath. This is defined as an accidental situation, with the calculated service life determining the length of time before which the pipe is replaced. The replacement time should be included in the operation manual.

6.6.6 Hydrogen embrittlement

Cathodically protected, high-tensile-strength steels can be subject to hydrogen embrittlement. ISO 13628-2 specifies required testing to confirm satisfactory performance of high-strength wires of unbonded flexible pipes subject to cathodic protection.

7 System design considerations

7.1 General

Clause 7 relates to the overall flexible pipe system and not specifically to the flexible pipe itself. Clause 7 gives recommendations on system-related design issues, as follows:

a) general system design requirements;

b) flowline design requirements;

c) riser design requirements;

d) floating pipes;

e) ancillary component design;

f) system interfaces.

In addition, system issues significantly impacting the overall project are identified throughout Clause 7. Detailed consideration of these issues at an early stage in the project can result in significant cost savings and design simplifications.

7.2 General system requirements

7.2.1 Introduction

In 7.2.2 to 7.2.9, requirements that are common to all flexible pipe systems are covered.

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7.2.2 Transported-fluid considerations

7.2.2.1 The fluid velocity is important, particularly if abrasive materials, such as sand in the produced fluids, can result in wear of the pipe’s internal layer. Fluid velocities of the flowline and riser system are based on system pressure drop and the internal friction parameter for the flexible pipe. The friction parameter varies significantly between smooth- and rough-bore pipes because of the carcass construction in a rough-bore pipe. Typical values for absolute friction factor are as follows:

Rough-bore pipe: ID (mm)/250

Smooth-bore pipe: 0,005 mm (0,000 2 in)

7.2.2.2 The roughness values (see 7.2.2.1) can generally be considered to be conservative. The friction is strongly influenced by the carcass characteristics, such as ID and profile dimensions, for the rough-bore pipe. A more accurate friction factor can be calculated from tests, if required.

7.2.2.3 The design of flexible pipe systems should consider the effect of variations in internal fluid density over the life of the project, particularly for riser systems, where a change in fluid density can change the shape of the riser configuration. In the case of two-phase flow, the effect of slug-induced vibration should be considered.

7.2.3 Corrosion protection

7.2.3.1 The metallic components of the flexible pipe system exposed to corrosive fluids should be selected to be corrosion-resistant or alternatively be protected from corrosion. Corrosion protection can be achieved by one or more of the following methods:

a) coating;

b) application of corrosion inhibitors;

c) application of special metallic materials or cladding;

d) specification of corrosion allowance;

e) cathodic protection.

7.2.3.2 The implications for overall system design of providing corrosion protection should be assessed. ISO 13628-2 and ISO 13628-10 contain corrosion protection requirements, and Reference [18] contains guidelines on the design of cathodic protection systems.

7.2.4 Thermal insulation

7.2.4.1 If the fluid temperature inside the system is to be maintained at a particular level, thermal insulating layers can be added to the flexible pipe cross-section to provide added thermal insulation. The insulating material used should be compatible with the annulus fluids to which it is likely to be exposed. Typically, both pressure and temperature limits apply to the use of these insulating materials and should be considered in the selection process. ISO 13628-2 and ISO 13628-10 specify minimum requirements for the use of thermal insulating layers.

7.2.4.2 Design of a flexible pipe to meet a specified thermal-insulation coefficient may include thermal resistance from the surrounding environment. Burial or trenching and backfill provides significant thermal resistance and can minimize or avoid a requirement for thermal insulation layers.

7.2.5 Gas venting — Unbonded pipe

7.2.5.1 Gas venting enables gas that has diffused through the internal pressure sheath of the flexible pipe to escape, and thus avoid build-up of gas pressure in the annulus of the flexible pipe system (see 8.2.2).

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7.2.5.2 A gas-venting system is comprised of small-bore pipes connecting the pipe annulus to the gas-relief valves in the pipe end fittings. Burst discs may also be placed along the outer sheath of the flexible pipe for flowline systems. ISO 13628-2 specifies that burst discs shall not be used on risers. The minimum requirements for the design of gas-relief valves and burst discs are given in ISO 13628-2. At the topside connection, the gas bleed-off system from a flexible riser should be connected to process vents through a check valve, or vented locally to atmosphere through a gas-relief valve. The gas bleed-off system should never be capped during operation to avoid excessive pressure build-up in the annulus.

7.2.6 Pigging and TFL requirements

7.2.6.1 The user should specify that any pigs or tools be passed through the flexible pipe. If pigging is required for the flexible pipe system, the following are recommended, as they may have an important impact on the system layout. Design issues include whether to use loops (pipes in parallel) or subsea receivers.

7.2.6.2 Foam or PU pigs can be used for smooth-bore pipes. Brush, foam or PU pigs can be used for rough-bore pipes. Scraper pigs are not suitable for flexible pipes.

7.2.6.3 Flexible pipe intended for use in TFL service should be constructed with an innermost layer that does not impede or suffer significant damage from the passage of TFL tools. For TFL service, the pipe shall conform to ISO 13628-3 requirements with regard to design, fabrication, and testing and to ISO 13628-3:2000, Annex A, with regard to internal diameter and drift testing.

NOTE For the purpose of this provision, API RP 17C is equivalent to ISO 13628-3.

7.2.7 Fire resistance

ISO 13628-2 and ISO 13628-10 list the issues to be considered in assessing the resistance to fire of the flexible pipe. Ultimately, fire resistance tests can possibly be required. Additional resistance against fire may be provided by the application of an insulating protective cover on the outer sheath of the pipe. Special consideration should be given to the effect of fire on the interface between pipe and end fitting.

7.2.8 Piggy-back lines

7.2.8.1 The flexible pipe should be sufficiently protected against pipe and steel scuffing and the potential transfer of high temperatures from the steel to the flexible pipe if a flexible pipe is piggy-backed to a steel pipeline or other steel structure.

7.2.8.2 The piggy-back system should be designed with the following considerations where an umbilical or smaller diameter line is piggy-backed to a flexible pipe:

a) hydrodynamic interaction, including shielding, solidification, hydroelastic vibrations, lift and marine growth;

b) relative motion between the lines;

c) relative changes in length between the two lines (particularly due to different expansion coefficients between flexible and steel lines);

d) clamp loads;

e) loads and wear of the flexible pipe;

f) creep and long-term degradation of pipe and clamp materials;

g) internal pressure, tension, external pressure, bending and torsion-induced change in cross-section geometry of the pipe.

7.2.8.3 The method of connecting the piggy-backed line at the vessel interface should be carefully designed for the case of a flexible-pipe riser.

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7.2.9 Connector design

7.2.9.1 The materials from which connectors are to be manufactured should be compatible with those within the flexible pipe and any interfacing topside piping or seabed pipeline.

7.2.9.2 If release functions are required in connector design, their abandonment philosophy should be clearly identified and detailed prior to manufacturing commencement. See 4.4.4 for a description of typical disconnection systems.

7.2.9.3 System design and fatigue loads should be clearly identified prior to connector design commencement. Any exposed valves, either open or closed, shall be capable of sustaining such pressures if strength or leak testing of a flexible pipe is carried out through a connector.

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7.3 Flowline design requirements

7.3.1 Seabed and overland routing

7.3.1.1 Routes should be selected with regard to the probability and consequences of all forms of pipe damage. The following factors should be taken into account:

a) installation;

b) seabed or overland route contour and conditions;

c) trenching or rock dumping (if applicable);

d) location of other installed equipment and pipelines;

e) pipe expansion;

f) accuracy of structure positions;

g) accuracy of installation-vessel positioning system;

h) as pulled-in configuration;

i) ship traffic;

j) fishing activities;

k) offshore operations;

l) corrosivity of the environment;

m) launching of lifeboats;

n) anchoring and mooring of other installations and vessels.

7.3.1.2 The pipe route should be selected to

a) minimize the need for seabed preparation,

b) minimize the vertical imperfections to be crossed,

c) ensure space for individual trenching, if required,

d) minimize pipe length.

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7.3.1.3 The layout (for example, location of wellheads, manifolds, mooring lines, and PLEMs, etc.) significantly influences the selection of flowline layouts and riser configurations and should be considered early in the design.

7.3.2 Protection

7.3.2.1 Pipe protection against damage caused by objects, such as fishing gear, anchors and mooring lines, should be considered, and requirements specified in agreement by the purchaser and manufacturer.

7.3.2.2 The impact energy and geometry of objects considered should be defined in the project design premise (see ISO 13628-2 and ISO 13628-10). Impact loads should be quantified for the intended service as normal or abnormal operations following the results of a safety analysis. The recommended requirements for pressure-containment equipment (such as the pipe structure, end fittings and connectors) are as follows:

a) normal operations: such equipment should not be permanently deformed;

b) abnormal operations: such equipment should not leak.

7.3.2.3 Based upon this classification and the protection method adopted, representative calculations should show that the pipe structure, end fitting and connector utilization comply with ISO 13628-2 and ISO 13628-10.

7.3.2.4 The following should be taken into account in the evaluation of the optimum technical and economical protection method:

a) seabed or ground conditions;

b) pipe and protection facility installation;

c) pipe expansion from temperature, pressure, etc.;

d) bending as a result of upheaval buckling;

e) inspection and maintenance;

f) pipe retrieval.

7.3.3 On-bottom stability

7.3.3.1 General

7.3.3.1.1 The stability of a flowline section on the seabed or ground is directly related to its (submerged) weight, the environmental forces and the resistance developed by the soil. A stability analysis should demonstrate that the (submerged) weight of the unburied flowline is sufficient to meet the required stability criteria. Pipeline stability is to be considered for both installation and operation conditions. Flotation and sinking of the pipe for the most critical internal fluid conditions should be checked. Issues to be considered during the stability analysis should include the following:

a) lateral displacement from an installed position as a result of expansion, settlement or hydrodynamic effects;

b) geometric limitations of the surrounding system;

c) distance from other pipes, structures or obstacles;

d) internal fluid density and its variation during the service life;

e) pipeline tension, curvature and torsion;

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f) interaction with lateral buckling resulting from axial forces;

g) fatigue damage;

h) wear and deterioration of outer sheath;

i) damage to sacrificial anodes;

j) loading on end connections.

7.3.3.1.2 The suitability of mattresses, with respect to pipe cover abrasion and damage from protrusions, should be confirmed if their incorporation is required to provide stability. The general form and size of rocks, if rock dumping is provided, should be such that no damage is sustained to the pipe during deployment.

7.3.3.2 Analysis methods

7.3.3.2.1 The following stability analysis methods may be employed:

a) dynamic analysis, involving a full dynamic simulation of the pipeline resting on the seabed and including modelling of soil resistance, hydrodynamic forces, boundary conditions and dynamic response;

b) generalized stability analysis based on a set of non-dimensional stability curves that have been derived from a series of runs with a dynamic-response model;

c) simplified stability analysis based on a quasi-static balance of forces acting on the pipe.

7.3.3.2.2 Further details on the above analysis are given in References [30] and [1].

7.3.3.3 Stability criteria

The pipe supplier or designer should specify and justify stability criteria for the particular application, which may be based on guidelines in References [30] and [20]. As a minimum, the design criteria specified in ISO 13628-2 and ISO 13628-10 should be satisfied.

7.3.4 Upheaval buckling

7.3.4.1 Introduction

7.3.4.1.1 A flexible pipe laid in a trench can be susceptible to upheaval buckling from longitudinal expansion of the flowline caused by internal pressure and temperature loadings. Internal pressure is the dominating factor contributing to upheaval buckling of flexible pipe.

7.3.4.1.2 In addition, changing the lay angle of the pipe can produce longitudinal expansion of the pipe, with the optimal angle being approximately 55° for a two-ply pipe. Additional pairs of plies can change the optimal angle significantly.

7.3.4.1.3 The flexible flowline may be allowed to buckle provided that the design criteria of 7.3.4.4 are not violated. The potential for upheaval buckling can be evaluated by analytical or experimental methods. The parameters that influence the upheaval behaviour of a flexible flowline and that should be incorporated into any investigation of upheaval buckling include the following:

a) operational pressure and temperature distributions along the flowline, including hydrotest conditions;

b) vertical imperfections in the flowline foundation;

c) variations in uplift resistance along the line, such as varying soil-cover height and conditions, soil longitudinal friction, soil rotational stiffness and its contribution to bending resistance of the pipe;

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d) uplift resistance as a function of pipe uplift displacement;

e) stiffness properties of the pipe cross-section as a function of pressure and temperature; in particular, axial compression stiffness and bending stiffness of the pipe;

f) relaxation with time of the initial lay pretension stresses in the pipe.

7.3.4.2 Methods of prevention

7.3.4.2.1 Measures to prevent or limit the extent of upheaval buckling include the following:

a) burying the pipe in a trench;

b) rock dumping;

c) wide and open trench to allow horizontal snaking;

d) laying the pipe with internal pressure to provide initial pretension in the line prior to burial;

e) optimizing tensile-armour lay angle.

7.3.4.2.2 A feasible way of pretensioning a flexible pipeline is to restrain the pipe (by rock dumping, for example) while it is subjected to axial expansion due to internal pressure. Consider the following when evaluating the resulting effective pretension in the line:

a) residual axial compression loads due to the frictional resistance between the pipe and the seabed;

b) relaxation of pretension loads because of possible straightening of formed loops (lateral buckles);

c) creep of pipe materials with time.

7.3.4.3 Analysis methods

7.3.4.3.1 A linear model can be used to determine if upheaval buckling can occur. If it is a concern, then a non-linear model is required for analysis of upheaval buckling. The non-linear model should account for varying soil cover from imperfection geometry, non-linear pipe/soil interaction and geometric non-linearities because of large deflections of the flowline. It may be assumed that the material properties exhibit a linear behaviour.

7.3.4.3.2 An initial imperfection in the installed flowline configuration is characterized by an imperfection amplitude and a corresponding imperfection wavelength, assuming a symmetrical shape about the imperfection apex. In the unloaded condition, the pipe is assumed to be fully supported by the soil. Subjecting the pipe to temperature and pressure loads generates an axial compression force in the pipe, causing the pipe to buckle into a new equilibrium shape characterized by a buckling wavelength and a buckling amplitude, thereby creating a resulting uplift amplitude at the apex of the imperfection.

7.3.4.4 Design criteria

7.3.4.4.1 The upheaval buckling design criteria should be based on the following.

a) The pipe contains no bends below its minimum allowable bend radius.

b) The pipe does not deviate beyond the trench or berm boundaries.

c) Movement restrictions imposed by the trench and infill do not result in pipe structure stresses or loads that violate the design criteria in ISO 13628-2 and ISO 13628-10.

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d) The upheaval-buckling process does not subject the pipe to other failure modes that can cause leakage of the pipe, such as exposing the pipe to trawl-board snagging.

e) There is an adequate safety margin against snap-through buckling.

7.3.4.4.2 The uplift displacement is to be limited to a maximum of 0,75 l_{ult}, where l_{ult} is the burial depth, to avoid an upheaval creep mechanism taking place because of variations in temperature and pressure during the service life of the line.

7.3.4.4.3 The distance between the pre- and post-buckling equilibrium curves at specified design conditions shall not be less than 0,1 m (3,94 in) when plotted in a temperature (or pressure) versus uplift displacement plane to ensure an adequate safety margin against snap-through buckling failure.

7.3.4.4.4 The uplift resistance of the protection cover shall be documented. It is necessary to give consideration to a possible decrease in uplift resistance because of undrained cover or backfill or change in cover properties as a result of the installation method employed.

7.3.4.4.5 Following the installation of a flexible pipe, which is susceptible to upheaval buckling, the design requirements shall be verified with regard to the following:

a) vertical imperfections of installed line;

b) burial depth and berm height/width.

7.3.4.4.6 Documentation shall exist verifying that the required cover is present prior to taking a trenched pipeline with natural backfill into service. The pipe configuration that results if a pipeline is situated in an open trench should be checked when the line is brought into service.

7.3.5 Pipeline crossing

7.3.5.1 Suitable protection should be placed between a flexible pipe that crosses another flexible or steel pipe or umbilical in service, unless it can be shown that the MBR and other design criteria are not violated. Protection can include sand bags, stabilization mattresses, structural bridges or low-friction matting. The number of crossovers should be minimized by the installation procedures if multiple lines are installed in a single trench.

7.3.5.2 A gas-carrying pipe should be placed above a liquid pipe if a crossover involves both liquid- and gas-carrying pipes, unless the liquid pipe is lighter than the gas pipe, accounting for content. Any protection facility should take such movement into account where crossed flexibles are susceptible to movement.

7.3.5.3 Abrasion sleeves constructed of metal or polymer should be provided where a number of pipes come into contact under constant or frequent movement. The sleeves should sufficiently cover the maximum extent of relative movement and have enough thickness to account for expected wear. The sleeve requirements should be determined during the detail design of the pipe system.

7.4 Riser design requirements

7.4.1 Riser configuration

7.4.1.1 A considerable part of flexible-riser-system design is the determination of configuration parameters so that the riser can safely sustain the extreme sea-state loadings for which it is to be designed. A safe riser design nowhere exceeds maximum allowable tension or minimum allowable bend radius criteria, as per ISO 13628-2 and ISO 13628-10, when subjected to these extreme wave and current loadings. A well designed riser configuration is safe and provides compliancy to vessel motions in a cost-effective manner. A riser that is compliant to vessel motions minimizes the station-keeping requirements for the vessel and, in turn, reduces mooring costs.

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7.4.1.2 Large riser rotations, combined with large tensions near the riser/vessel or riser/seabed termination points, are also an undesirable riser response to sea-state loading. In this case, large bend stiffeners are required at the pipe-end fitting to avoid exceeding the minimum allowable bend criterion in the flexible pipe at this location.

7.4.1.3 Flexible risers are commonly deployed in one of the five standard configurations listed below and as illustrated schematically in Figure 4:

a) free-hanging catenary;

b) lazy-S;

c) steep-S;

d) lazy wave;

e) steep wave.

7.4.1.4 Key points about these riser configurations are described in 7.4.1.5 to 7.4.1.7.

7.4.1.5 Free-hanging catenary is the simplest, and generally the least expensive, riser configuration. A key problem with this solution, however, is that if there are any significant first-order wave motions at the vessel connection (particularly heave), these motions are transferred directly to the seabed and this inevitably leads to compression at the riser touchdown point. Buckling and overbending of the pipe below its allowable limit are consequences of this effect. Furthermore, the free-hanging riser is not very compliant to vessel motions: riser top tension increases rapidly with far vessel offset, and large vessel-offset motions result in correspondingly large and undesirable motions of the riser/seabed touchdown point.

The free-hanging configuration, because of its simplicity, is always worth considering as a potential solution, particularly for mild-environment, deep-water applications. In deep-water applications, the hang-off loads on the vessel can be large due to the suspended riser length.

7.4.1.6 S-configurations enable flexible lines to ascend to the floating vessel in bundles over a single buoy. The analysis of the hydrodynamic behaviour of the buoy is an important consideration in the design of these systems. In general, the steep-S riser buoy is more susceptible to torsional instability than is the lazy-S solution.

The introduction of a subsea buoy (see Figure 14) into the riser configuration has two main functions.

a) It provides a filter to stop the direct transfer of dynamic motions to the seabed that occurs with the free-hanging configuration.

b) It supports part of the weight of the riser, thereby reducing static tension at the vessel connection.

The change in seabed touchdown point is controlled by the lateral motion of the subsea buoy. Increasing the size of the buoy correspondingly also increases the lateral restoring force through the buoy tethers, and this in turn tends to reduce the lateral motions of the buoy. However, a larger buoy is also susceptible to increased hydrodynamic loading.

7.4.1.7 The buoyancy for wave configurations (see Figure 14) is applied to the pipe in a distributed manner rather than as a concentrated point load as for the S-configurations. Generally, the wave configurations are more compliant to environmental loading than the S-configurations and ascend to the floating vessel as individual lines (or clamped bundles). While the increased compliancy to vessel motions of the wave configurations is a definite advantage, the compliant nature of the riser configuration itself to environmental loading, and particularly to cross-loading, makes riser interference with adjacent risers or structures an important design consideration.

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In general, the steep-wave riser is less compliant than the lazy wave. The shape of the lazy-wave riser is particularly susceptible to variations in internal fluid density, though undesirably large motions can be avoided by designing a flexible-pipe cross-section with low drag-to-weight properties.

The lazy-S wave shown in Figure 4 is a modification of the steep-wave configuration. Close to the seabed touchdown, the tension in the riser is transferred via a riser clamp to an anchor line, which is tied to the seabed by a clump weight or a suction anchor. The riser itself touches down on the seabed almost like a lazy-wave configuration, except in this instance the touchdown point is well controlled by the near-vertical riser anchor line and an optional horizontal anchor line clamped between the seabed section of the riser and the clump weight or suction anchor.

7.4.2 Riser interference

7.4.2.1 The riser system design should include evaluation or analysis of potential riser interference (including hydrodynamic interaction) with other risers and between risers and mooring legs, tendons, vessel hull, seabed or any other obstruction. Abnormal service conditions including the case of one mooring line damaged should also be considered. Interference should be considered during all phases of the riser design life, including installation, in-place, disconnected and unusual events. The accuracy and suitability of the selected analytical technique should be assessed when determining the probability and severity of contact.

7.4.2.2 Riser systems should be designed to control interference that can damage the risers or other parts of the system. Hydrodynamic interaction of multiple risers, including shielding, should be considered. The effect of marine growth should also be considered.

7.4.2.3 Either of two design approaches may be taken to control riser interference. One approach requires that the riser system have an acceptably low probability that the clearance between a riser and another object is greater than a specified minimum value. The other approach permits contact between the riser and the other object but requires analysis and design for the effects of contact.

7.4.2.4 Interference can occur between a riser and any object that has dynamic characteristics different from those of the riser and that is sufficiently close to it. Objects can include the vessel hull, a riser of different size, a riser having different properties (such as different contents, extent of marine growth, top tension or tension distribution), other boundary conditions or a riser in a different flow field caused by wake effects. Clearly, this type of interference is more severe than between risers with similar dynamic characteristics, and the size and direction of impact loads should be quantified.

7.4.2.5 Interference between adjacent wave-type risers at the buoyancy section should not be allowed.

7.4.2.6 Quasi-static analyses should identify the critical load combinations of wind and current profiles and headings, and vessel offsets, which minimize the clearance between the riser and the adjacent structure.

Dynamic analyses should identify the critical load combinations of vessel draft, vessel orientation, wave frequency and wave heading that maximize riser motions and deflections, in the presence or absence of currents.

The dynamic load cases are typically based on the critical load combinations determined from the quasi-static analyses.

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7.4.3 Load-bearing structures

7.4.3.1 Load-bearing structures used to support flexible pipes should be designed such that the pipe is not subjected to excessive wear, bending or crushing. As such, steel materials should be provided with suitable cathodic or coating protection, and all surfaces in contact with the flexible pipe should be provided with a surface radius greater than the permissible MBR for the flexible pipe.

7.4.3.2 Structures within a flexible pipe system should be designed to accommodate flexible pipe movements. Load-bearing steel components should be designed in accordance with relevant steel standards for offshore-structure design.

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7.4.4 Pipe attachments

Interactive forces between pipe and any attachment should be determined along with resultant pipe deflections. Due consideration should be given to mid-water support buoys with respect to their overall behaviour within the system to minimize dynamic effects imposed on the pipe.

7.4.5 Riser bases

Riser bases should be located in relation to the overall system such that the pipe does not exceed design MBR in any load case and the maximum excursion capability of the flexible-pipe top end is facilitated. Installation tolerance for the riser base should be accounted for in the riser system design.

7.4.6 Jumper and spool pieces

7.4.6.1 Each flexible pipe jumper and spool piece should be analyzed in accordance with the load cases defined in the design premise (see ISO 13628-2 and ISO 13628-10). All associated equipment should be subjected to a similar level of analysis in order to establish suitability. The analysis shall take account of seabed conditions and pipe stability.

7.4.6.2 The configuration of a spool piece should be such that minimal loading is imposed on the flexible pipe, with special emphasis being placed on the area immediately around the end fitting. Spool pieces and their systems should be manufactured so that pipe lengths provide sufficient flexibility during installation and operation.

7.5 Ancillary components

7.5.1 General

Design requirements for typical ancillary components in flexible pipe systems are presented in 7.5.

7.5.2 Connectors and rigid pipe components

Connectors and rigid pipe components should be designed according to the same requirements as the flexible-pipe end fitting as specified in ISO 13628-2 and ISO 13628-10 or should be a standard connector (such as API 16A [8], ISO 13628-4 [24], and ANSI/ASME B16.5 [2]) rated for the design pressure and other imposed loads.

7.5.3 Bend stiffeners

ISO 13628-2 and ISO 13628-10 contain recommended procedures for the design, material selection, manufacture, testing and marking of bend stiffeners.

7.5.4 Bend restrictors

ISO 13628-2 and ISO 13628-10 contain recommended procedures for the design, material selection, manufacture, testing and marking of bend restrictors.

7.5.5 Bellmouths

7.5.5.1 A bellmouth is one type of bend limiter for a flexible pipe and is used for dynamic applications where flexible risers are pulled through guide tubes to vessel deck level. The lower end is flared to avoid overbending, thus producing the bellmouth. The bellmouth design is based on the maximum offset angle of the flexible riser and its minimum allowable bend radius. The effect of bellmouth contact pressure on the structural layers' alternating stress should be considered in evaluating the fatigue life of flexible pipe.

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7.5.5.2 The simplest shape of bellmouth has a constant radius along its length. This shape, however, does not provide the best protection against fatigue. Therefore, it is more advantageous to apply a large radius at the top section where the pipe is in regular contact with the bellmouth, and a smaller radius at the bottom section, where there is only intermittent contact in extreme conditions.

7.5.5.3 The shape of a bellmouth with a linear variation in curvature along the bellmouth can be defined as a function of s as given in Equations (3) to (5):

$$\phi(s) = \frac{\left(1-\alpha^2\right)\cdot K_\mathrm{b}^2}{4\Phi_\mathrm{b}}\cdot s + \alpha \cdot K_\mathrm{b} \cdot s \quad (3)$$

$$K(s) = \frac{\left(1-\alpha^2\right)\cdot K_\mathrm{b}^2}{2\cdot\Phi_\mathrm{b}}\cdot s + \alpha \cdot K_\mathrm{b} \quad (4)$$

$$s_\mathrm{b} = \frac{2\cdot\Phi_\mathrm{b}}{(1+\alpha)\cdot K_\mathrm{b}} \quad (5)$$

where

$\phi(s)$ is the angle between the bellmouth axis and tangent at a point S on the curved wall;

$K(s)$ is the curvature at a point S on the curved wall;

Φ_b is the angle of bottom entry;

K_b is the curvature at bottom entry, equal to $1/r_\mathrm{b}$;

r_b is the minimum allowable bend radius;

s_b is the length of bellmouth measured along the curved wall;

α is the ratio between minimum (top) and maximum (bottom) curvature.

7.5.5.4 Figure 22 is a schematic drawing of the parameters used in the design of a bellmouth.

7.5.5.5 In general, both the required length and diameter of a bellmouth are dependent on the entry angle, and the length is also dependent on the ratio of minimum (top) and maximum (bottom) curvature.

7.5.5.6 The entry angle, Φ_b, should be at least 5° greater than that calculated to be required from all design load cases, accounting for all effects including vessel rotation.

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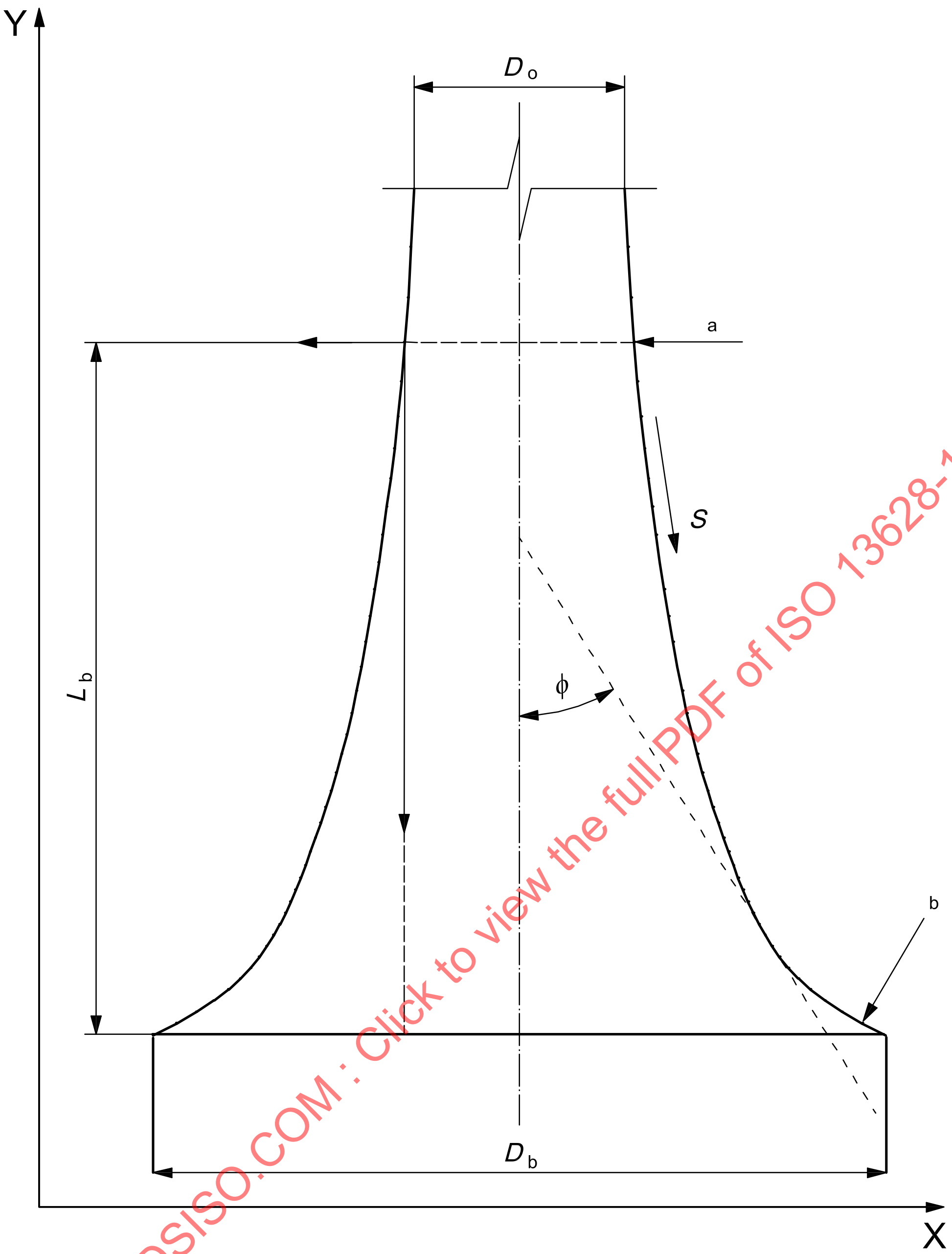

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Key

X longitudinal or vertical axis

Y lateral or horizontal axis

l_s length of bellmouth, measured along the curved wall

ϕ angle between X-axis and tangent at a point on the curved wall

L_b length of bellmouth, measured along the X-axis

D_b diameter at bellmouth bottom end

D_o diameter at bellmouth top end

α ratio between minimum (top) and maximum (bottom) curvature

[a] $s = 0$, $\phi = 0$, $K = \alpha K_b$.

[b] $s = l_s$, $\phi = \phi_b$, $K = K_b$, $r_b = 1/K_b$.

Figure 22 — Parameters used to define a bellmouth shape

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7.5.6 Clamping devices

7.5.6.1 Permanent clamping devices should be designed according to the requirements for load-bearing structures. If such clamps are applied, sufficient testing of similar clamps on samples of the proposed pipe in simulated conditions should be carried out and fully documented prior to installation.

7.5.6.2 Clamping should not impose local or preferential loading on the pipe structure so that its pressure and structural integrity are compromised during its design life. Clamping should not accentuate fatigue, abrasion or fretting in the pipe structure beyond the limits imposed by the appropriate usage factors. The materials selected for the clamps should be creep-resistant and suitable for long-term exposure in the specified environment.

7.5.7 Buoyancy devices

7.5.7.1 The analysis should identify the interactive forces between pipe and buoyancy devices and resultant pipe deflections. The design should show that sliding of the buoyancy devices along the pipe is prevented.

For example, the clamping force should be sufficient to ensure that the friction between the buoyancy clamp and pipe is greater that the maximum longitudinal loads on the buoyancy devices, including a safety factor of at least 1,0.

7.5.7.2 When selecting either a steel or polymer material, consider the following:

a) suitability for water depth;

b) length of service at water depth;

c) resultant size and dynamic loading effects on pipe;

d) durability;

e) previous history under similar conditions;

f) safety;

g) handling characteristics.

7.5.7.3 The arch-supporting structure should be designed in accordance with load-bearing structures (see 7.4.3). Attachment of buoyancy modules to a riser should take account of hydrodynamic forces, self weight, inertial forces, slamming forces and effect of pressure on module clamp contact pressure.

7.5.7.4 Buoyancy modules are to maintain sufficient buoyancy over their service life to fulfil their function; long-term resistance to hydrostatic pressure is required. All materials in the structure should be selected based on the environmental requirements with sufficient corrosion resistance for the specified service life.

7.5.7.5 Damage to one single buoyancy element should not result in unacceptable loss of buoyancy for the pipe system as a whole. This can require the installation of bulkheads in steel buoyancy tanks. After loss of 10 % of distributed buoyancy or one compartment in a subsea buoy/arch system, the riser configuration should still be fit for purpose.

7.5.7.6 Materials (such as synthetic foam) for buoyancy modules should be qualified by tests in order to confirm their resistance to hydrostatic pressure for the specified water depth. Water absorption and creep due to hydrostatic pressure over the specified service life should be included in the analysis of the performance of the materials. The loss of buoyancy from water absorption should be documented and the end-of-life value used for a design check.

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7.5.8 Riser base

The riser base, including pipework, structural supports, and foundation, should be designed as described in References [20] and API RP 2A-WSD [3]. The pipe and J-tubes should, where applicable, be arranged such that no bending moments are imposed on the end fitting of the static pipe. The following issues can be pertinent to the field in question:

a) gravity or piled structure;

b) isolation/manifolding facility;

c) emergency abandonment procedure;

d) riser configuration.

All such details should be fully evaluated prior to design commencement.

7.5.9 Temporary lifting appliances

Temporary appliances should be designed in accordance with industry standards, such as Reference [20]. The lifting gear, as a general rule, should be designed for dynamic loading duties. This requirement should also apply for equipment such as shackles and forerunners with associated gear.

7.5.10 Tether design

The strength of a tether (such as S-type riser configuration), if required for a flexible static or dynamic riser, should allow the pipe to separate from the tether prior to failure of the pipe structure (unless a pipe failure or load-limiting joint is designed at the tether connection). The tether should be designed for all events with probability of occurrence greater than 10^{-4}.

7.6 System interfaces

7.6.1 General

Interface issues should be considered at an early stage of a project, as they may have a serious impact on both the pipe and system design. Clear interface definition allows the development of an optimized overall solution for the system. Relevant issues are described in 7.6.2 to 7.6.9.

7.6.2 Connection location

Connection of the risers above or below the water line has important implications for design, installation, and use (condition monitoring).

7.6.3 Bend limiter selection

Selection of bellmouths or bend stiffeners should be addressed prior to the design of the topsides interface.

NOTE Bellmouths require significantly more space than stiffeners.

7.6.4 Location of bend limiter

A spool piece should be considered whether the bend limiter is located at the end fitting or at the end of an I-tube.

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7.6.5 Flowline installation conditions

Consideration should be given to upheaval-buckling requirements and to the possible need to pressurize the flowlines prior to burial if trenching and back filling is used.

7.6.6 Connection design

Consideration should be given to the possible future requirement for the use of internal inspection tools. This requires a pigging system to be designed to allow access for the launch of inspection tools. This also applies where pigs might possibly be launched from the top connection to the flexible.

7.6.7 Connectors

Aspects (such as height and location of flanges, diverless or diver-assisted tie-ins and flange and hub specification) should be specified.

7.6.8 I- and J-tubes

Use of I- and J-tubes affects the flexible-pipe installation options, and should be considered during the design of the tubes. Any requirement for spool pieces at the end of I-tubes significantly affects the loads on the I-tube.

7.6.9 Subsea connections

Use of riser configurations with horizontal connections (such as the lazy-S) can simplify installation and significantly reduce the complexity of the PLEM/riser base structure.

8 Analysis considerations

8.1 Introduction

Clause 8 provides recommendations for flexible pipe analysis techniques, defines the loads typically experienced in pipe applications, and provides guidelines for the evaluation of the pipe or system response to these loads.

8.2 Analysis techniques

8.2.1 Local analysis

8.2.1.1 Local cross-section analysis is a complex subject, particularly for combined loads, because of the composite layer structure of a flexible pipe. Local analysis is required to relate global loadings to stresses and strains in the pipe. The calculated stresses and strains are compared to the specified design criteria (ISO 13628-2 and ISO 13628-10 list relevant criteria) for the load cases identified in the project design premise; see 5.5 for guidelines on selection of load cases.

8.2.1.2 The simplified equations given in FPS 2000 [23] may be used for a preliminary check of loads on flexible pipe. For detailed design, more refined analysis techniques that account for all relevant effects are required. The required analysis can be performed by a number of computer programs. Minimum requirements for the cross-section analysis methodology are provided in ISO 13628-2 and ISO 13628-10.

8.2.1.3 Load effects in pipe-wall sections may be documented by prototype testing. Numerical analysis methods may also be used to predict local stresses. Under numerical analysis, the analysis results may be validated by prototype testing.

8.2.1.4 Design formulas should be related to the specific type of pipe design and can be validated for those specific designs by strain-gauge results from prototype tests. Justification for extrapolation of results should be documented. The actual load situation in the pipe should be considered, especially with regard to combined loading when considering use of analytical methods.

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8.2.1.5 Any software tool developed by the manufacturer used for riser analyses should be

a) verified against closed-form analytical solutions,

b) validated by a range of numerical tests to show that the generic model/software tool is internally consistent and that it does not contain detectable flaws,

c) calibrated against full-scale tests by means of manipulating the independent variables of the software model to obtain a match between the observed and simulated distributions of the dependent variables,

d) confirmed to predict values within the [$-q$ %, $+p$ %] accuracy range from the observed values of the full-scale tests.

A report summarizing the verification, validation and confirmation of the version of the software tools intended for use should be available for the purchaser's review and approval. It is necessary that this report be updated with subsequent major software version releases that add key functionality or modify methodology and numerical schemes.

8.2.2 Analysis of pipe-wall environment

8.2.2.1 The pipe wall for either bonded or unbonded construction is the space occupied by the primary reinforcement elements.

8.2.2.2 The analysis of the pipe-wall environment of a flexible pipe is an important consideration, particularly for the determination of gas-release requirements and metallic-material failure modes. The following pipe-wall-environment characteristics should be considered for the design of the flexible pipe:

a) permeated gas and liquids;

b) external fluid ingress (seawater).

8.2.2.3 The polymers used for the internal pressure sheath allow fluids in the pipe to permeate the pipe wall. This permeation rate (leakage) is negligible with regard to pipe performance (flow capacity). The pipe system design, however, shall allow for safe escape of the permeated gas. Gas permeation from the conveyed fluid into the pipe wall should be calculated using a qualified procedure. The permeation rate is a function of internal and external pressures, surface areas, sheath thickness and permeability coefficient.

NOTE The permeability coefficient depends on material, gas component and temperature.

8.2.2.4 H_2S gas permeation into the pipe-wall environment determines if a particular application is considered as sweet or sour service. The pressure in the pipe wall and the concentration of H_2S in the pipe wall shall be calculated to make this determination. In addition, CO_2 permeation rates are required to determine the annulus pH level.

8.2.2.5 After a transient period, an equilibrium condition is reached in which the partial pressures in the pipe wall are lower or at a maximum equal to the partial pressures in the pipe bore, with the actual value dependent on pressure, temperature, polymer materials, etc.

8.2.2.6 The partial pressure of H_2S in the pipe wall can be assumed, as an initial approximation, to be the same as in the pipe bore. This is likely to be conservative, as the pipe-wall pressure is limited to the gas-escape pressure at the particular location accounting for external seawater pressure. Differences can exist between the fluid composition in the pipe bore and pipe wall because of the different permeation rates of H_2S and other components.

8.2.2.7 Parameters that influence the actual partial pressure of H_2S in the pipe wall are discussed in Reference [38]. The partial pressure should then be used to check against NACE TM0177 requirements. If testing is required, the partial pressure of H_2S used in testing should be greater than or equal to the calculated pressure.

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8.2.2.8 The pipe wall of an unbonded flexible pipe intended for static service should be assumed flooded with seawater. The outer sheath for unbonded flexible pipe intended for dynamic service should be qualified as watertight. In addition, the service life, with the pipe wall flooded with seawater, should be calculated and specified in the operation manual.

8.2.2.9 Any software tool developed by the manufacturer used for riser analyses should be

a) verified against closed-form analytical solutions,

b) validated by a range of numerical tests that the generic model/software tool is internally consistent and that it does not contain detectable flaws,

c) calibrated against full-scale tests by means of manipulating the independent variables of the software model to obtain a match between the observed and simulated distributions of the dependent variables,

d) confirmed to predict values within the [$-q$ %, $+p$ %] accuracy range from the observed values of the full-scale tests.

A report summarizing the verification, validation and confirmation of the version of the software tools intended for use should be available for the purchaser's review and approval. It is necessary that this report be updated with consequent major software version releases that add key functionality or modify methodology and numerical schemes.

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8.2.3 Global analysis

8.2.3.1 General

8.2.3.1.1 Global analysis is performed to evaluate the global load effects on the pipe during all stages of installation, operation and retrieval, as applicable. The static configuration and extreme response of displacement, curvature, force and moment from environmental effects should be evaluated in the global analysis.

8.2.3.1.2 Global load effects generally should be documented by numerical analysis methods, such as the finite-element method. The analysis should account for three-dimensional dynamic response, stochastic response (irregular sea) and non-linear effects. The computer model and results should be fully documented.

8.2.3.1.3 Static and quasi-static analysis methods are permitted for use during preliminary configuration design. However, all time-varying loads (such as waves) should be modelled with dynamic analyses in the detailed design stage of a project to accurately account for inertia effects.

8.2.3.1.4 Critical phases during installation and operation may be analysed by a stepwise time-integration procedure. Very large changes in the riser configuration require a non-linear-solution procedure. Non-linear time-domain simulations are required for dynamically sensitive structures. The wave conditions considered can be described by deterministic or stochastic methods. Structural damping may be taken into account with a proportional-type damping used without the inertia component.

8.2.3.1.5 Pipe characteristics and operational data should be considered in the analysis. For some applications, the bending stiffness characteristics of the pipe are critical, such as for light lines that are subject to severe dynamic motions or the seabed touchdown region in the lower catenary section of a lazy-S configuration. It is necessary that the bending stiffness in such cases be assessed accurately to determine whether buckling is occurring or whether MBR design criteria are being violated. Parameters relevant to the pipe-bending stiffness include the number, thickness (including tolerances) and material in the polymer layers, mean temperature in the layers (pipe is stiffer at lower temperatures), non-linear material characteristics (aged and unaged material) and internal pressure. The effect of the tensile-armour layers on the stiffness can generally be ignored, as the armour wires can slip when the pipe is bent to a high curvature.

8.2.3.1.6 Hydrodynamic loads may be calculated by means of Morison's equation (8.3.1.2). Coefficients in 8.3.1.4 may be used. Tangential forces also should be taken into account for flexible pipes with buoyancy elements.

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8.2.3.1.7 Interaction is required for riser configurations with a part of the riser resting on the sea floor. A complete non-linear formulation should be used if the local behaviour close to the sea floor is of particular interest.

8.2.3.1.8 The minimum effective tension (see 8.4.5) should be examined in order to check for possible buckling of the pipe. The effective tension is normally required to be positive. It should be shown that any effective compression is tolerable for the pipe (see 5.4.1.9 for compression criteria).

8.2.3.2 Static analysis

8.2.3.2.1 The aim of the static analysis (sometimes aided by preliminary dynamic analysis) is to determine the initial static geometry of the pipe configuration. The design parameters selected for the static analysis are typically length(s), mass, buoyancy requirements, and the location of seabed touchdown point and subsea buoy(s). The loads considered in the static analysis stage are generally gravity, buoyancy, internal fluid, vessel offsets and current loads.

8.2.3.2.2 The following three extreme cases should be investigated for flexible risers:

a) near-position analysis;

b) far-position analysis;

c) maximum out-of-plane excursion.

8.2.3.2.3 The extreme positions are not necessarily in the plane of the riser, particularly if environment directionality effects are considered.

8.2.3.3 Dynamic analysis

8.2.3.3.1 The next stage in the design procedure (dynamic applications only) is to perform dynamic analyses of the system to assess the global dynamic response. A system layout and vessel position is chosen from the static analysis and a series of dynamic load cases is considered. These load cases combine different wave and current conditions, vessel positions and motions, and riser-content conditions to provide an overall assessment of the riser suitability in operating and extreme environmental conditions. See 5.5 for recommendations on load-case selection.

8.2.3.3.2 In the dynamic-analysis phase, the effect of vessel motions should be combined with wave and current forces to obtain the response of the riser. The hydrodynamic forces can be calculated based on Morison's equation (8.3.1.2). The vessel motions can be obtained from model tests, computer simulations or from knowledge of the vessel response amplitude operators and the wave data.

8.2.3.3.3 Analysis in the frequency domain is generally inappropriate, because of the geometrical nonlinearities generally associated with dynamic behaviour of flexible risers. Consequently, flexible riser analyses are usually performed with time-domain simulations.

8.2.3.3.4 Analyses for the static and dynamic analysis phases are often interrelated in the sense that a certain amount of iteration is needed to achieve a preliminary sizing and layout design. A coarser mesh can often be adequate for preliminary dynamic analysis.

8.2.3.3.5 Any results from a dynamic analysis should be scrutinized for their accuracy and convergence prior to accepting them for design. Particular attention should be given to the adequacy of mesh selection and time stepping used in the analysis. Sensitivity of the response to the wave approach direction and wave period should be evaluated to produce the most unfavourable load conditions.

8.2.3.3.6 Either regular waves or irregular seas, in time domain or in frequency domain, can be used for dynamic analysis. The regular-wave/time-domain approach is recommended for preliminary sizing of the riser configuration. The critical results from regular-wave analyses should be verified with irregular-wave runs to ensure that the response variables are adequately captured. Similarly, the critical results from frequency-domain analyses should be verified with time-domain analyses to ensure that the response variables are adequately captured.

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8.2.3.3.7 The following significant response parameters are typically required from a dynamic analysis at all riser locations of structural, boundary and geometrical discontinuities, namely at riser top, buoyancy and touchdown-point areas, and flange connections:

a) maximum and minimum riser angles;

b) maximum effective tension and/or compression;

c) minimum bend radius;

d) movement and curvature of riser at touchdown point;

e) buoy displacement and tether tension;

f) riser tension and departure angle at support buoy;

g) effective tension, bending moment, shear force and displacement at flange connections;

h) location of point of no motion on the seabed;

i) tension at the end of the model with the purpose of determining the tension at the seabed termination;

j) clearances between risers for multiple risers;

k) clearance from structure or seabed;

l) clearance between risers and mooring lines.

The angles and tensions of the riser at the connection points can be used to design bend limiters to prevent overbending of the riser at these locations. The measured angles in the case of vessel connections should account for the relative rotation (pitching) of the vessel.

8.2.3.4 Computer programs

A number of proprietary computer programs are available for riser analysis, based on both finite-element and finite-difference methods. Any software tool, developed by the manufacturer or acquired from software vendors, used for riser analyses should be

a) verified against closed form analytical solutions,

b) validated by a range of numerical tests to show that the generic model/software tool is internally consistent and that it does not contain detectable flaws.

A report summarizing the verification, validation and confirmation of the version of the software tools intended for use should be available for the purchaser's review and approval. It is necessary that this report be updated with consequent major software version releases that add key functionality or modify methodology and numerical schemes.

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8.2.3.5 Modelling considerations

8.2.3.5.1 The following modelling considerations are critical for accuracy of results:

a) mesh size in relation to radius of curvature obtained from the analysis;

b) selection of C_d and C_m for wave load calculations (see 8.3.1.4);

c) selection of boundary conditions;

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d) selection of time step and duration for dynamic analysis;

e) type of finite element;

f) selection of damping model and coefficients.

8.2.3.5.2 Running multiple analyses to check the sensitivity of the results to these parameters is desirable in some cases.

8.2.3.6 Analysis of multiple configurations

8.2.3.6.1 Risers used in a production facility are bundled together in many situations. Three types of bundles are as follows:

a) free bundle;

b) integral bundle;

c) multibore risers.

8.2.3.6.2 The risers in a free bundle are free to move independently and are connected only at the termination points and to a subsea buoy. In the analysis of a free bundle, all risers should be included individually in a single model (single-riser models or equivalent models are not recommended for detail design). The free-bundle model should be sufficiently detailed so that all motions and loads in the risers, subsea buoy and tethers can be calculated. The hydrodynamic interaction of the risers is minimal, provided they are separated by a distance greater than five times their individual diameters, unless there is a large enough riser array to create wake synchronization or other flow disruptions.

8.2.3.6.3 The riser pipes in an integral bundle are connected together at short intervals [such as 10 m (10,94 yd)] so that they all move as one unit. The analysis of such bundles can be carried out by suitably combining the individual riser-line properties and treating the bundle as an equivalent single pipe. The total tension in bundles with risers with unequal properties is distributed based on the axial stiffness of the individual risers. Also, an asymmetric bundle arrangement produces unsymmetrical hydrodynamic loads, which can lead to torsional rotation of the riser bundle. In modelling such bundles, the following is recommended.

a) The overall motion of the bundle is compared to that expected from individual risers.

b) The relative motions of the individual risers in a bundle are assessed so that the possibilities of riser entanglement and external wear are minimized.

c) The distribution of the tension at the terminal points is evaluated; for preliminary design it can be conservatively assumed that the largest pipe in the bundle takes the entire load.

8.2.3.6.4 The global analysis requirements for multibore risers are the same as for standard risers.

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8.2.4 Service-life analysis

8.2.4.1 General

8.2.4.1.1 Pipe design service life shall be specified and documented. Design service life may be based on specific project or application duration or may be related to a replacement programme. It is necessary to give consideration in the design of flexible pipe to service life or replacement of components/ancillary equipment as part of an overall service-life policy.

8.2.4.1.2 Specification of pipe service life may also be related to an in-service inspection programme. The inspection method and inspection interval shall be documented and justified with respect to suitability for the specific application; see Clause 13.

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8.2.4.1.3 Evaluation of service life should address the following, as a minimum:

a) metallic-material corrosion and other failure modes (SSC, HIC, erosion, hydrogen embrittlement);

b) wear of metallic material;

c) fatigue of metallic material;

d) polymer/elastomer material degradation;

e) wear/abrasion of polymers/elastomers;

f) end-fitting design.

8.2.4.1.4 The wear and fatigue failure modes are generally only applicable to dynamic applications. The metallic materials can be selected so as not to corrode or alternatively the corrosion rate can be calculated based on the predicted annulus environment and accounted for in the pipe design. Corrosion fatigue tests can be necessary for the armour wires. Other potential failure modes, including SSC, HIC, erosion and hydrogen embrittlement, should be accounted for by material selection, with reference to the requirements of ISO 13628-2 and ISO 13628-10.

8.2.4.1.5 Wear and fatigue in the metallic layers is discussed in 8.2.4.2. Polymer/elastomer layer degradation and wear/abrasion of polymers/elastomers is accounted for by material selection for the specified application and by ageing analysis/testing; see 5.4.1.10 and 5.4.2.9 for recommendations on permissible levels of degradation and Clause 6 for guidelines on material selection and ageing tests. The end fitting should be designed to comply with the requirements of ISO 13628-2 and ISO 13628-10, with particular emphasis being placed on material selection and fatigue analysis.

8.2.4.1.6 Fatigue damage should be calculated at all critical locations along the riser arc length. Proper consideration should be given to the determination of riser damping. The critical locations are defined at the structural, boundary and geometrical discontinuities of the riser configuration in the bend-stiffener, touchdown, sag-bend and hog-bend areas. At each critical location, the following sources of fatigue damage should be evaluated:

a) wave-frequency-induced motions for all wave systems defined in the Metocean criteria;

b) slow drift (second-order) vessel motions;

c) vortex-induced vibration (VIV) frequencies of the riser under steady current conditions;

d) VIV motions of the riser-tower that supports the flexible riser in a hybrid riser system and/or the vessel hull if applicable;

e) oscillations during installation and handling;

f) slugging.

8.2.4.2 Fatigue and wear analysis

8.2.4.2.1 Flexible pipes are complicated structures, particularly from a fatigue and wear point of view. Several potential fatigue and wear mechanisms that can be critical exist for each type of pipe. Therefore, each application should be carefully evaluated, particularly for riser applications. Fatigue calculations for flexible risers involve substantial uncertainties because of simplifications in the long-term load data and mathematical models, and complexities in the wear and fatigue processes. An in-service condition and integrity monitoring programme should be implemented (see Clause 13) if appropriate.

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8.2.4.2.2 Potential failure mechanisms for the tensile-armour wires include the following:

a) wear between layers and strands of individual cables;

b) fatigue of armour wires in dry annulus conditions and in corrosive annulus environment;

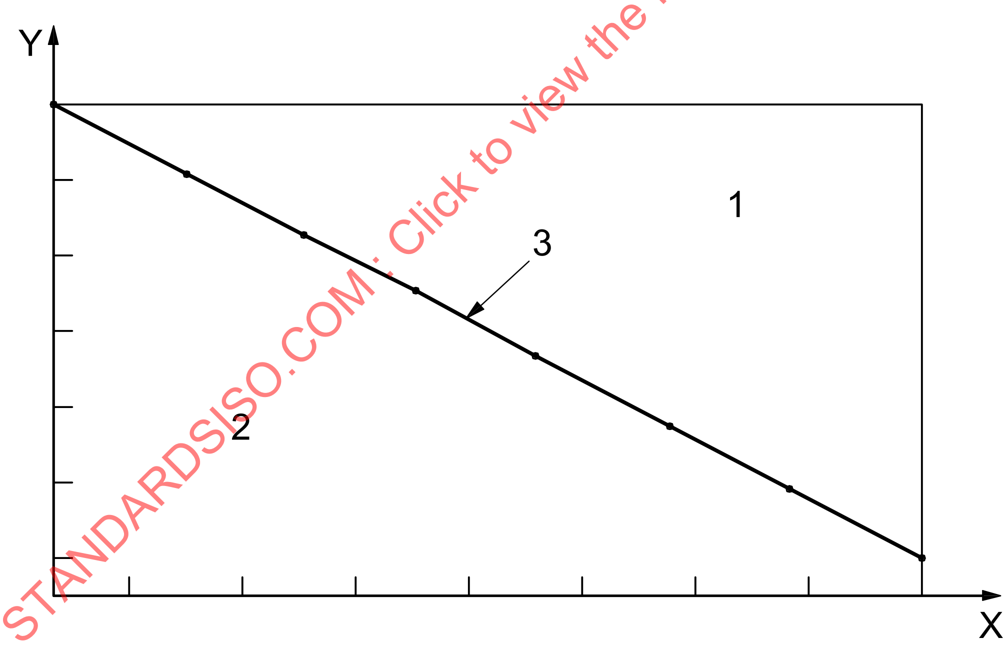
c) fretting fatigue of individual wires — unbonded pipe;

d) wear or fretting between strands within cables;

e) corrosion of armour wires.

8.2.4.2.3 In bending of an unbonded flexible pipe, the armour layers slide over each other, with a resulting potential for wear. The wear rate is a function of the contact pressure, wear coefficients and degree of slippage (bending related). Models have been developed using experimentally derived data to simulate this failure mode. However, this problem has generally been overcome in current designs by the use of polymer/elastomer anti-wear layers between the armour layers. The service-life analysis should confirm the functional performance of this layer for the specified design life, particularly for high-temperature applications. Similar sliding occurs between the individual strands in reinforcing cables.

8.2.4.2.4 The fatigue analysis should show that the extreme stresses in the tensile armours of unbonded and reinforcement layers of bonded pipe are below the material endurance limit (Goodman line in Figure 23), or fatigue damage calculations should be performed. The Haigh diagram should be based on relevant test data and should account for material properties, wire sizes and shapes, and service environment. Figure 23 is an example of a classical Haigh diagram, showing the fatigue and non-fatigue regions.



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Key

X mean stress, σ_m

Y alternating stress, σ_a

1 fatigue region

2 non-fatigue region

3 Goodman line

Figure 23 — Example of a Haigh diagram

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8.2.4.2.5 Fatigue-damage calculations may be based on a limited number of sea-state classes, provided selection of such classes is based on conservative criteria. See 5.5.5 for guidelines on the selection of load cases for fatigue analysis. Fatigue life may be calculated based on the S-N fatigue approach under the assumption of linear cumulative damage. The S-N data should be derived based on the requirements of ISO 13628-2 and ISO 13628-10. Calculations should be performed for all critical locations in the riser, such as at connection points and in the sag-bend region, based on combinations of mean and alternating stresses.

8.2.4.2.6 Conditions leading to fretting fatigue can cause a large reduction in fatigue strength of individual armour wires or cables, particularly in the low-stress/long-life region. The Goodman line under fretting conditions can be considerably lowered in the Haigh diagram for armour wires. The potential for fretting fatigue should, therefore, be the subject of close scrutiny.

8.2.4.2.7 Fretting-fatigue cracks are nucleated at the stick/slip interface, primarily by the oscillating tangential (friction) force transmitted in the stick region. Important parameters include surface reactions (oxidation and other environmental interactions), water ingress (a result of damage to the outer sheath) and lubrication. The crack-driving force of the tangential stresses has decayed when cracks reach a length of about 1 mm (0,04 in). The cracks can become arrested at that point in the absence of normal stresses in the wire. The cracks can continue to grow with oscillating normal stresses, and the net result is a significant reduction in fatigue life, particularly in the low-stress/long-life region. This emphasizes the requirement for dynamic axial stresses in prototype fatigue tests.

8.2.4.2.8 Interlocked pressure armour can also fail from fatigue, fretting fatigue or wear, and therefore this potential failure mode should also be addressed in the service-life analysis. A single fracture of the pressure-armour wire can be critical for the whole pipe. Theoretical models can be used to predict the service life of the interlocking profile. These models should be validated by experimental test results. The primary loading parameters to be considered for the pressure armour are as follows:

a) static stress and contact pressure from internal pressure and axial tension;

b) dynamic stresses, sliding, and friction forces as a result of bending;

c) combined effect of corrosion, wear and fatigue.

8.2.4.2.9 A critical parameter in pressure-armour fatigue calculations is the residual stress in the wires after preforming. The residual stress should be accurately assessed, for example, by local finite-element analysis. If fatigue in this layer is a problem, consideration can be given to taking account of the hydrotest effect in changing the residual stress state of the wires, thereby improving the fatigue performance of the layer. The test pressure should not cause stresses in the pipe above the criteria defined in ISO 13628-2 and ISO 13628-10. The manufacturer should document test results for the formed wires to verify the improvement in structural strength.

8.2.4.2.10 Fatigue analysis of end fittings and connectors, in addition to the armour layers, should be performed where relevant. The analysis should be based on standard methodologies and account for all relevant fatigue loads; the load cases from the fatigue analysis of the armour layers may be used.

8.2.5 Component analysis

8.2.5.1 All ancillary components of the flexible pipe system should be included explicitly in the global analysis at the detailed design stage, where practical. This includes buoyancy modules, subsea arch/buoy systems, tethers and bend stiffeners. In addition, local analysis of the individual components can be necessary.

8.2.5.2 It is necessary that the components in a pipe system be designed with regard to the same design parameters as the flexible pipe, including load cases (global loads and service conditions), and service life. Components should be designed in accordance with recognized codes and standards, with reference to the design guidelines in 7.5.

8.2.5.3 Component interference, which refers to the rubbing together or impact of system components, is also included in component analysis. The interaction between pipes in a bundle system is one potential

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interference problem. Possible impact between system components, such as between buoys or chains and risers, is another potential problem. See 7.4.2 for guidelines on interference issues.

8.2.5.4 Possible “weathervaning” of the subsea buoy/arch system is a critical aspect for certain flexible riser configurations. Generally, care shall be used to ensure that unsymmetrical hydrodynamic loads do not cause the buoy/arch system to weathervane and twist the riser beyond acceptable levels. The riser configuration and buoy/arch system should be designed to avoid this problem.

8.3 Loads

8.3.1 Hydrodynamic loads

8.3.1.1 Wave kinematics

8.3.1.1.1 In the derivation of hydrodynamic forces, it is first necessary to define the wave-induced water-particle velocities and accelerations: the wave kinematics. Common practice is to model the wave using linear Airy wave theory. In some cases, particularly for shallow water, a non-linear theory, such as Stoke’s fifth-order wave theory, can apply.

8.3.1.1.2 Linear wave theory calculates only the kinematics for infinitesimal wave heights. Stretching techniques are available to extend the theory to finite wave heights. The riser response is generally not sensitive to the stretching theory, except possibly for shallow water. Significant amplification of the wave kinematics can occur adjacent to large structures (such as the columns of a semi-sub) and, where relevant, this can need to be considered in the riser design. One method for modelling this amplification is to use increased hydrodynamic coefficients at the relevant location.

8.3.1.2 Morison’s equation

8.3.1.2.1 The general practice for modelling of hydrodynamic forces on flexible pipes is to use the Morison formulation, which is largely empirically based. The formula was originally derived for calculating the hydrodynamic forces on vertical, shallow-water, fixed piles with only wave loading. It has since been extended to apply to arbitrarily orientated, moving structures (such as risers) with both wave and current loading. The transverse Morison load per unit length, f_m, due to fluid-structure interaction is typically written as given in Equation (6):

$$f_m = \frac{1}{2} \rho_w \, D_d C_d \, V_{RN} \left| V_{RN} \right| + \rho_w \frac{\pi D_d^2}{4} C_m \, \dot{V}_{WN} - \rho_w \frac{\pi D_d^2}{4} \left(C_m - 1 \right) \dot{V}_{PN} \qquad (6)$$

where

V_{RN} is the normal relative fluid velocity, i.e. the relative fluid/structure velocity in the transverse direction;

$\dot{V}_{WN}$ is the normal water-particle acceleration;

$\dot{V}_{PN}$ is the normal structural acceleration;

D_d is the effective drag diameter;

C_d is the drag coefficient;

C_m is the inertia coefficient;

ρ_w is the seawater density.

8.3.1.2.2 This formulation represents the most commonly used extension of the original Morison’s equation. A number of comments are appropriate here.

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The inertia component of the original Morison's equation is replaced by two terms – one proportional to the normal water-particle acceleration, the other to the normal structure acceleration – because the inertia force on a moving cylinder in a wave field comprises a hydrodynamic "added mass" term representing the additional inertia or resistance to motion due to the fluid "entrained" with the moving member, in addition to the force on a stationary member in an accelerating fluid (the term in the original Morison formulation).

The fluid velocity in the drag term is replaced directly by the relative fluid structure velocity (including current). The validity of this is open to question but this approach is in widespread use.

8.3.1.3 Limitations to Morison's equation

The following comments are relevant to the formulation of Equation (6):

The acceleration of the fluid flow for the inertia-force term is evaluated at the centreline of the riser. Therefore, higher-order convective acceleration terms are neglected.

The inertia, added mass and drag coefficients are time invariant. Time-varying parameters may be used; generally, sufficient data are not available.

The hydrodynamic forces are determined by the acceleration and velocity components normal to the riser centreline. The axial component of the three-dimensional hydrodynamic force can be approximately accounted for by calculating a tangential drag force as a function of the tangential velocity squared.

The riser response is in line with the incident flow. The lift force is omitted. The fluctuating lift and drag forces as a result of vortex shedding are generally neglected. For short jumpers or "taut" configurations, however, vortex-shedding response should be taken into account.

The force on a member in close proximity to another is affected by the wake field due to interference and shielding effects. It is possible that the wake of the first member dynamically excites the member behind it. Conversely, it is possible that an adjacent large member shields a smaller member and leads to a reduction in hydrodynamic force. These effects, which in general influence only the drag force component, are difficult to incorporate into Morison's equation.

If several risers are close together, there is a tendency for a proportion of the mass of fluid enclosed collectively by them to act as part of the structure. This leads to increased "added mass" forces, which may be modelled empirically by increasing C_m and also modifies the inertia forces, which should not be changed.

8.3.1.4 Drag and inertia coefficients

8.3.1.4.1 The drag, C_d, and inertia, C_m, coefficients incorporated into Morison's formulation are empirical coefficients that have been derived from a large body of reported experiments. These experiments have shown good agreement between measured forces and forces calculated from Morison's equation.

8.3.1.4.2 In theory, the drag and inertia forces are a function of the Reynold's number, the Keulegan-Carpenter number, the structure geometry and the surface roughness, and strictly should be considered as varying along a member and with time. In practice, this renders hydrodynamic force computations impractical, and a constant coefficient is invariably used in riser analysis. This introduces a considerable source of uncertainty in the accuracy of results.

FPS 2000 [23], DNV-OS-C101 [20], and Rodenbusch and Kalstrom [62], provide recommendations on the selection of drag and inertia coefficients for flowlines and risers. In flexible-pipe analyses, C_m is usually taken to be 2,0, while C_d varies between 0,7 and 1,2. It is recommended that sensitivity studies be performed to investigate the effect on global analysis results of the selected coefficients. The selection of hydrodynamic coefficients for large system components (such as buoyancy tanks) can be critical and should be carefully evaluated. Consideration should also be given to the potential effect of VIV and marine growth on hydrodynamic coefficients.

For wave-type riser configurations, which use distributed buoyancy modules, the buoyancy section is subject to significant tangential as well as transverse hydrodynamic forces. Some recommendations on the selection of tangential hydrodynamic coefficients for buoyancy-module riser sections are given in Reference [40].

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8.3.2 Gravity and buoyancy loads

The analysis should include the gravity and buoyancy loads from all components of the system, including flexible pipe, buoys and clump masses. Consideration should also be given to loads resulting from marine growth and ice accumulations.

8.3.3 Internal fluid loading

The mass of the internal fluid should be included in all analyses. Variation in the density should be considered. Changes in the internal fluid density over the design life can significantly affect some riser configurations, particularly the wave configurations. It also can be necessary, for some applications, to consider the effect of slugs (liquid and gas) on the system. The loads induced by slugs, which should be accounted for in the analysis, are gravity, inertia, centrifugal forces and Coriolis loads.

8.3.4 Seabed and soil interaction loads

The effects of the seabed, including frictional loads, should be included where relevant. In particular, these are required for flowline-stability analyses and motion analysis for riser sections lying on the seabed (lazy configurations). FPS 2000 [23] lists representative soil stiffness and friction coefficients for flexible pipes in contact with the seabed. The soil stiffness and friction coefficients are reproduced in Table 18.

Table 18 — Typical soil stiffness and friction coefficients for flexible pipes

Seabed type	Direction	Stiffness kN/m^2 (lbf/in^2)	Friction coefficient
Clay	Axial	50 to 100 (7,25 to 14,50)	0,2
	Lateral	20 to 40 [a] (2,90 to 5,80)	0,2 to 0,4 [c]
	Vertical	100 to 5 000 [a] (14,50 to 725,0)	—
Sand	Axial	100 to 200 (14,50 to 29,0)	0,6
	Lateral	50 to 100 (7,25 to 14,50)	0,8
	Vertical	200 to 10 000 [b] (29,0 to 1 450,0)	—

a Value increases with increasing undrained soil shear strength.

b Value increases with increasing soil density.

c Value increases with decreasing soil shear strength.

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8.3.5 Temperature and pressure loads

Temperature- and pressure-induced elongation are generally only a concern in trenched flowlines where there is a possibility of upheaval buckling. In addition, short, unbonded jumper flowlines can experience significant compression loads from temperature and pressure effects, in which case the pipe can need to be reinforced with additional polymer layers to prevent bird-caging.

8.3.6 Vortex-induced loads

8.3.6.1 The sensitivity of flexible risers to vortex shedding has been the subject of a number of experimental investigations, which have shown that although VIV occurrs in the modelled risers, the vibration amplitudes are insufficient to cause fatigue damage. This can be attributed to the following:

a) relatively low vibration amplitudes, probably a result of the inherent structural damping;

b) complexity of flow incident to typical flexible riser systems and the difficulty in obtaining coherence of vortices in a heaving inclined riser;

c) hydrodynamic damping.

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8.3.6.2 Many of the factors contributing to VIV are difficult to model accurately in small-scale tests. In full scale, especially with deep-water risers, the effects of VIV can become more significant due to the following:

a) increased tension-reducing influence of structural damping;

b) increase in hydrodynamic drag coefficients from VIV;

c) strong currents present in some deep-water regions.

8.3.6.3 As a result of the above, the effects of VIV on both the structural strength of components and on riser global behaviour, particularly with respect to the potential for interference, should be reviewed on a case-by-case basis. Current practice is to conduct analysis with increased effective hydrodynamic cross-section to account for vortex-induced loading.

8.4 Global-response evaluation

8.4.1 Regular-wave and irregular-wave approaches

8.4.1.1 The objective of performing dynamic analyses is to predict the lifetime maximum or extreme response of the flexible pipe system. The two approaches commonly used for this purpose are regular-wave and irregular-wave approaches.

8.4.1.2 The regular-wave approach is based on a deterministic sea-state description of the wave environment using a single wave height and period to model the sea-state. These parameters are derived using wave statistics or simple physical considerations. The advantage of the approach is that the response calculation is straightforward, periodic input generally giving periodic output with no further requirement for statistical post-processing.

8.4.1.3 In the irregular-wave approach, consideration should be given to performing analyses for a number of wave periods to identify the critical system responses for both short- and long-wave periods. For example, the short-period can give the critical loads at the vessel connection, while the long period can give larger motions in subsea buoy systems.

8.4.1.4 The limitation of the regular-wave approach is that its use is uncertain in systems whose response is strongly dependent on frequency. It is often impossible to determine whether or not the result is conservative, particularly in the case of flexibles where conventional methods and software for the estimation of eigenfrequencies contain significant uncertainties. In such situations, the use of the irregular-wave approach can be necessary.

8.4.1.5 The irregular-sea approach is based on a stochastic description of the wave environment. The sea-state is modelled as a wave spectrum with energy distributed over a range of frequencies. The most common spectra used are the Pierson-Moskowitz (fully developed sea) and the JONSWAP (developing sea) spectra. The response in this case is also stochastic, and statistical post-processing is necessary to identify the design value of the response. A 3 h irregular-wave duration should normally be considered.

8.4.1.6 If a full 3 h simulation is not performed, the duration of the simulated wave record should not be less than 30 min, provided the generated sea-state is qualified with respect to theoretically known statistical properties of a Gaussian process. The extreme response for the irregular wave should be found by using a recognized, most-probable-maximum extrapolation technique.

8.4.2 Formulation of equations of motion

8.4.2.1 The formulation of the motion equations for solution of global response analyses involves consideration of the following main issues:

a) 2D versus 3D response;

b) 3D wave kinematics;

c) use of small-angle versus large-angle theory;

d) modelling of intermittent seabed contact and friction effects.

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8.4.2.2 A simplification for some riser analyses is the use of planar (two-dimensional) analysis in which vessel motion, waves, current and any initial displacement of the riser are all assumed to be in the same plane. For many cases, especially for initially straight (vertical) risers, this is an adequate assumption that can significantly reduce the resources required for a single analysis. Planar analysis is therefore useful for preliminary design work.

8.4.2.3 Spread seas and non-collinear wave and current loads cannot be solved directly with two-dimensional techniques. In some cases, reasonable approximations still permit the use of two-dimensional formulations. However, certain problems are inherently three-dimensional and, therefore, require a three-dimensional analysis. This is generally the case for flexible risers.

8.4.2.4 The “small angle” assumption has been used for formulating some riser-analysis methods, particularly for vertical, rigid risers. Use of the small-angle theory simplifies the solution through approximation of the curvature term, which limits its use to cases where the maximum angle change is less than 10°. A large-angle formulation shall be used for analyses where the maximum angular change is greater than 10°, which is typically the case for flexible risers subjected to extreme loading conditions. A number of large-angle formulations are described in References [56] and [36].

8.4.2.5 Interaction of the seabed with flexible pipes is an important consideration in global analysis. The vertical restraint of the seabed can be modelled as either a rigid surface or an elastic foundation. Use of either method should be evaluated for the particular application. In general, the rigid surface model is satisfactory, but is dependent on the coefficient of elasticity of the seabed soil. The analysis should be able to accurately simulate the non-linear behaviour if a riser is strongly impacting with the seabed.

8.4.2.6 The axial and lateral resistance to movement of the pipe at the soil interface can be modelled by a constant friction model or a hysteresis model. The friction force in a hysteresis model is gradually built up as the pipe slides on the seabed, up to the maximum value depending upon the normal force and the friction coefficient; if the movement is reversed, the build-up starts in the opposite direction. However, the hysteresis model is difficult to apply in practice because the history of deformations is required. For this reason, a constant friction may be used if a proper hysteresis model is not available. In this case, it is recommended that the accuracy of the results be evaluated using sensitivity studies.

8.4.2.7 The equations of motion are differential equations and, therefore, do not have a closed-form solution. The selection of appropriate solution methods is therefore critical for efficient analyses.

8.4.3 Solution of equations of motion

8.4.3.1 Spatial solution

8.4.3.1.1 Spatial solution of the equations of motion can be based on analytical techniques (generally not applicable to global analysis of flexible pipes) or approximate numerical methods. The numerical methods used can be either finite-element or finite-difference-based.

8.4.3.1.2 A numerical solution to the equilibrium equations is typically obtained by assembling equations for each element comprising the riser into a system of equations describing the force displacement relationships for all DOFs. By combining all equations for elements connected to a particular node, in a manner consistent with requirements for equilibrium at the node and compatibility between elements, equations relating forces at all global DOFs to displacement at each DOF at the node are obtained. Assembling all such equations for N global DOFs leads to a system of N coupled algebraic equations. These equations can be expressed in matrix form, as given in Equation (7):

$$[\boldsymbol{M}_{\mathrm{m}}]\{\ddot{x}\}+[\boldsymbol{M}_{\mathrm{C}}]\{\dot{x}\}+[\boldsymbol{M}_{\mathrm{K}}]\{x\}=\{\boldsymbol{R}\} \quad (7)$$

where

$[\boldsymbol{M}_{\mathrm{m}}]$ is the mass matrix;

$[\boldsymbol{M}_{\mathrm{C}}]$ is the damping matrix;

$[\boldsymbol{M}_{\mathrm{K}}]$ is the stiffness matrix;

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$\{R\}$ is the load vector;

$\{\ddot{x}\}$ is the acceleration vector;

$\{\dot{x}\}$ is the velocity vector;

$\{x\}$ is the displacement vector.

8.4.3.2 Temporal solution

8.4.3.2.1 Frequency domain

Frequency-domain analysis can be used if there are no non-linearities that significantly affect the system response. Frequency domain may be used for fatigue analysis, as it allows for reasonable statistical estimates of forces in the pipe. The linear fatigue analyses should generally be combined with non-linear static analyses for flexible-riser systems.

The principal advantage of frequency-domain analysis is a reduction in computational effort for linear systems, coupled with very simple, unambiguous output. Analysis of linear systems is well understood, and the application of frequency-domain results to design criteria for truly linear systems is straightforward. The limitations of frequency-domain analysis are the difficulties and added complexities associated with modelling non-linear behaviour. This generally invalidates the technique for use in large-displacement, flexible-riser analyses.

There are several applications of the method to riser analysis in the literature, though most apply to rigid-riser analysis. The application of the method to flexible-riser analysis is described in Reference [46]. Important considerations in frequency-domain analysis include proper linearization of the wave and current drag forces, and careful selection of analysis frequencies. Frequencies used in the analysis should result in adequate definition of the wave-energy spectrum, vessel-response characteristics and natural frequencies of the riser.

8.4.3.2.2 Time domain

Time-domain analysis is generally required for flexible-riser design, where accurate representation of the non-linear behaviour is important. Non-linear effects encountered in flexible-riser analyses, including large deformations, non-linear loads and seabed interaction, can be directly modelled in the time domain. Time domain can also be used to assess the relative accuracy of equivalent frequency-domain analyses and calibrate them for use in design.

Analysis in the time domain requires a definition of the environment and the applied loading (such as vessel motions) as a function of time, typically by simulating wave-time histories. Time-domain analysis essentially requires a solution of the equilibrium position at discrete points in time, by considering inertia, damping and applied loads.

The equilibrium equation can be solved by implicit or explicit integration methods. Explicit methods solve for response at $t + \Delta t$ based on equilibrium conditions at time t. Implicit methods solve for response at $t + \Delta t$ based on equilibrium at time $t + \Delta t$. This has implications on the numerical effort required to perform the integration. Explicit methods typically require fewer computations per time step but often require shorter time steps to achieve an accurate solution. Implicit methods often require substantial numerical effort at each time step (like decomposition of the coefficient matrix) but can often utilize larger time steps and are more typically used for flexible-riser analysis.

All methods have some degree of integration error that is associated with frequency and amplitude of the integrated response. In certain situations, slight errors in frequency alone can accumulate and lead to numerical “beating” of the response. It is important to recognize and understand these errors when performing time-domain analysis, particularly for the purpose of simulating long time histories and developing statistics for extremes.

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8.4.3.2.3 Modal analysis

A modal analysis may be performed to determine the mode shapes and natural frequencies of the riser system. It may be used to determine

a) the natural frequencies of the riser system for VIV analysis; the number of modes should be sufficient to determine the riser response at the highest VIV frequency range;

b) the basis for selecting the wave periods for strength/interference/fatigue/installation analyses when considered with the motion/velocity/acceleration RAOs at the riser hang-off.

An important consideration in modal analyses is the modelling of nonlinearities, such as the effect of the seabed in lazy-riser configurations.

8.4.4 Modelling considerations

8.4.4.1 Model discretization

8.4.4.1.1 Finite-element or finite-difference techniques are typically employed to reduce the differential equilibrium equations to a set of coupled algebraic equations that can be solved numerically. Discretization of the riser shall be done carefully to avoid numerical errors resulting from too coarse a mesh, while producing a model that can be analysed with a reasonable amount of computational effort.

8.4.4.1.2 The level of discretization that is ultimately acceptable depends on the numerical representation of tension variation, the spatial variation in physical properties of the riser, the magnitude of applied load, the frequency content of the applied load and the accuracy of the desired results. In general, coarser meshes are acceptable for determining approximate displacement solutions to problems dominated by vessel motions, while finer meshes are essential for accurately determining stresses in the splash zone or at discontinuities, such as support points.

8.4.4.2 Frequency content selection

8.4.4.2.1 The frequency content of the input sea-state spectrum is accurately represented for irregular sea analyses. The following comments apply.

a) The total spread of frequencies should cover all frequencies with significant energy.

b) The discretization of the spectrum (i.e. number of frequencies used) should accurately represent the sea-state. The discretization can be based on an equal-area approach or an equal-frequency increment approach, but the equal-area approach is recommended.

8.4.4.2.2 For time-domain analyses, the sea-state spectrum is synthesized into a wave time history and may be achieved by a number of methods, including Monte Carlo and digital-filtering approaches. The realized spectrum (from the time history) should be compared to the input spectrum for accuracy of the synthesis method.

8.4.4.3 Time-step selection

8.4.4.3.1 The time step used for a time-domain analysis depends on the solution methodology and software program. All methods require that the time step be small enough to accurately reflect important frequencies in the load or response. This is analogous to proper spatial discretization of the model and careful selection of frequencies in the frequency-domain method. Large time steps can result in a quicker analysis that is accurate for the frequencies represented but may miss important high-frequency contributions.

8.4.4.3.2 The time-stepping scheme used can be based on fixed or variable steps. Fixed steps are recommended. Variable time steps, however, can result in significantly less computational effort. Results from variable time-step analyses should be checked to ensure that changes in the time step do not induce numerically spurious values.

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8.4.5 Effective tension

8.4.5.1 Effective tension is an important parameter in riser analysis, though it is a subject of much debate. The equation for effective tension, γ_e, is as given in Equation (8):

$$\gamma_e = \gamma_a + (P_o \cdot A_o) - (P_i \cdot A_i) \quad (8)$$

where

γ_a is the axial (true wall) force;

P_i is the internal pressure;

P_o is the external pressure;

A_i is the internal cross-sectional area of pipe;

A_o is the external cross-sectional area of pipe.

8.4.5.2 Effective tension has a real effect on the displacement of a tensioned beam, and it is often convenient to treat γ_e as a physical quantity. Effective tension, however, is not a physical, tensile force, nor is it an internal force of any kind. Effective tension is a grouping of applied load terms within the equation of motion. Dynamic-analysis results normally report the effective tension, not the true wall tension.

8.4.5.3 It is important to understand this distinction when formulating the analysis model as well as to avoid misinterpreting results of typical riser analyses. For example, the lateral force at any cross-section of a riser is equal to shear plus the effective tension times the slope. This calculation is valid only because it is equivalent to integrating pressure around the tube circumference and adding the shear and the lateral component of tension. Detailed discussions on effective tension are provided in References [48] and [61].

8.4.5.4 Low or even negative effective tension over a portion of the riser does not imply that the riser is unstable, nor does it cause the riser to instantaneously experience Euler buckling. The direct consequence of low or negative effective tension is low lateral stiffness, the result of which is adequately estimated by the standard global riser analysis if changes in effective tension are accounted for. Any effective compression that occurs should be shown to be tolerable for the pipe; see the design criteria in Clause 5.

9 Prototype testing

9.1 General

9.1.1 Clause 9 gives guidelines on the requirements for prototype tests and presents procedures for performing these tests. See ISO 13628-2 and ISO 13628-10 for factory-acceptance and material-test requirements.

Prototype test documentation is intended to be reviewed by the independent verification agent as part of the pipe design methodology verification (see ISO 13628-2 and ISO 13628-10).

9.1.2 The requirements for prototype testing are subject to agreement between the manufacturer and the purchaser, and can be based on the recommendations given in Clause 9. As an alternative to prototype testing, the manufacturer may provide objective evidence that the product satisfies the design requirements. Objective evidence is defined as documented field experience, test data, technical publications, finite-element analysis or calculations that verify the performance requirements, and may be used if the envelope of applications for an established design is proposed to be marginally extended.

9.1.3 The number and range of prototype tests that can be performed on flexible pipe is extensive. Prototype tests are generally destructive and are therefore expensive to undertake. Cost and/or time implications make it impossible to perform a full range of prototype tests for each pipe design.

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9.1.4 For high-temperature applications, the design of the end-fitting sealing mechanism for unbonded pipe is critical. The test procedures currently being used are given in Annex A and Annex C for both static and dynamic applications. These protocols may be superseded based on results of future tests. Close attention should be paid to surface preparation and thickness and to oil storage and oxygen content.

9.1.5 A selected group of tests for qualification of a prototype design normally includes material and FAT tests, as specified in ISO 13628-2 and ISO 13628-10.

9.2 Design programmes

9.2.1 As a minimum, class I prototype testing is recommended for new or unproven flexible-pipe designs. The objectives of prototype testing should be as follows:

a) prove or validate new or unproven pipe designs;

b) validate the manufacturer's design methodology for a new pipe design.

9.2.2 The second objective increases the level of confidence in the design methodology and thereby reduces the requirements for prototype testing in the future. The requirements for the manufacturer's design methodology are specified in ISO 13628-2. The design methodology should provide a conservative estimate of the failure load for the particular prototype test. A confidence limit should be established by which the design methodology can be shown to be conservative.

9.2.3 Fundamental to reducing prototype test requirements is the necessity to increase confidence levels in the design methodology. All tests performed should be used to validate the design methodology and so minimize future requirements for prototype testing. It is fully permissible to use validated analytical approaches to perform extrapolations from relevant tests, taking parameter variations into account, subject to the recommendations of Clause 9.

9.3 Classification of prototype tests

Prototype tests are classified into three classes as follows:

a) class I: Standard prototype tests, as most commonly used;

b) class II: Special prototype tests, used regularly to verify specific aspects of performance, such as installation or operating conditions;

c) class III: Tests used only for characterization of the pipe properties.

Table 19 lists tests that come under these classifications. The loading used in the dynamic fatigue test listed as a class II test may be single or combined loading. The selection depends on the application; a combined bending and axial test is recommended.

Procedures for class I and II tests are given in 9.6 and 9.7, respectively. Procedures for class III tests should be in accordance with the specifications of the purchaser or manufacturer.

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Table 19 — Classification of prototype tests

Class	Type	Description	Test condition/comment
I	Standard prototype tests	a) Burst pressure test	Typically in straight line
		b) Axial tension test	At ambient pressure
		c) Collapse test	With outer sheath perforated or omitted
II	Special prototype tests	a) Dynamic fatigue test	Bending, tension, torsional, cyclic pressure, rotational bending or combined bending and tension fatigue tests
		b) Crush strength test	Installation test
		c) Combined bending and tensile test	Installation test
		d) Sour-service test	To examine degradation of steel wires
		e) Fire test	
		f) Erosion test	To examine degradation of carcass
		g) TFL test	Also includes pigging test
		h) Vacuum test	Bond strength in test for bonded pipes
		i) Kerosene test	Detect permeation or leakage of hydrocarbon through liner of bonded pipe
		j) Adhesion test	Verify bond strength of bonded pipe
		k) Full-scale blistering test	Determine suitability of bonded pipe to gas service
III	Characterization and other prototype tests	a) Bending-stiffness test	To MBR (non-destructive)
		b) Torsional-stiffness test	To allowable torque (non-destructive)
		c) Abrasion test	Test for external abrasion
		d) Rapid-decompression test	
		e) Axial-compression test	Upheaval buckling and compression capacity
		f) Thermal-characteristics test	Dry and flooded conditions
		g) Temperature test	High- and low-temperature cycling
		h) Arctic test	Low-temperature test
		i) Weathering test	UV resistance
		j) Structural-damping test	Characterization test

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9.4 Test requirements

9.4.1 General

The requirements for prototype tests should consider whether the pipe is a new design or new application, and what the critical failure modes and consequences are. In addition, scaling limitations and applicable tests should be addressed. These are discussed in 9.4.2 to 9.4.5.

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9.4.2 New pipe design or application

9.4.2.1 A new pipe design is defined by a substantive change or modification to one of the following:

a) pipe manufacturing process (structural layers, internal pressure sheath or end fitting);

b) pipe structure;

c) pipe application.

9.4.2.2 Tables 20 and 21, respectively, identify critical issues related to pipe structure and application, as well as recommendations on prototype test requirements. The requirements for prototype testing of a new design are very dependent on the application and this should be considered. For example, a large difference exists between a low-pressure static flowline and a high-pressure riser application.

Table 20 — Recommendations for prototype tests — Modifications to pipe structure design

No.	Design modification	Recommendation on requirement for prototype tests
1	Internal/external diameter	Probably not required. However, it can be necessary for large variations from previously qualified designs to be verified by prototype testing; see 9.4.4.
2	Number and order of layers	Required for substantive change to structural layers only.
3	Metallic-layer construction	Required if cross-sectional shape or material type is substantially changed. Material qualification required.
4	Polymer/elastomer layer	Material qualification tests only required.
5	Spiralling angle	Only required for angle θ changes outside the following, where θ is measured relative to longitudinal axis: — carcass or pressure-armour (unbonded) layers: $\theta < 80°$; — tensile-armour (unbonded) and reinforcement (bonded) layers: $20° < \theta < 60°$.
6	End fitting	Required for substantive change to the end-fitting design, in particular: — change in armour/reinforcing-layer anchoring system; — change in epoxy material; — change in internal/external fluid-integrity systems (sheath/liner anchoring).
7	Lubricant (unbonded)	Not required. Material qualification is required.
8	Materials	Generally sufficient for materials testing to be performed.
NOTE	The above recommendations can vary for different applications, such as flowlines and risers.	

Table 21 — Recommendations for prototype testing — Changes in pipe application

No.	Change in pipe application	Requirement for prototype testing
1	Transported fluid	Generally not required. Compatibility to transported fluid can generally be determined by material testing. However, for unusual transported-fluid conditions, prototype testing can be required. In particular, the following require consideration for prototype tests: — sour-service and corrosive environments; — high-temperature and low-temperature applications; — high-pressure applications.
2	Service life	Not required for static applications, as material testing is generally more relevant. Not required for dynamic applications if previous testing can be extrapolated to the required service life.
3	External environment	Dependent on the environmental conditions. Not required if interpolation from previous tests can be performed.

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9.4.3 Failure modes

The requirements for prototype tests should consider the criticality and consequences of pipe failure. In particular, potential defects, the consequences of these defects and the causes should be identified. The major potential defects in unbonded flexible pipes are identified in 13.3. Table 22 identifies critical prototype tests that can be used to verify the pipe design for some of these potential defects and failure modes. This table should be referred to when determining prototype test requirements.

Table 22 — Potential flexible-pipe failure modes and associated critical prototype tests

Pipe component	Failure mode	Prototype test
Carcass layer	1) Collapse failure modes:	
	— due to external and/or pressures;	Collapse test
	— due to armour layer pressure;	Tensile test
	— due to installation loads.	Combined bending and tensile test, crush strength test
	2) Wear.	Erosion test
	3) Material failure.	Material tests
Internal pressure sheath or bonded pipe liner	1) Rupture due to pressure.	Burst test
	2) Creep extrusion.	Burst test and temperature test
	3) Material failure.	Material tests
	4) Wear.	Erosion test
	5) Fatigue.	Dynamic fatigue test
Structural layers	1) Structural failure due to loading:	
	— tension;	Tensile test
	— compression;	Axial compression test
	— pressure.	Burst test
	2) Wear and fatigue.	Dynamic fatigue test
	3) Bird-caging.	Axial compression test
	4) Adhesion/delamination for elastomers.	Adhesion test
	5) Material failure.	Material tests
Insulation layers	1) Loss of insulation due to flooding.	Thermal characteristics test
	2) Installation crushing loads.	Crush strength test
End fitting	1) Pressure sheath/liner pull-out.	Temperature test
	2) Reinforcing/reinforcing-layer anchoring.	Dynamic test, tension test
	3) Epoxy failure.	Dynamic test, temperature test
NOTE Detailed lists of potential pipe defects are given in 13.3.		

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9.4.4 Scaling limitations

9.4.4.1 Scaling of previous test results may be used to verify the members of a product family in accordance with the guidelines of 9.4.4. Tables 1 and 2 list the flexible-pipe product families. The pipe design principles and functional operation should be similar for scaling purposes. In addition, the design stress levels in relation to material mechanical properties should be based on the same criteria, i.e. equivalency in utilization or accumulated fatigue damage. The following scaling limitations are recommended.

a) The test pipe may be used to qualify pipes of the same family having equal or lower pressure rating.

b) Testing of one pipe of a product family should verify products with an internal diameter of 5,08 cm (2 in) larger or smaller than the size tested.

c) The temperature range and number of cycles verified by the test product should include all temperatures that fall entirely within that range for the particular test fluid component.

d) The test fluid should verify all products with the same materials as the tested pipe.

9.4.4.2 The scaling comparison may also be made based on pressure times internal diameter ($P \times D_i$), with the test pipe qualifying pipes with a lower $P \times D_i$ value, subject to the internal diameter limitations.

9.4.5 Applicable prototype tests

9.4.5.1 In 9.4.5, the prototype tests are described which are applicable to the design modifications and application changes listed in 9.4.2. Tables 23 and 24 list the requirements for class I and class II prototype tests, respectively, as defined by Table 19. These requirements are subject to the recommendations of 9.4.2 to 9.4.4, inclusive.

9.4.5.2 Changes to transported fluid, service life or external environment do not require class 1 prototype tests, but can require materials testing as in ISO 13628-2 and ISO 13628-10.

Table 23 — Recommendations for class I prototype tests

Design modification or change in application	Recommended class I prototype tests		
	Burst	**Tension**	**Collapse**
Internal/external diameter	X	X	X
Number or order of layers	X	X	—
Internal carcass	—	—	X
Internal pressure	X	—	X
Pressure-armour layer	X	—	X
Tensile-armour layer	—	X	—
Spiralling angle	X	X	—
End-fitting design	X	X	—

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Table 24 — Recommendations for class II prototype tests

Design modification or change in application	Recommended class II prototype tests
New design or more severe dynamic loading conditions	Dynamic fatigue test
New installation system or water depth	Crush strength test
Installation of new design or deeper water using horizontal laying spread	Combined bending and tension test
Sour-service conditions	Sour-service test
Critical fire-protection requirements and untested design	Fire test or calculated fire-survival time conservatively calculated by a method validated by previous fire-test results
Severe sand production and severe consequences of failure	Erosion test

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9.5 Test protocol

9.5.1 Test sample

9.5.1.1 Prototype testing should be conducted on full-size products that represent the specified dimensions for the relevant components of the end product being verified. This does not apply to the length of the flexible pipe, excluding end fittings. The minimum length excluding end fittings should be the greater of 3 m (9,84 ft) or 10 × D_i, unless specified in the test procedures in 9.6 and 9.7. The test samples should be subjected to FAT testing.

9.5.1.2 The actual dimensions of pipe subjected to prototype testing should be within the allowable tolerance range for dimensions specified for normal production pipe. These actual dimensions should represent the worst-case conditions, where practical. The sample should include any weak points that can occur in the final product, including welds, repaired or damaged sections and process variations.

9.5.1.3 Test samples should represent the actual product that is supplied, considering both the design and manufacturing procedures. Consideration should be given to potential differences between sample and production pipe if samples are made up using semi-manual procedures (for example, not from a production run). It can be necessary to consider reproducing some of the critical test results on production samples to verify the manufacturing equipment and procedures.

9.5.1.4 All tests should be carried out with end fittings mounted that are identical to those used on the product to be qualified, except where recommended by this part of ISO 13628.

9.5.2 Test equipment

Test equipment should conform to internationally recognized standards. All test equipment and instrumentation should be calibrated on a regular basis, at least once a year. Current certification and calibration certificates for all test equipment should be included in the test report.

9.5.3 Test procedures

9.5.3.1 If tests require variables (such as temperature or pressure) to be constant, the particular variable should be stabilized prior to commencement of the test. Stabilization is defined as follows for pressure and temperature parameters:

a) pressure variation for 1 h is within ± 1 % of the test pressure;

b) temperature variation for 1 h is within ± 2,5 °C (36,5 °F) of the test temperature.

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9.5.3.2 The necessity for pressure cycling the sample prior to test start-up should be evaluated by the manufacturer when structure accommodation (bedding-in) can affect the results. For example, in a burst test where deformation measurements are required, a minimum of three cycles (from zero to test pressure) performed as follows is generally sufficient:

a) first cycle for structure accommodations (bedding-in);

b) second cycle for accurate measurements;

c) third cycle to verify measurements from second cycle.

9.5.3.3 The load-application requirements are different for each test type, and are discussed in the individual test descriptions. The load-application rate should be representative of the load-application rate applied under factory and field acceptance testing, installation and service conditions. The maximum loading rate should not exceed 5 % of the expected maximum load per minute.

9.5.4 Post-test examination

Pipe dissection should be performed whenever a sample fails. Failure evaluations and abnormalities should be reported. All relevant items should be photographed. The examination document should include a written statement describing any defects that were found in the test sample and whether or not these defects resulted in design criteria being violated.

9.5.5 Documentation

9.5.5.1 Before testing, the manufacturer should issue to the purchaser a detailed test procedure that should include the following items as a minimum:

a) type of tests to be performed;

b) schedule and duration of tests;

c) test descriptions (including sketches and equipment set-up);

d) type and size of samples to be tested;

e) equipment descriptions (including accuracy, calibration, and sensitivity);

f) data forms to be filled during the tests;

g) acceptance criteria;

h) predicted results and failure modes, where applicable;

i) references to applicable quality control procedures, codes, standards, etc.;

j) documentation of as-built dimensions and material strength.

9.5.5.2 After testing, the manufacturer should submit a detailed test report to the purchaser for approval. This test report should contain the following as a minimum:

a) gathered data and final results;

b) report on post-test examination;

c) comparisons between predicted and observed values;

d) conclusions.

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9.5.6 Availability of results

Tests should, as much as possible, be carried out in a consistent manner, such that the results are applicable to future designs. All test results should be available for verification of future designs. Tests should be conducted, where practical, such that the results and records can be accepted in lieu of repeated testing for other applications.

9.5.7 Intermediate results

Results of all tests, including results at intermediate stages, should be compared with analytical results from the design programme of the manufacturer. Discrepancies should be investigated and reported to the purchaser. If possible, intermediate results should also be used to define pipe properties, such as axial and bending stiffness.

9.5.8 Validity of test results

Test results are valid unless a substantial change to the process (test procedure, design, or manufacturing procedure) invalidates the results.

9.5.9 Accelerated tests

9.5.9.1 Accelerated tests may be performed by increasing the following, subject to the approval of the purchaser:

a) cyclic frequency;

b) internal pressure;

c) magnitude of movement;

d) temperature.

9.5.9.2 The manufacturer should provide documented evidence for accelerated tests that the variation in test parameter does not significantly affect the results or change the mode of failure, and that the test period is satisfactory.

9.5.10 Multiple tests

Single samples can be subjected to multiple tests, with non-destructive tests (such as bending, torsional stiffness tests, and FAT tests) performed prior to a destructive test. It is necessary to evaluate the test sequence carefully to ensure that earlier tests do not affect the results of subsequent tests.

9.5.11 Repeatability of results

The design parameters and manufacturing tolerance parameters that affect the performance should define the bounds for the qualification achieved and should be accounted for in the definition of the acceptable application envelope when a single sample is tested. Application of the test results in design and analysis should use the critical parameters in a conservative manner.

9.6 Procedures — Standard prototype tests

9.6.1 General

In 9.6.2 to 9.6.4, procedures for the standard class I prototype tests, namely burst, tensile and collapse tests are contained.

9.6.2 Burst test

9.6.2.1 Description

Figure 24 illustrates the test set-up for the burst test. The burst test should be performed with the specimen in a straight configuration. The minimum length of the test sample, excluding end fittings, should be either two times the pitch length of the outer armour wires/reinforcing cables for a straight configuration or three times the pitch length of the outer wires for a bent pipe. The test fluid is generally water.

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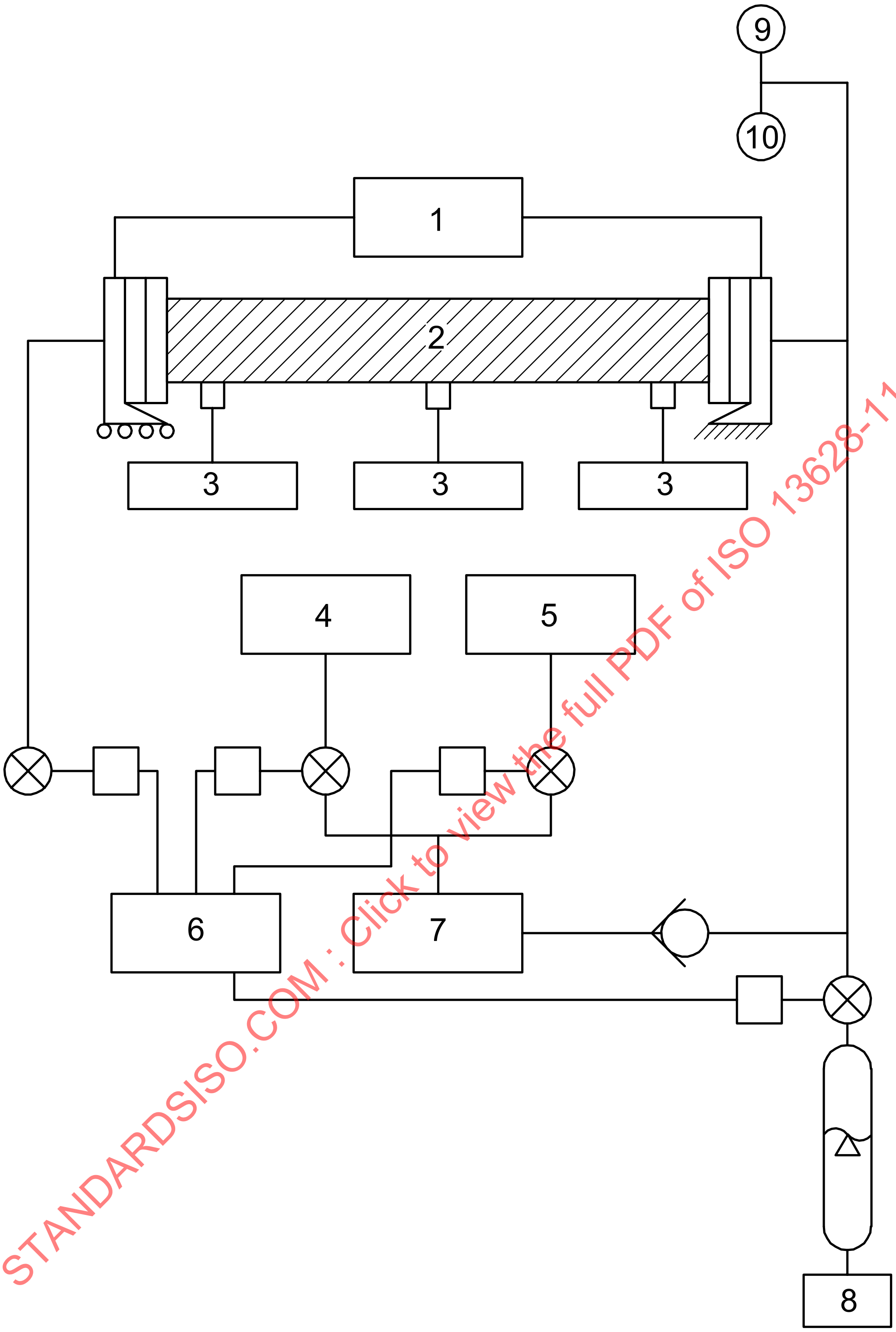

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Key

1 linear measurement device
2 specimen
3 thermocouple (optional)
4 60 °C (140 °F) hot water (optional)
5 ambient-temperature water
6 counter and controller (optional)
7 circulation pump (optional)
8 pump
9 pressure gauge
10 temperature gauge

NOTE This pressure and optional temperature test is similar to ASTM D2143 [15].

Figure 24 — Schematic of set-up for the burst test

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9.6.2.2 Procedure

The requirement for pressure cycling (see 9.5.3) should be considered prior to commencement of the burst test. The first 50 % of the expected load shall be applied at a maximum rate of 1 %/s with no holding period prior to applying the balance of the load at a maximum rate of 5 %/m without holds. Failure is defined by a sudden loss in pressure. The burst pressure, mode and location of failure should be noted. Internal pressure, pipe twist and pipe elongation should be continuously monitored during the test.

9.6.2.3 Acceptance criteria

The measured burst pressure should be greater than the design requirements specified in ISO 13628-2 and ISO 13628-10. Failure of the end fitting itself or failure due to armour wire/reinforcing layer pull-out from the end fitting should not occur.

9.6.2.4 Analytical requirements

The effect of tension and bending on burst pressure should be analyzed.

9.6.2.5 Alternatives

The burst test may be performed with the sample bent to its design MBR.

9.6.3 Axial-tension test

9.6.3.1 Description

Figure 25 illustrates the test set-up for the axial-tension test. The axial-tension test should be performed with the specimen empty and free to twist. The minimum length of the test sample, excluding end fittings, should be two times the pitch length of the outer armouring wires/reinforcing cables. One or more pigs can be used to check the reduction in the internal diameter during the test.

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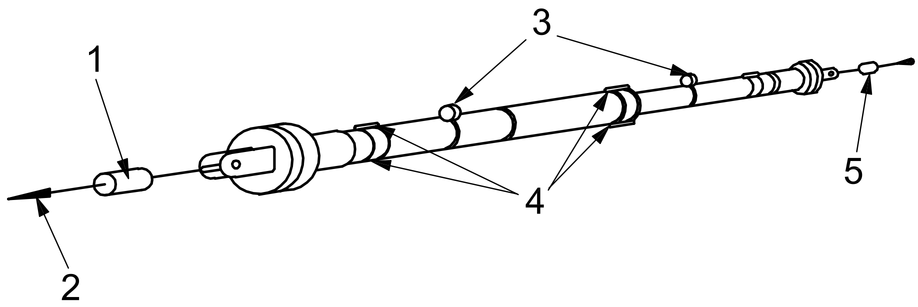
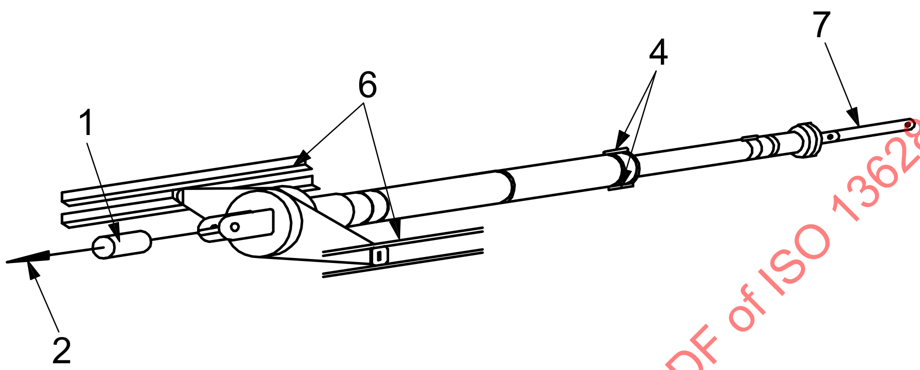


a) **Tensile test — Free in torsion**



b) **Tensile test — Fixed in torsion**

Key

1 tensile gauge
2 pulling jack
3 angular sensors
4 elongation sensors
5 swivel
6 translating guides
7 coupling bar

NOTE 1 The test can be conducted at ambient temperature, design pressure, or both.

NOTE 2 Strain gauges are optional. If used, they indicate only surface conditions or the conditions at the layer where they are applied. They are likely not to be representative of the general stress of the pipe.

SAFETY PRECAUTIONS — Since catastrophic failure is probable, protect personnel conducting the test.

Figure 25 — Schematic of set-up for the axial-tension test

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9.6.3.2 Procedure

One end of the sample is fixed and an axial load applied to the other end at the rate specified in 9.5.3. Load application should sufficiently show that dynamic amplification is not introduced. As a guideline, load application should be completed in approximately 5 min. The failure tension, mode and location of failure should be noted. In addition, applied load, elongation and twist of the sample should be continuously recorded. Failure occurs if the tensile load drops or sudden elongation occurs.

9.6.3.3 Acceptance criteria

The measured failure tension should be greater than the design requirements specified in ISO 13628-2 and ISO 13628-10. Failure of the end fitting itself or failure due to armour wire/reinforcing layer pull-out from the end fitting should not occur.

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9.6.3.4 Analytical requirements

The effect of internal pressure and fixing the ends from rotating on the failure tension should be analyzed.

9.6.3.5 Alternatives

The axial-tension test may be performed with the pipe full of water at design or a lower internal pressure. The internal pressure in this case should be continuously monitored during the test with a sudden pressure drop (indicating an internal sealing failure) or reduction in tensile load taken as failure of the sample. The test may also be performed with the ends of the pipe fixed in rotation.

9.6.4 Collapse test

9.6.4.1 Description

9.6.4.1.1 Figure 26 illustrates the test set-up for the collapse test. The test set-up should be such that the end fittings (or sealed simple end caps) are not exposed to external pressure or, if exposed, a rigid bar should be installed between the two ends to eliminate end-cap loads. The rigid bar may be omitted if the manufacturer wishes to demonstrate that the pipe design is suitable for compression loads. The test should be performed with the specimen in a straight configuration. The minimum length of the sample, excluding end fittings, should be $5 \times D_i$.

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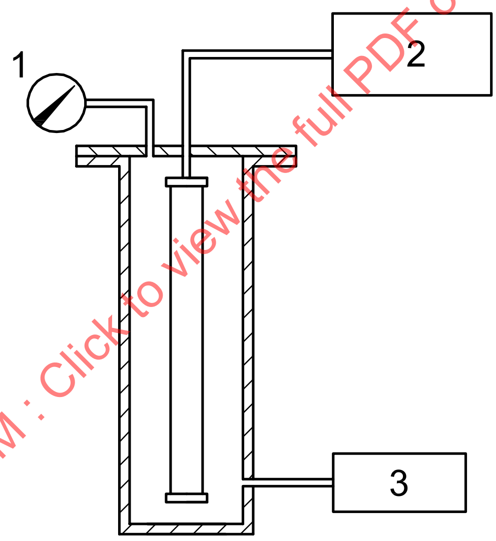
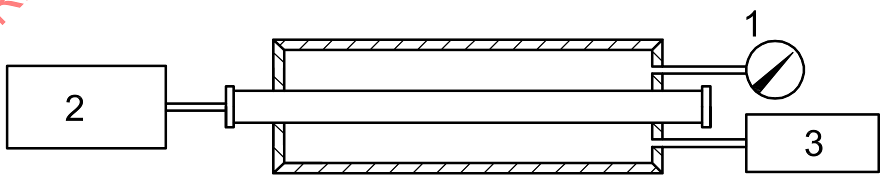


a) Set-up 1 [a]



b) Set-up 2

Key

1 pressure gauge

2 volumetric measurement device

3 pressure source [b]

[a] The pipe specimen in set-up 1 is axially stiffened.

[b] The pressure vessel and pressure source shall be capable of operating up to pipe collapse pressure.

Figure 26 — Schematic of set-up for the collapse test

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9.6.4.1.2 The outer sheath should be removed or perforated such that water ingress into the annulus of the pipe occurs prior to the test. The sample should be at ambient internal pressure and may be empty or filled (partially or completely) with water. In general, water is used as the test fluid. It is not necessary to include the tensile-armour layers or the outer sheath in the sample. If included in the sample, intermediate sheaths should also be removed or perforated, unless the pipe design is based on an impervious intermediate sheath.

9.6.4.2 Procedure

The external pressure may be applied at a maximum rate of 10,34 MPa/min (103,42 bar/min or 1 500 psi/min) until failure occurs in the pipe. Failure is defined as a sudden variation of the volumetric measurement or, depending on the test equipment, a sudden pressure loss. The collapse pressure, mode and location of failure should be noted.

9.6.4.3 Acceptance criteria

The measured collapse pressure should be greater than the design requirements specified in ISO 13628-2 and ISO 13628-10.

9.6.4.4 Analytical requirements

The effect of bending and axial tension, including that of the outer sheath, on the collapse pressure should be analyzed.

9.6.4.5 Alternatives

The sample may include end fittings. The test may be performed with a leak-proof outer sheath or with support to prevent axial compression of the pipe. The test may also be performed with an axial tension load applied.

9.7 Procedures — Special prototype tests

9.7.1 General

In 9.7.2 to 9.7.12, the recommended procedures for class II prototype tests are listed, namely dynamic fatigue, crush strength, combined bending and tensile, sour-service, fire, erosion, TFL, vacuum, kerosene, adhesion and full-scale blistering tests.

9.7.2 Dynamic fatigue test

9.7.2.1 Description

9.7.2.1.1 Figure 27 illustrates the overall definition of the dynamic test programme, including riser and bend-limiter design. Figure 28 illustrates a typical test set-up. The sample is hung vertically or tensioned horizontally from a rocker arm which can apply cyclic rotations. A tension load is applied to the opposite end. There are two types of full-scale dynamic tests, a service simulation and service-life model validation. The objective of a service simulation test is to determine the structural integrity of the top section of the flexible pipe, including end fitting and bend limiter, under simulated operational conditions. The objective of a service-life model validation test is to apply loading which results in cumulative damage equal to 1,0 based on the service-life analysis for a structural layer, normally either the pressure armour or the tensile armour.

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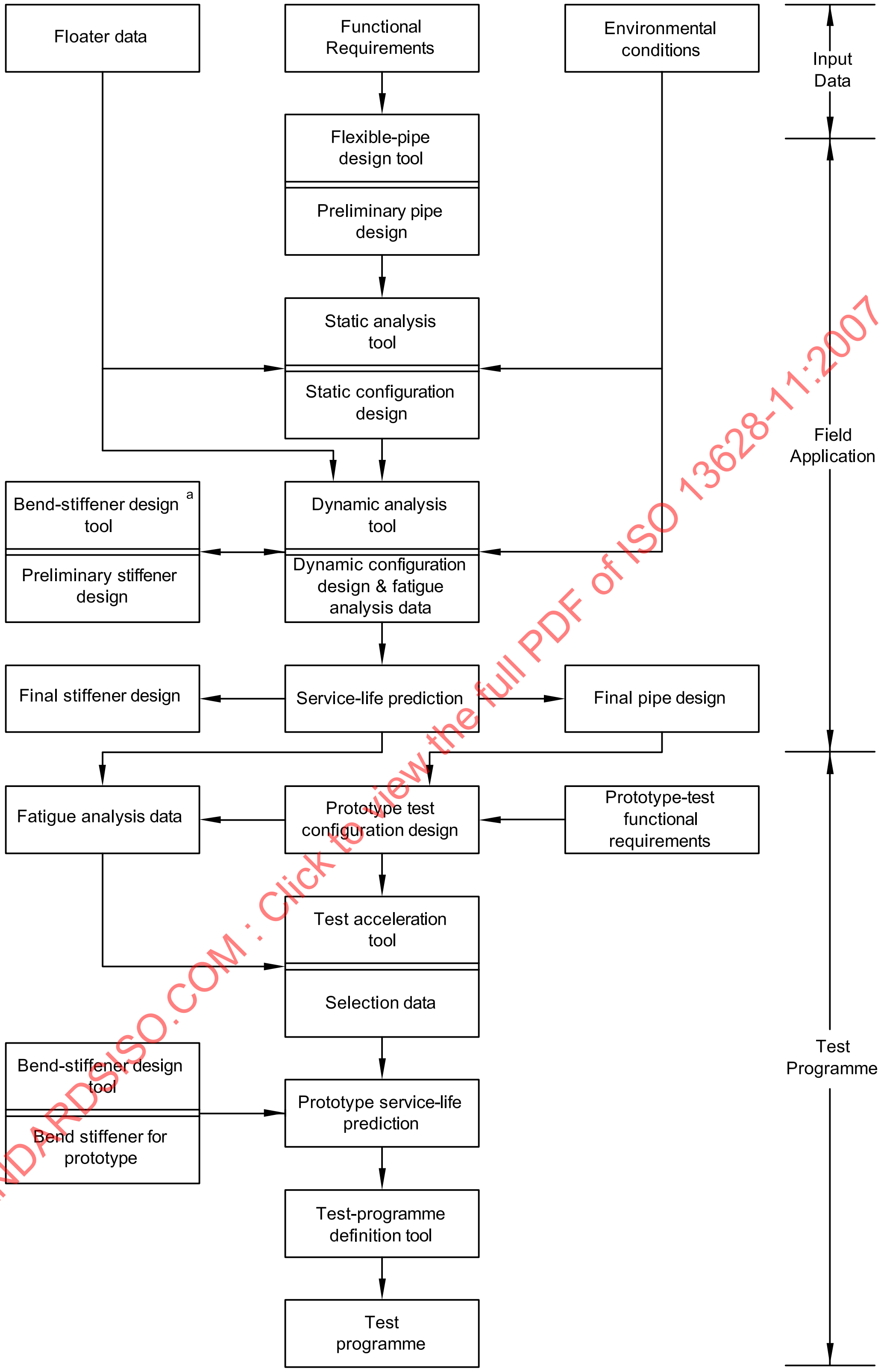

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NOTE The objective of the flowchart is to show flexible-riser and bend-stiffener design and the definition of a dynamic qualification programme.

[a] The bend-stiffener design may be modified for the prototype sample to change the stress levels in the pipe.

Figure 27 — Dynamic fatigue test-programme definition

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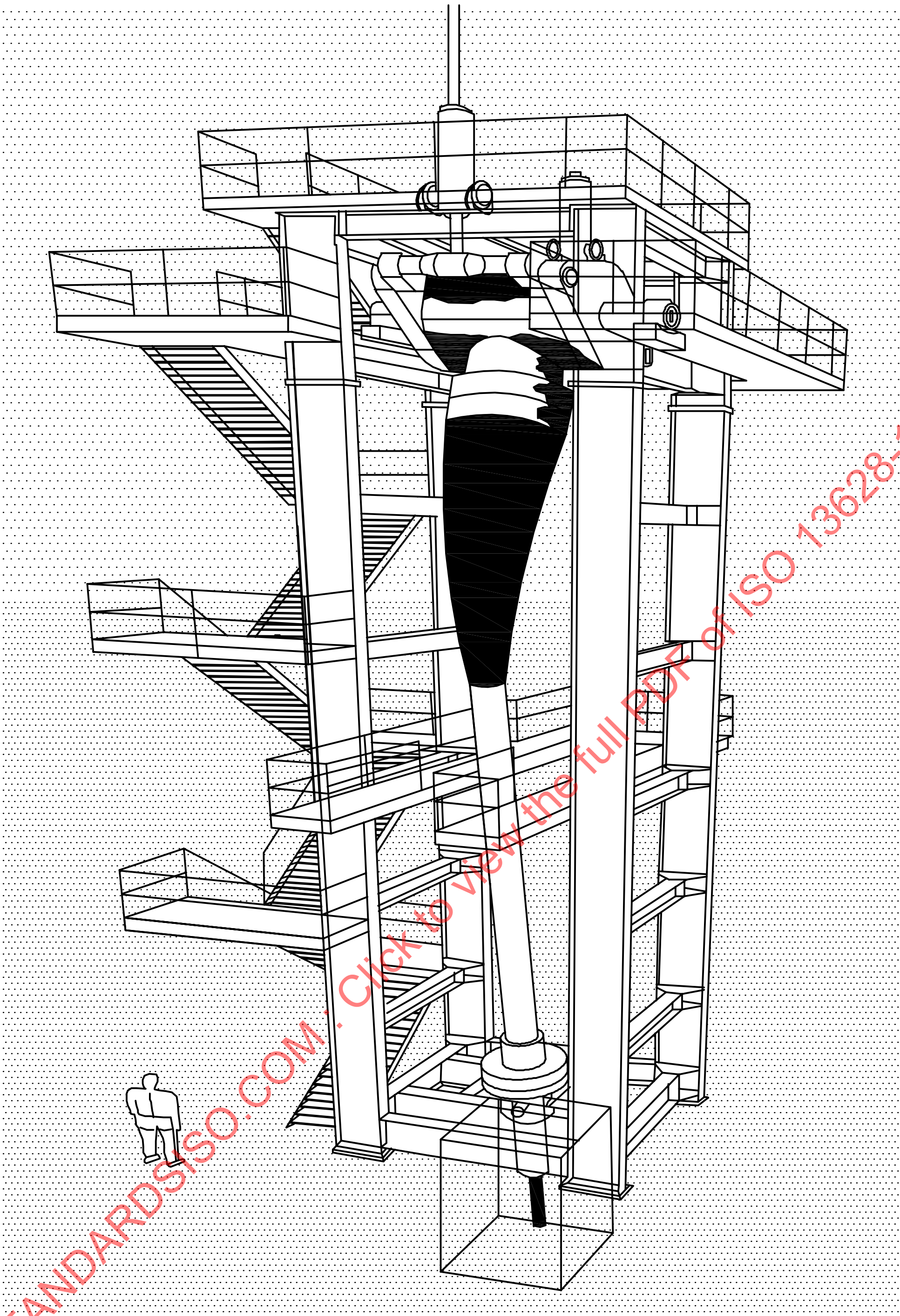

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Figure 28 — Typical set-up for a dynamic fatigue test

9.7.2.1.2 The minimum length of the test sample, excluding end fittings, should be as follows.

a) The length between the lower end fitting and the bottom of the bend-protection device should be at least three times the pitch of the outer armour wires/reinforcing cables.

b) The length between the top end fitting and the top of the bend-protection device should be at least one pitch of the outer armour wires, unless the end fitting is attached to a bend stiffener.

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9.7.2.1.3 The test sample should have end fittings attached at both ends, with a bend stiffener attached to the top end fitting. As an alternative, a pipe without a bend stiffener may be tested if the set-up includes a suitable bellmouth. The sample should be subjected to maximum operating internal pressure and a conservative tensile load related to the dynamic environment.

9.7.2.2 Procedure

9.7.2.2.1 The cyclic loading of the riser top should be divided into a number of blocks, each with a different angle amplitude, frequency and number of cycles. The frequency for each load case should be specified by the manufacturer. Typically the frequency increases as the angle range is reduced. A higher frequency can reduce the total test period but can generate an unacceptable temperature increase in the riser top because of friction between the layers. Local test-site conditions, including temperature, machinery and cooling requirements, influence the cycling rate. Thermal analysis is recommended to determine the cycling rate. Table 25 provides an example of a typical cycling programme.

Table 25 — Sample dynamic fatigue test programme

Block No.	Mean angle °	Cycle amplitude °	Minimum angle °	Maximum angle °	Relative No. of cycles [a]
1	5,0	1,25	3,75	6,25	1,000
2	5,0	2,50	2,50	7,50	0,550
3	5,0	3,75	1,25	8,75	0,250
4	5,0	5,00	0,00	10,00	0,075
5	5,0	7,50	-2,50	12,50	0,025
6	5,0	10,00	-5,00	15,00	0,010
7	5,0	15,00	-10,00	20,00	0,001

[a] No more than 25 % of the cycles of any block containing more than 1 % of the total cycles should be applied prior to switching to another block.

9.7.2.2.2 In a service simulation test, the total number of cycles in all blocks should be approximately 2×10^6 to 4×10^6. The number of cycles in each block depends on the application (such as floater motions and environmental conditions). Table 25 includes an example of a relative distribution of cycles per block. The load cases should be selected such that the structural layer most susceptible to fatigue (i.e. shortest life calculated in the service-life analysis) experiences cumulative damage in the test greater than or equal to that experienced in service over the field life. The difference in annulus environment between test and field conditions should be considered in comparing the test damage with the field damage. The loading should be applied either randomly or in groups of a specified percentage of all of the load blocks. Non-destructive inspection may be conducted periodically to check for damage to the structural layers in the bending zone. Approximately 400 000 cycles are applied with a single angle range, tension and internal pressure in a service-life model validation test. This block is selected based on achieving a cumulative damage of 1,0 in the layer most susceptible to damage. The test conditions may be adjusted to attempt to achieve 1,0 cumulative damage in any of the structural layers based on the service-life analysis.

9.7.2.2.3 The last block, with the largest cycle amplitude, normally represents the extreme operation conditions in the service simulation test. A limited number of cycles is required to represent this condition, preferably at the end of the test programme. Application of the largest-amplitude block is held until the end because it may artificially improve the fatigue performance of the pipe by strain-hardening the armour wires. The largest-amplitude blocks may be applied at both the beginning and the end of the test to create a more conservative test if it can be shown that strain-hardening does not occur.

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9.7.2.2.4 The following variables should be continuously recorded:

a) number of cycles;

b) internal temperature;

c) external ambient temperature;

d) internal pressure;

e) applied tension load;

f) actual angles applied.

9.7.2.2.5 The end of the initial dynamic fatigue test is defined as failure of the pipe (or bend stiffener) or, alternatively, successful completion of all cycles. The sample should be subsequently pressure-tested at a minimum of 1,25 times the design pressure with the tensile load applied if fatigue failure of the pipe does not occur. The pipe should be non-destructively inspected to verify the condition of the structural layers prior to conducting additional dynamic loading upon completion of the test. Table 28 lists proposed methods of non-destructive inspection. The dynamic fatigue test may be continued in a service simulation test if there is notable damage to one of the structural layers that does not result in failure of a pipe layer. It may also be continued in a service-life model validation test if the non-destructive inspection does not indicate any notable damage. Notable damage is defined in 9.7.2.3.

9.7.2.2.6 A layer-by-layer dissection of the test sample should be conducted to record the condition and evidence of degradation of the pipe structure over an area including the location of highest curvature variation. Layers that show signs of damage should be subjected to detailed examination.

9.7.2.3 Acceptance criteria — Service simulation

The pipe should have passed the test sequence without leakage or failure of the pipe structural layers as defined in Table 26. If there is notable damage to any of the structural layers, the test should be continued for an additional 25 % cumulative damage to the layer that is notably damaged. See 13.3 and Tables 27 and 28 for other defects that may be considered to affect the integrity of the pipe structure. A test pipe that has been through a service simulation test is expected to suffer some layer degradation from the as-built condition. The acceptance criteria for each layer should be clearly agreed between the purchaser and manufacturer prior to completion of the initial dynamic test.

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Table 26 — Acceptance criteria — Service simulation

Layer	Failure definition	Notable damage
Internal carcass	Through-wall crack or loss of interlock that can cause pipe collapse or damage to the pressure sheath if the pipe is bent to the SBR in any plane	Deformation of profile, loss of cross-section
Pressure armour	Through-wall crack or loss of interlock that can cause failure of the internal pressure sheath if the pipe is bent to the SBR in any plane	Variance from the profile shape that results in the service life (by analysis) being reduced below the field life
	—	Non-through-wall cracks in areas with the highest alternating stress
Tensile armour	Torsion imbalance greater than 1°/m in the field hydrotest (one end free to rotate)	Less than 5 % of the armour wires broken in any layer
	Axial stiffness of the pipe reduced by a factor of 20 % from value at beginning of test	—
	More than 5 % of the armour wires broken in any layer	—

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9.7.2.4 Analytical requirements

The result of this test is a curvature histogram indicating the number of cycles per class without failure of the pipe structure, end fitting or bend stiffener and documentation of the dissection. A comparison of the predicted and actual results based on the service-life analysis should also be provided. This information can be used to estimate the lifetime of a particular riser design for the expected history of floater motion and environmental conditions.

9.7.2.5 Alternatives

This particular test focuses on fatigue at a riser top connection. Alternative test set-ups are required if other sections of the riser are considered critical, such as riser sag bend or seabed touchdown region for catenary risers. In this particular test configuration, the following parameters may be altered:

a) internal pressure;

b) internal temperature;

c) mean angle;

d) cycle amplitude;

e) number of cycles.

In addition, strain in the outer tensile wires/reinforcing cables near the bend stiffener may be recorded.

9.7.3 Crush-strength test

9.7.3.1 Description

9.7.3.1.1 The crush-strength test determines the suitability of a particular design for installation with tensioners. The number of tensioner belts is typically three or four.

9.7.3.1.2 The test set-up should represent the tensioner system on the particular installation vessel. In particular, the number of belts and geometry of shoes should be comparable. The minimum length of the sample should be two times the pitch length of the outer armouring wire when tensile loads are applied.

9.7.3.2 Procedure

The flexible pipe sample should be positioned empty, without internal pressure, on the test device. The crushing load is increased from zero up to 110 % of the pipe design compression capacity at a rate not greater than 1 % of the maximum load per second (1 %/s). The compression load should be kept constant (within ± 2 %) for a period of at least 1 h. In the loaded condition and after unloading completely, the ovalization of the pipe is measured. Test loads should be based on the load expected during installation with a safety factor. The radial load is a function of pipe mass, depth and other factors.

9.7.3.3 Acceptance criteria

The permissible ovalization of the pipe in the loaded condition is 3 % and in the unloaded condition is 0,2 %. The value for the unloaded condition may be increased if the larger value is used in collapse calculations; see 5.4.2.4.

9.7.3.4 Analytical requirements

The effect of tensile load on the crush strength of the flexible pipe should be analysed.

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9.7.3.5 Alternatives

The crush-strength test may be performed with a tensile load applied. It is recommended that the tensile load be at least the design installation tension and be applied prior to the compression load at a rate not to exceed 1 % of the load per second. Also, the compression load can be increased in steps until the acceptance criteria are exceeded, so as to determine the maximum compression load of the pipe.

9.7.4 Combined bending and tension test

9.7.4.1 Description

9.7.4.1.1 The combined bending and tension test verifies the installation of a particular flexible-pipe design with a horizontal installation spread. This test simulates the passage of the pipe over the sheave of an installation vessel. It is not necessary in this test for the sample to include production-type end fittings. It is necessary only that the terminations be capable of transferring the tensile load to the flexible pipe. Damage due to the dissection process should be ignored.

9.7.4.1.2 The test sample should be positioned empty, at ambient internal pressure, on a special device that simulates the pipe-laying sheave of the installation vessel, with an identical bend radius and transverse profile. The sample should also be connected to a suitable tensile load machine. The straight section of pipe connected to the tensile load machine should be at least the length of the pipe bent over the sheave.

9.7.4.2 Procedure

9.7.4.2.1 The axial load is applied at a rate not greater than 1 % of the design installation tension per second up to 110 % of the design tension. The allowable variation in the design tension should be ± 2 %. This load is held for a minimum period of 1 h.

9.7.4.2.2 The external diameter of the pipe is measured at two locations 90° apart on the pipe circumference in the curved section of the pipe, with one measurement location being the contact face of the pipe. The tensile load is released and the diameter measurements retaken.

9.7.4.3 Acceptance criteria

The allowable variations in the external diameter are as follows:

a) loaded condition: ± 3 %;

b) unloaded condition: ± 1 %.

9.7.4.4 Analytical requirements

The effect of different sheave bend radii and tensile loads on the pipe deformation should be analysed.

9.7.4.5 Alternatives

After completion of the above test, the tensile load may be increased in steps not greater than 1 % of the design installation tension per second until the acceptance criteria above are exceeded. This is defined as the failure installation tension.

9.7.5 Sour-service test

9.7.5.1 Description

9.7.5.1.1 In addition to bench tests of the steel wire/cable materials (see ISO 13628-2 and ISO 13628-10), to verify performance in sour-service conditions, prototype tests on a full-scale pipe may also be carried out. Tests of this kind may be used to generate a realistic sour-service environment in the pipe annulus (unbonded) containing the steel wires and at the cable surface (bonded), and, in addition, simulate wire loading conditions by flexing the pipe.

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9.7.5.1.2 The test is normally carried out while simulating a wet annulus for unbonded pipe, either with salt water to test the failure condition or with fresh water to simulate normal operating conditions assuming shutdowns have caused condensation. Rubberized cables are normally used for bonded pipe tests.

9.7.5.1.3 Two approaches may be taken, as follows:

a) injection of a known concentration of H_2S/CO_2 into the wet annulus directly;

b) injection of the known H_2S/CO_2 concentration into the pipe bore and allowing the annulus/cable surface to reach an equilibrium state from permeation through the internal pressure sheath.

NOTE Only approach b) is relevant to bonded flexible pipe.

9.7.5.1.4 In either case in 9.7.5.1.3, it is necessary to carry out a prediction of the steady-state annulus/cable surface conditions based upon a diffusion/corrosion model agreed upon with the flexible-pipe manufacturer.

9.7.5.1.5 It is likely that to achieve steady state in a reasonable period of time (2 months to 3 months), an artificially high concentration is necessary for an initial period to accelerate stabilization, unless the concentration of H_2S is high. Prediction of the stabilization process should also be made using a consistent diffusion/corrosion model agreed upon with the manufacturer.

9.7.5.1.6 The test fluid characteristics may simulate service conditions for the pipe product, or be in accordance with NACE TM0177 if a general qualification is sought. The test should be designed to obtain saturation of the steel components in the annulus of the pipe or at the surface of the cable to a level at least equal to the design partial pressure (in the annulus/pipe bore [bonded]) of H_2S and CO_2. The internal fluid in the pipe should be at design pressure.

9.7.5.1.7 The fluid temperature is recommended to be approximately 25 °C (77 °F), unless operational temperature is expected to be considerably less, in which case the operating temperature should be used. The test sample should include end fittings identical to those proposed for the application.

9.7.5.1.8 Tests based on injection into the pipe bore are preferred, because the diffusion of H_2S and CO_2 correctly models pipes in service.

9.7.5.1.9 Tests for dynamic risers may be carried out in two phases: first injection of H_2S/CO_2 while the pipe is static and then, once the desired equilibrium is reached, flexure of the pipe, producing known alternating stresses. The alternating stresses should be representative of the stress range blocks modelled in a dynamic fatigue programme (see 9.7.2), adjusted so as to generate a known level of fatigue damage in the wires/cables.

9.7.5.1.10 The resulting fatigue damage following completion of the full-scale-exposure dynamic flexure test, can be assessed by completing in-air fatigue tests on samples of the wire to determine the “remaining life.” The pipe to be tested has to be sited in a facility suitable for large-scale sour-service testing. This normally comprises a concrete bunker or an enclosed space with extraction ventilation in accordance with local health and safety regulations.

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9.7.5.2 Procedure

9.7.5.2.1 Exposure of the flexible-pipe armour wires/reinforcing cables to H_2S and CO_2 is achieved by flowing fluid (water plus dissolved gas components through the annulus or oil plus gas components through the bore) through the pipe sample at a predetermined rate.

9.7.5.2.2 Sampling of fluid from the pipe outlet (annulus/bore) is required to determine the consumption of H_2S and CO_2. Where injection is into the bore, sampling of the annulus is also required.

9.7.5.2.3 The test solution is then continuously injected for a given period of time after equilibrium is reached to determine either the corrosion rate (static pipes) or fatigue performance (dynamic pipes).

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9.7.5.2.4 The pipe should first be pressure-tested and then dissected at the end of the exposure test,

9.7.5.2.5 It is necessary to make a decision at this point as to whether burst test data are required, which may be most appropriate for static flowlines, or if remaining fatigue-life data are required. In the latter case, appropriate to dynamic risers, the pipe should be dissected and wire samples bench-tested for remaining fatigue life compared to new, unexposed formed wires.

9.7.5.2.6 A burst-pressure test should be carried out in stages, raising the pressure by 20 % of design (or smaller steps if desired) from the exposure test pressure, with a hold time of at least 3 h between each step. The fluid in the pipe should be clean of H_2S, while precautions should still be maintained for H_2S due to release of the gas when burst occurs.

9.7.5.2.7 Flexure of a pipe to simulate dynamic service conditions can be most conveniently achieved by installation in a horizontally flexing frame. One or both pipe ends can require that bend stiffeners be installed to control curvature. The pipe flexure should be designed so as to induce appropriate tensile loads for fatigue in the tensile wires or reinforcing cables in an area of maximum curvature of the pipe, in addition to realistic loadings in the pressure armour (unbonded).

9.7.5.3 Acceptance criteria

9.7.5.3.1 Full-scale sour-service tests are a very challenging task and should be considered as part of a product development programme, rather than as part of a product qualification for a specific project. Test duration can exceed a calendar year and interpretation of the results can be complex.

9.7.5.3.2 Static pipe tests may be assessed on the basis of decay of the burst pressure over time because of corrosion, assumed to be linear with time after equilibrium is reached. This is with a proviso that the corrosion is generalized rather than local pitting. If the latter, then the average depth and rate of growth of pits may be used to predict expected service life.

9.7.5.3.3 Dynamic pipe tests are rather more difficult to predict, as the combination of the loading environment and the corrosion phenomena is complex. The manufacturer and user should together develop a model that is mutually acceptable to predict service life.

9.7.5.4 Analytical requirements

An analytical model, which is accepted by both manufacturer and user prior to the tests, should be available for the corrosion rate and the loading conditions (including annulus environment and the service-life assessment).

9.7.6 Fire test

9.7.6.1 Description

9.7.6.1.1 The objective of the fire test is to determine the survival time for the flexible pipe in a particular fire situation. The fire resistance can be designed into the pipe structure or may be achieved by non-integral passive fire protection.

9.7.6.1.2 The fire test may be carried out using the conditions defined in Reference [26]. These can be summarized as a fire temperature of 700 °C (1 292 °F) and a fire duration of 30 min.

9.7.6.1.3 The pipe should be tested at the design pressure. The pipe internal fluid may be water or another agreed fluid. The fluid should be stationary to simulate worst-case loading conditions. The end-fitting design used in the application should be used in the test sample.

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9.7.6.2 Procedure

9.7.6.2.1 The pipe is pressurized to the design pressure. The fire test should commence once pressure stabilization occurs. Both the flexible-pipe body and end fitting should be subjected to the required test conditions. Pressure in excess of the design pressure may be relieved.

9.7.6.2.2 Pipe failure should be considered to have occurred if the pressure in the pipe drops below 90 % of the test pressure. The survival time is then defined by the time from fire start-up to pipe failure.

9.7.6.3 Acceptance criteria

The survival time should exceed the design requirements.

9.7.6.4 Analytical requirements

There are no analytical requirements for this test.

9.7.6.5 Alternatives

Alternatively, the test set-up may be as given in Reference [22] (furnace or propane burners). The flame temperature should be based on the worst-case likely fire loading condition. Typical flame temperatures for a jet fire are approximately 1 100 °C (2 012 °F) and for a pool fire are approximately 1 000 °C (1 832 °F), specifically for a pipe engulfed by flames. Flame temperatures of 400 °C to 600 °C (752 °F to 1 112 °F) can be appropriate if the pipe is not engulfed.

9.7.7 Erosion test

9.7.7.1 Description

9.7.7.1.1 Figure 29 illustrates a typical test set-up for an erosion test. The test sample should be fixed at its minimum bend radius in a 90° angle. Erosion rates can be determined by thickness reduction (localized erosion rate) or by mass loss (average erosion rate) in the internal carcass.

9.7.7.1.2 The internal fluid composition should represent design conditions or be conservative. Consideration should be given to the following:

a) flow rate;

b) sand content;

c) particle size;

d) temperature;

e) pressure;

f) corrosive-gas content.

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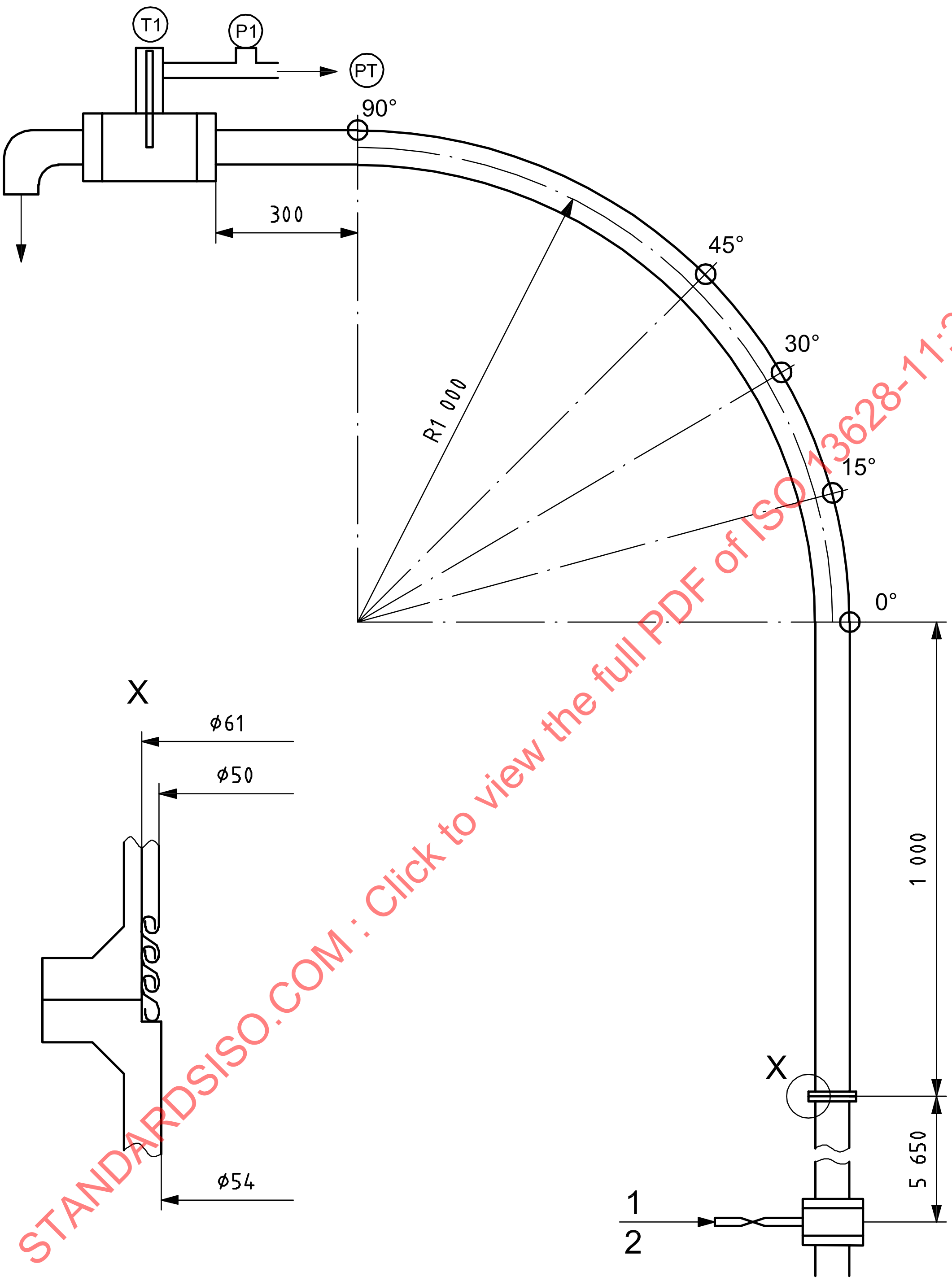
Dimensions in millimetres



Key

1 water

2 sand

Figure 29 — Example of set-up for the erosion test

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9.7.7.2 Procedure

The test fluid should be circulated through the flexible pipe for a minimum of 7 days. Erosion measurements should, as a minimum, be made at five points around the bend (0°, 15°, 30°, 45°, and 90° measurement points are recommended) after completion of the test.

9.7.7.3 Acceptance criteria

The erosion rate should be such that the design requirements for the pipe are not violated for the specified service life.

9.7.7.4 Analytical requirements

The effect of variations in the test-fluid composition, flow rate, and pipe bend radius should be analysed.

9.7.7.5 Alternatives

The effect of corrosive fluids on the erosion rate may be tested to determine corrosion-enhanced erosion rates.

9.7.8 TFL test

9.7.8.1 The purposes of the TFL test are to verify that TFL pumpdown tools adequately drift through the flexible pipe and to determine flexible-pipe wear rates because of repeated tool travel. The test unit simulates a TFL pipe run using a flexible pipe that is 45,72 m (150 ft) long.

9.7.8.2 The pipe is attached to both ends of a pump and manifold unit that provides measurable hydraulic fluid power and a means for reversing the fluid direction inside the pipe. The flexible pipe is laid out in two configurations: a wide “U” shape with a 3,66 m (12 ft) bend radius, and a narrow “U” shape with a 1,52 m (5 ft) bend radius (measured to the centreline).

9.7.8.3 A TFL pumpdown tool string is inserted in the pipe prior to hook-up. The TFL tool string should consist of four “up” locomotives, four “down” locomotives and a running tool. The running tool can be either a TFL drift mandrel or two “sharp-shouldered” drift mandrels, in which the first drift’s spring-loaded keys are oriented 90° out from behind the second drift’s keys. Both running tools should be run through both test configurations and cycled through the pipe several times.

9.7.8.4 In general, the TFL drift-mandrel tool string should be able to pass freely through the pipe in either direction (see ISO 13628-3 for drift-mandrel dimensions, forces and pressures). The tool strings and the pipe interior should be inspected for adverse wear or damage after the tests are completed.

NOTE For the purpose of this provision, API RP 17C is equivalent to ISO 13628-3.

9.7.8.5 If specialized running tools for an application are known (such as paraffin scraper, sand-wash wand, or “kick-over” tool), then it is recommended to run these tools in the test loop as well.

9.7.9 Vacuum test

9.7.9.1 Description

9.7.9.1.1 The vacuum test is intended for bonded flexible pipes only. The objective of the vacuum test is to indicate the adequacy of the bond strength of the liner to other pipe layers.

9.7.9.1.2 The vacuum test is not applicable to pipes in which an internal steel interlocked carcass is used. In addition, the vacuum test is possibly not practical for long [> 11 m (36 ft)] or small-diameter pipes.

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9.7.9.2 Procedure

9.7.9.2.1 The pipe should be vacuum tested to a pressure of 85 kPa (0,85 bar) gauge and held for a 10 min period.

9.7.9.2.2 A clear plastic window should be fitted at either end of the test sample so that visual inspection of the interior can be made by an adequate light source in one end with its beam directed to the other.

9.7.9.3 Acceptance criteria

9.7.9.3.1 Collapse of the pipe liner, failure of adhesion between layers within the pipe body, blisters and other deformities should not occur.

9.7.9.3.2 The pipe should be examined outside as well as inside for any possible deformities.

9.7.9.4 Analytical requirements

There are no analytical requirements for this test.

9.7.9.5 Alternatives

This test can be carried out within 24 h of the kerosene test to determine the resistance of the pipe to permeation or migration of fluids or gases. The vacuum test “pulls” the kerosene out of the pipe body if significant permeation or migration can occur.

9.7.10 Kerosene test

9.7.10.1 Description

9.7.10.1.1 This prototype test is intended for bonded flexible pipes only. The objective of the kerosene test is to detect any permeation or leakage of a hydrocarbon liquid through the pipe liner.

9.7.10.1.2 This test may be followed immediately by a vacuum test to further detect any residual kerosene that may have migrated into the pipe body.

9.7.10.1.3 This test is primarily for bonded flexible pipe with no internal interlocked steel carcass.

9.7.10.2 Procedure

9.7.10.2.1 The pipe should be laid out straight and filled with kerosene, venting all air. The pipe should then be pressurized to the design pressure and held at this pressure for 24 h.

9.7.10.2.2 Consideration should be given to cycling the pressure, prior to initiating the test, to help stabilize the pressure over the 24 h period.

9.7.10.3 Acceptance criteria

After 24 h, the pipe should be depressurized, drained, dried and observed for any blistering, leakage or separation of the liner from the carcass or from the end fitting.

9.7.10.4 Analytical requirements

An analytical model for the permeation of fluids or gases should be available and accepted by both manufacturer and purchaser prior to the tests.

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9.7.10.5 Alternatives

A vacuum test should be performed after completion of the kerosene test to further detect the permeation or migration of fluids or gases into the pipe body.

9.7.11 Adhesion test

9.7.11.1 Description

9.7.11.1.1 This prototype test is intended for bonded flexible pipe only. The adhesion test is used to verify the bond strength of the manufactured pipe.

9.7.11.1.2 Adhesion tests should be performed on samples made from materials taken from current manufacture and on samples representative of every tenth hose thereafter (in the case of specific lengths).

9.7.11.1.3 Samples should be built with the same cross-section make-up as the production pipe and should be built at the same time as the production pipe or as agreed on by the purchaser and manufacturer. The sample piece may be built with the cables at the reinforcing layer wound in the radial direction (i.e. a lay angle of 90° to pipe longitudinal axis) to facilitate this test. Vulcanization should occur under the same conditions as the production pipe.

9.7.11.2 Procedure

Adhesion tests should be carried out according to either ASTM D413 [14], machine method, or ISO 36 [17], using strip pieces.

9.7.11.3 Acceptance

The measured adhesion strength should not be less than 6 N/mm.

9.7.12 Full-scale blistering test

9.7.12.1 Description

9.7.12.1.1 The full-scale blistering test is performed to determine the suitability of a particular pipe design for service in a gas-containing environment and hence qualify the materials used for service.

9.7.12.1.2 The pressure, depressurization rate, temperature and fluid type should, as a minimum, be consistent with conditions the pipe is expected to be subjected to during a typical application. It is preferable to use an inert gas of similar molecular structure to the gas expected to be conveyed and with a minimum CO_2 content of 5 %.

9.7.12.1.3 The test pipe should be at least 3 m (9,84 ft) long including end fittings or sufficiently long as to ensure that any beneficial effects the end fittings have on influencing the outcome are eliminated.

9.7.12.2 Procedure

9.7.12.2.1 The manufacturer should have documented procedures to ensure that the test gas occupies 100 % of the internal pipe volume. Once the pipe is filled with the test gas, the pressure should be gradually increased at a rate not greater than the manufacturer's test procedure to the design pressure and held for a period of at least 2 h to allow for stabilization. If necessary, the pressure shall be considered stabilized when the pressure drop is less than 1 % in a 1 h period. The pressure should be cycled to this pressure until stabilization is achieved. The pipe should then be held at this pressure to ensure saturation of the pipe body with gas for a length of time not shorter than that of the manufacturer's test procedure.

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9.7.12.2.2 Once saturation of the pipe body is achieved, the pipe should be depressurized at a rate equal to the expected depressurization rate or else a minimum of 7 000 kPa/min (70 bar/min).

9.7.12.2.3 The procedures set out in 9.7.12.2.1 and 9.7.12.2.2 should be repeated for the expected number of cycles or a minimum of 60 cycles.

9.7.12.3 Acceptance criteria

Once the test is complete, the end fittings should be cut off the test pipe, the pipe body should be cut in half lengthwise and the half shells cut radially into three approximately equal lengths. The carcass layer should be removed to expose the elastomer surface beneath it. When the six sample pieces are inspected on all surfaces at 1x magnification, there should be no evidence of delamination, blistering or voids in the elastomer layers.

9.7.12.4 Analytical requirements

The soak time should be computed based on the measured permeability of the elastomer to the gas under consideration.

9.7.12.5 Alternatives

Small-scale blistering-resistance tests that reflect the design requirements, relating in particular to fluid conditions, pressure, temperature, number of depressurizations and depressurization rate, may be performed (see ISO 13628-10) as an alternative to this test.

In addition, the full-scale prototype test piece can be used to measure adhesion of the elastomer to the end fitting once the blistering test is completed. The full-scale blistering test can also be carried out on the pipe after it has been used in a full-scale fatigue test programme.

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10 Manufacturing

10.1 General

10.1.1 ISO 13628-2 and ISO 13628-10 specify manufacturing requirements for unbonded and bonded flexible pipes. Clause 10 describes the processes involved in the manufacture of the pipe. In addition, guidelines on the selection of manufacturing tolerances are given. Guidelines on assembly of end fittings are also included.

10.1.2 Furthermore, Clause 10 provides guidelines on marking and storage of flexible pipes. The marking guidelines supplement the minimum requirements for marking given in ISO 13628-2 and ISO 13628-10.

10.2 Manufacturing — Unbonded pipe

10.2.1 General

The manufacturing of unbonded flexible pipe is composed of two main stages, as follows:

a) fabrication of the flexible-pipe body;

b) assembly and mounting of the end fittings.

These two stages in the process are described in 10.2.2 and 10.2.3, respectively.

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10.2.2 Manufacturing processes

10.2.2.1 General

The main processes in the fabrication of the flexible-pipe body are as follows:

a) carcass forming;

b) polymer extrusion;

c) pressure-armour winding;

d) tensile-armour winding;

e) tape winding.

Depending on the pipe design, processes a) and c) are possibly not required.

10.2.2.2 Carcass forming

In the carcass-forming process, flat metallic strips are pulled into a forming head in which they are shaped into an interlocking helical tube; see Figure 7.

10.2.2.3 Polymer extrusion

10.2.2.3.1 Extruded components in a flexible pipe include polymer sheaths (internal pressure, intermediate, or outer sheath) and solid anti-wear layers. The stations and equipment in the polymer extrusion line are typically as follows (for a rough-bore structure):

a) payoff reel (or basket) with the inner carcass layer;

b) caterpillar (pre-extrusion);

c) extruder;

d) quench tanks (hot and cold water);

e) caterpillar (post-extrusion);

f) take-up reel (or basket).

10.2.2.3.2 The control of the extrusion process is important for quality of finished product, and a feedback control system is recommended (see ISO 13628-2).

10.2.2.4 Pressure-armour winding

10.2.2.4.1 The pressure-armour winding machine preforms, interlocks and winds the wires circumferentially around the internal pressure sheath using shaped wires; see Figure 7. Payout/take-up reels or (baskets) and caterpillars are used to control the feed of the pipe through the winding machine.

10.2.2.4.2 The interlocking pressure armour is laid as one or two wires at a lay angle of close to 90°. A flat back-up layer can also be wound on top of the interlocked layer using the same process.

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10.2.2.5 Tensile-armour winding

10.2.2.5.1 The tensile-armour winding machine takes flat, round or shaped wires and preforms and winds the wires onto the surface of the pipe. The number of wires wound in one layer is typically between 30 and 80. The wires are generally laid with an angle range between 20° and 60°. The wires are stored in individual drums connected to the winding machine. The drums rotate with the winding machine while feeding it with wire.

10.2.2.5.2 Two machines in sequence or one machine used twice can be used to apply the double-crosswound tensile-armour layers used in most applications. These machines can be subject to regular stoppages for reloading of drums and welding of new wires.

10.2.2.6 Tape winding

Tape winding machines are used to apply anti-wear, manufacturing aid or insulation layers. These machines are typically used in sequence with one of the other processes.

10.2.3 End fittings

10.2.3.1 The end fitting is a critical part of the flexible pipe. A well designed transition zone is required for all the pipe-wall components to converge into one flange or connector piece that carries all the pipe-wall forces.

10.2.3.2 The pressure- and tensile-armour layers are locked to the end termination body to ensure reliable attachment in both radial and axial directions. The pressure integrity of the external and internal sealing layers (polymer sheaths) is provided by a seal arrangement that also ensures radial and axial attachment. The zone near the end fitting does not have the same flexibility as the rest of the pipe. This zone, corresponding to the length of a couple of turns of the tensile armour, therefore, does not have the same curvature capacity (flexibility) as the main pipe section.

10.2.3.3 Figure 8 illustrates a typical unbonded-pipe end fitting. Most of the components in the end fitting are applied manually with special tools and fixtures. Quality control of all processes in the fabrication of the end fitting is therefore critical.

10.2.3.4 The main steps in the process are as follows:

a) separate individual layers of pipe;

b) mount inner seal assembly and main end-fitting body;

c) clamp pressure-armour layer;

d) secure tensile armours around body;

e) mount external jacket;

f) mount outer locking assembly (sealing of outer sheath);

g) fill voids in end fitting with epoxy resin and allow to set.

10.2.3.5 Bend stiffeners, when required at the end of the flexible pipe, are usually mounted on the pipe prior to the end fitting and subsequently pulled up and attached to the end fitting once it is mounted.

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10.2.4 Tolerances

10.2.4.1 In 10.2.4.2 to 10.2.4.9, guidelines on the selection of manufacturing tolerances are provided; see ISO 13628-2. The tolerances specified in 10.2.4.2 to 10.2.4.9 are defined in terms of percentage of nominal values.

10.2.4.2 For unbonded flexible pipes, the length tolerance for lengths up to 100 m (328 ft) should typically be ${}^{+1}_{0}$ m. For unbonded lengths greater than 100 m (328 ft) the length tolerance may be increased to ${}^{+1}_{0}$ %. The tolerance can typically be ± 1 % for bonded pipes. For certain projects there can be additional requirements on the length tolerance to be considered, including those described in 10.2.4.3 to 10.2.4.6.

10.2.4.3 It can be necessary to reduce the tolerances for certain applications (such as jumpers).

10.2.4.4 Some applications can have problems if the length is too long, for example, for long flowlines a maximum tolerance of + 1 % can be too large because of insufficient space at the end connection to accommodate excess length. This can be more critical for trenched pipe.

10.2.4.5 Consideration should be given to possible problems caused by the individual risers having different lengths if two or more risers are clamped together (such as with umbilicals in some applications).

10.2.4.6 The calculation of the required flowline length should accurately account for all parameters, including undulations in the route, accuracy of end point locations, installation tolerances, manufacturing tolerance and orientation of the flowline to the component (for example, the pipe can be laid in a loop around the component, such as at a wellhead, and connected at a 90° orientation to the main flowline direction).

10.2.4.7 The recommended tolerance on the flexible pipe overall outer diameter is ± 3 %. The tolerance on internal diameter should be ${}^{+2}_{0}$ % for carcass layers that are not manufactured on a mandrel. It is recommended that the tolerance on the internal diameter be ${}^{+2}_{0}$ % for internal polymer sheaths that are not extruded on to an inner carcass.

10.2.4.8 Tolerances should be established and controlled by the manufacturer for each layer of the pipe. Table 27 lists recommendations on critical aspects of dimensional tolerances for the flexible-pipe layers.

10.2.4.9 The manufacturer should check pressure and armour layer tolerances for the allowable gap between adjacent wires or the allowable average gap over a group of wires against manufacturer specifications.

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Table 27 — Critical aspects in selection of unbonded flexible-pipe manufacturing tolerances

Recommendations for selected parameters			
Layer	**Thickness**	**Layer diameter (inner and outer)**	**Other parameters**
Internal carcass	The minimum value should meet the design requirements, considering the potential for erosion/corrosion over the service life. The strip thickness should be controlled by the manufacturer's material specification.	The minimum ID should ensure clear passage for equipment such as gauging pigs. The maximum OD should consider the effect on collapse resistance and tolerance of the other layers.	The maximum ovality should be less than that used in the calculation of collapse resistance.
Internal pressure sheath	The minimum thickness should be determined based on ISO 13628-2.	The maximum OD should consider the effect on hoop strength of the pressure-armour layer in accordance with ISO 13628-2.	Surface finish and texture to be controlled such that potential defects that could propagate through the layer thickness do not occur.
Pressure-armour layer	Thickness should be controlled by the manufacturer's material specification. The minimum thickness should consider the effect on hoop strength in accordance in with ISO 13628-2.	The maximum OD should consider the effect on hoop strength in accordance with ISO 13628-2. Variations in OD with length should consider the load sharing along the length in a tensioner installation.	The OD should be controlled such that gaps between the pressure-armour layer and the internal pressure sheath do not affect the load sharing between the carcass and pressure-armour layer under external radial compression and hydrostatic loading. The maximum gap should assure utilization is as specified in ISO 13628-2.
Intermediate sheath/ anti-wear layers	In dynamic applications, the minimum thickness should ensure that the sheath does not wear through over the service life. Where the intermediate sheath is to bear hydrostatic loading, the minimum thickness should ensure that the layer is not breached (lose pressure integrity) over the service life.	The maximum value should consider the effect of tolerance build-up on subsequent layers.	—
Tensile-armour layer	The minimum thickness should be controlled by the manufacturer's material specification. The minimum thickness should consider the effect on hoop and axial strength in accordance with ISO 13628-2.	The maximum diameter should consider the effect of tolerance build-up on subsequent layers, and ensure that the tensile wires lie flat against the pipe.	Variations in lay angle should ensure that allowable utilization is in accordance with ISO 13628-2. The maximum gap between wires should be determined considering the effect of circumferential stress concentration in the pressure armour (local bending of the pressure armours within the gaps). Where no pressure armour is present, the maximum gap should be determined based on ISO 13628-2.
Insulation layer	The minimum thickness should be controlled by the manufacturer's material specification. The minimum thickness should give an overall heat-transfer coefficient for the pipe smaller than the specified maximum.	The maximum outer diameter should consider the effect of tolerance build-up on subsequent layers, and ensure that the insulation lies flat against the pipe.	—
Outer sheath	The minimum thickness should assure watertight integrity over the service life, including at the end fittings. Shear transfer to the underlying layers during installation with a tensioner should also be considered. The variation in thickness along the length of a pipe should consider the effect of stress concentration and possible thinning during installation.	The maximum outer diameter should consider the effect on packaging, installation loading, hydrodynamic loading and attachment of ancillary equipment such as buoyancy clamps.	—
External carcass	The minimum thickness should consider the requirement for abrasion and impact protection in the specific application.	The maximum outer diameter should consider the effect on packaging, installation and hydrodynamic loading.	—

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10.3 Manufacturing — Bonded pipe

The manufacture of bonded flexible pipe is comprised of the following three main stages:

a) fabrication of the flexible-pipe body;

b) assembly and mounting of the end fittings;

c) curing of flexible pipe.

NOTE Stages b) and c) are interchangeable in sequence for some pipes.

10.3.1 Manufacturing processes

10.3.1.1 General

The main processes in the fabrication of the flexible-pipe body are as follows:

a) carcass forming;

b) preparation of compound and calendering;

c) elastomer winding;

d) reinforcement-armour winding.

Process a) may not be required, depending on the pipe design and application,

10.3.1.2 Carcass forming

Flat metallic strips are pulled into a forming head in which they are shaped into an interlocked helical tube; see Figure 7. Some bonded-flexible-pipe manufacturers do not carry out this task, preferring instead to obtain pre-manufactured carcasses.

10.3.1.3 Preparation of compound and calendering

10.3.1.3.1 The process by which the compound is prepared involves accurately weighing out each ingredient of the compound and mixing the ingredients in the specified order and at specified temperatures in a large “Banbury”-type mixer until a homogenous, consistent compound is formed.

10.3.1.3.2 The calendering process involves passing the prepared compound between rollers repeatedly until the compound takes on the form of a smooth, even sheet with no flaws or blisters. This sheet can be subdivided into smaller strips and subsequently wound onto reels for storage or cut and stored as smaller flat sheets. The friction caused by forcing the compound through the calendering rollers causes an increase in the temperature. This temperature should be controlled so as to ensure that over-curing does not occur during calendering. The compound is generally passed through a bath containing an anti-adhesion substance prior to storage. Alternatively, the compound material may be stored with plastic sheets between each layer.

10.3.1.3.3 The steel cables of the reinforcing layer may be incorporated into a sheet of compound during the calendering process or by an extrusion process. This facilitates winding of the reinforcing layer onto the pipe, and speeds up the fabrication stage. These sheets are generally stored on reels for ease of use.

10.3.1.4 Elastomer winding

10.3.1.4.1 The production pipe is generally built up by winding sheets of calendered elastomer onto a mandrel or interlocked steel carcass. The winding process continues with different compounds per the cross-sectional specification, including calendered reinforcing cables, until the pipe is fully built up.

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10.3.1.4.2 The control of the winding process is important for the quality of the finished product as irregular overlaps and gaps in the winding process can cause unevenness in the pipe cross-section (see ISO 13628-10).

10.3.1.4.3 The elastomer can also be extruded to build up the pipe cross-section although winding is more common; see 10.2.2.3.

10.3.1.5 Reinforcement-armour winding

10.3.1.5.1 The cables that make up the reinforcement can be wound onto the pipe body in two formats. The first format is simply by an armour-winding machine where the cables are stored in individual drums connected to the winding machine. The drums rotate with the winding machine while feeding it with cable as the pipe advances through the machine. In some cases the pipe rotates while the winding machine traverses horizontally. The second format is identical to the way in which the elastomer sheets are wound. The cables are pre-calenderized and stored on reels in long narrow strips. These strips are then wound onto the pipe body by rotating the pipe body and advancing either the pipe or winding machine at a predefined rate.

10.3.1.5.2 Two machines (or more) in sequence or one machine (or more) used twice can be used to apply the double crosswound armour cables.

10.3.1.5.3 The control of the winding process is important to maintain the quality of the finished product (see ISO 13628-10).

10.3.2 End fittings

10.3.2.1 The end fitting is a critical part of the flexible pipe. A well-designed transition zone is required for all the pipe-wall components to converge into a flange or connector piece that carries all the pipe-wall forces.

10.3.2.2 The cables of the reinforcement-armour layer are locked to the end termination body to ensure reliable attachment in both radial and axial directions. The pressure integrity of the external and internal sealing layers (elastomer cover and liner) is provided by curing the layer onto the end fitting which also ensures radial and axial attachment.

10.3.2.3 The end fitting can be swaged onto the pipe body in some cases. This involves an internal and external steel end-fitting piece that encapsulates the pipe body and, when swaged, compresses the pipe body sufficiently to ensure both fixity and sealing of the liner, cover and cables of the reinforcement layer. The end-fitting face in contact with the pipe body may be smooth or toothed. The toothed end fitting is designed to contact the cables of the reinforcement layer and so provide a stronger mechanical grip.

10.3.2.4 The zone near the end fitting does not necessarily have the same flexibility as the rest of the pipe. This zone, corresponding to the length of a couple of turns of the reinforcing cables, therefore, does not have the same curvature capacity (flexibility) as the main pipe section.

10.3.2.5 Bend stiffeners, when required at the end of the flexible pipe, are usually mounted onto the pipe prior to the end fitting and subsequently pulled up and attached to the end fitting once it is mounted. Alternatively, inherent stiffness may be introduced into the pipe during the manufacturing process by winding on additional elastomer layers.

10.3.2.6 The flexible pipe can be cured fully or partially cured prior to mounting the end fitting. Alternatively, the end fitting can be mounted prior to cure and cured with the pipe. The difference in procedures is partially due to the differing temperature and time required to cure elastomer compound and epoxy resin.

10.3.3 Curing process

10.3.3.1 Curing of the elastomer of bonded flexible pipes is generally accomplished by applying heat and pressure to the pipe in the presence of curing agents. Heat can be applied by a steam oven or by electrical inductance. Pressure is generally applied by wrapping the pipe tightly with nylon prior to cure.

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10.3.3.2 The elastomer compound changes properties irreversibly during the curing process, and the elastomer material making up the pipe cross-section initially flows, subsequently forming one composite cross-section.

10.3.3.3 A composite cross-section with minimal flaws is formed once proper manufacturing procedures are adhered to, followed by the manufacturer's documented curing procedures. However, a sample piece, identical in construction to the pipe should be constructed with the pipe, dissected and inspected for voids in accordance with the manufacturer's procedures. The acceptance criterion should be that no visible voids are observed.

10.3.4 Tolerances

10.3.4.1 In 10.3.4.2 to 10.3.4.5, guidelines on the selection of manufacturing tolerances are provided (see ISO 13628-10). The tolerances specified in 10.3.4.2 to 10.3.4.5 are defined in terms of percentage of nominal values.

10.3.4.2 The length tolerance for bonded flexible pipe should typically be $^{+1}_{0}$ %. Additional requirements on the length tolerance that can be considered for certain projects include the following.

a) The tolerances can require reduction for certain applications, such as jumpers.

b) Some applications can have problems if the length is too long. This can be more critical for trenched pipe.

EXAMPLE A maximum tolerance of + 1 % can be too large for long flowlines because of insufficient space at the end connection to accommodate excess length.

c) Consideration should be given to possible problems caused by the individual risers having different lengths if two or more risers are clamped together (such as with umbilicals in some applications).

d) The calculation of the required flowline length should accurately account for all parameters, including undulations in the route, accuracy of end-point locations, installation tolerances, manufacturing tolerance and orientation of the flowline to the component.

EXAMPLE The pipe can be laid in a loop around the component (such as at a wellhead) and connected at a 90° orientation to the main flowline direction.

10.3.4.3 The recommended tolerance on the flexible pipe overall outer diameter is ± 3 %. The tolerance on internal diameter should be $^{+2}_{0}$ % for carcass layers that are not manufactured on a mandrel. The recommended tolerance on the internal diameter is $^{+2}_{0}$ % for liners that are not built on an inner carcass

10.3.4.4 Tolerances should be established and controlled by the manufacturer for each pipe layer. Table 28 lists recommendations on critical aspects of dimensional tolerances for the flexible pipe layers.

10.3.4.5 The manufacturer should check reinforcement-armour-layer tolerances for the allowable gap between adjacent wires or the allowable average gap over a group of wires against manufacturer specifications.

10.4 Marking

10.4.1 General

ISO 13628-2 and ISO 13628-10 specify minimum requirements for marking of flexible pipes. The objective of 10.4 is to provide recommendations on additional markings that may be applied to the pipe. These additional markings are useful for particular applications and can make the pipe and its intended use more identifiable during its service life.

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The marking system should be sufficient to resist installation and operational abrasions, with letters and numbers at least 10 mm (0,39 in) high. All markings should be sufficiently clear to be read and/or recognized *in situ* by an ROV, and be suitable for the required service life in the design environment. This does not apply to markings that are required only for installation purposes (e.g. circumferential bands for length measurement or for clamp or buoyancy locations) and, therefore, are required to be sufficient only to resist the installation procedures.

Table 28 — Critical aspects in selection of bonded-flexible-pipe manufacturing tolerances

Recommendations on selected parameters			
Layer	**Thickness**	**Layer diameter (inner and outer)**	**Other parameters**
Internal carcass	The minimum value should meet the design requirements of ISO 13628-10, considering the potential for erosion/corrosion over the service life. The strip thickness should be controlled by the manufacturer's material specification.	The minimum ID should ensure clear passage for equipment such as gauging pigs. The maximum OD should consider the effect on collapse resistance and tolerance build-up of the other layers.	The maximum ovality should be less than that used in the calculation of collapse resistance.
Liner	The minimum thickness should be determined based on the requirements of ISO 13628-10.	The maximum OD should consider the effect of tolerance build-up on subsequent layers.	Surface finish and texture are controlled such that potential defects that could propagate through the pipe body do not occur.
Reinforcement-armour layer	The minimum thickness should be controlled by the manufacturer's material specification. The minimum thickness should consider the effect on hoop and axial strength in accordance with ISO 13628-10.	The maximum diameter should consider the effect of tolerance build-up on subsequent layers.	Variations in lay angle should ensure that allowable utilization is in accordance with ISO 13628-10.
Insulation layer	The minimum thickness should be controlled by the manufacturer's material specification. The minimum thickness should give an overall heat-transfer coefficient for the pipe smaller than the specified maximum.	The maximum outer diameter should consider the effect of tolerance build-up on subsequent layers and ensure that the insulation lies flat against the pipe.	—
Cover	The minimum thickness should assure watertight integrity over the service life, including at the end fittings. Shear transfer to the underlying layers during installation with a tensioner should also be considered. The variation in thickness along the length of a pipe should consider the effect of stress concentration and possible thinning during installation.	The maximum outer diameter should consider the effect on packaging, installation loading, hydrodynamic loading and attachment of ancillary equipment, such as buoyancy clamps.	—
External carcass	The minimum thickness should consider the requirement for abrasion and impact protection in the specific application.	The maximum outer diameter should consider the effect on packaging, installation and hydrodynamic loading.	—

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10.4.2 Flexible pipe

10.4.2.1 Nameplates (AISI 316 material is recommended) should be securely attached to both ends of the pipe. The nameplate should not be covered by any ancillary component, such as bend stiffeners or bend restrictors. Consideration is recommended for including the markings listed in Table 29, in addition to the requirements of ISO 13628-2 and ISO 13628-10.

10.4.2.2 Length measurements, typically every 10 m (32,8 ft), should be marked on the pipe and highlighted by a collared circumferential band all around the outer sheath to allow identification of the length of the pipe. The length markings should indicate the direction of the length measurement.

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10.4.2.3 The following marking recommendations can also be considered for riser applications.

a) Unique and logical markings should be applied to identify different risers or the locations for the attachment of any ancillary items, such as clamps or buoyancy modules.

b) The location of the seabed touchdown point should be marked, if applicable.

10.4.3 End fittings

In general, the nameplate with the pipe markings is attached to the end fitting and applies to both pipe and end fittings. Separate markings are, therefore, not generally required for the pipe and end fitting. Consideration should be given to the markings listed in Table 29 for the end fitting if there is the possibility of the end fitting being replaced. Special care should be taken to ensure that identification markings do not damage any surface anti-corrosion treatment on the end fitting.

Table 29 — Marking recommendations for flexible-pipe products

Mark [a]	Flexible pipe	End fitting	Comments
ISO 13628-2 and ISO 13628-10 designation	X	X	Required by ISO 13628-2 and ISO 13628-10
Serial number	X	X	Required by ISO 13628-2 and ISO 13628-10; should ensure full traceability of all materials, processes and tests during manufacture
Manufacturer name or mark	X	X	Required by ISO 13628-2 and ISO 13628-10
Date of manufacture	X	X	Required by ISO 13628-2 and ISO 13628-10; month and year
API licence number	X	X	Required by ISO 13628-2 and ISO 13628-10; API licensees only
API monogram	X	X	Required by ISO 13628-2 and ISO 13628-10; API licensees only
Design pressure [b]	X	X	Required by ISO 13628-2 and ISO 13628-10; in MPa units; specify absolute or differential pressure
Storage MBR	X	NA	Required by ISO 13628-2 and ISO 13628-10
Sweet- or sour-service applications	X	X	Designated by letters SW (sweet) or SO (sour)
Static or dynamic application	X	X	Designated by letters S (static flowline, riser or jumper) or D (dynamic riser or jumper)
Internal diameter [b]	X	X	Expressed in millimetres
External diameter [b]	X	NA	Expressed in millimetres
Design temperatures [b]	X	X	Minimum and maximum design temperatures, expressed in degrees Celsius
Length [b]	X	X	Length of flexible pipe including end fittings
End-fitting condition	NA	X	Designated by letters OEF (original end fitting) or REF (replaced end fitting)

[a] The marking for the pipe and end fitting may be covered by a single template attached to the end fitting.

[b] Imperial units (inches, psi, and °F) may be given in brackets after the SI units.

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10.4.4 Connectors and flanges

Marking requirements for connectors, flanges, and associated components should be as specified in API 6A [7].

10.5 Storage

10.5.1 General

10.5.1.1 Flexible pipe can be stored in a number of ways, with the most common being reels, baskets and crates or pallets. Reels and baskets, in particular, should be marked such that the manufacturer, serial number, flange and drum diameters, width, empty mass and mass capacity are identified.

10.5.1.2 The flexible pipe should be stored under environmental conditions that do not affect its performance characteristics. In particular, the following are recommended.

a) The storage temperature should be within the acceptable limits of the flexible pipe structure and its end fittings.

b) The end fitting connections should be protected to prevent damage of the seal area, threads, and other areas susceptible to damage.

   1) The strapping of the end fitting should ensure that it cannot become loose and possibly damage the pipe.

   2) Securing of the end fitting should not damage the pipe by overbending the section adjacent to the fitting.

c) The flexible pipe should be covered to prevent degradation by ultraviolet radiation for materials sensitive to sunlight.

d) End-cuts of flexible pipe should be covered for long-term storage.

e) The possible effect of the test fluid on the flexible-pipe materials should be taken into consideration if flexible pipe is stored for a long period of time after having been pressure-tested.

f) Long-term pipe storage can cause a permanent curvature set of the pipe because of the polymer layers and can require consideration in installation planning.

10.5.1.3 Product handling while in storage should be kept to a minimum. A full and thorough inspection programme for the flexible pipe while in storage should be performed. Inspection reports should be provided to the purchaser.

10.5.1.4 Repairs carried out while in storage should be performed under permanent or temporary cover along with the environmental-control facilities normally provided during manufacture. Work carried out in the storage area should be strictly controlled and performed in such a manner as to cause no damage or contamination to stored products. The storage area should be subject to purchaser acceptance and should be in a location where the pipe is not susceptible to damage.

10.5.2 Reels

10.5.2.1 Reels rotated around a horizontal axis are the support most commonly used for storage of flexible pipe in long lengths. Reels, when driven by a winch system, can also be used to maintain the flexible pipe's tension during installation and recovery. The tension applied to the pipe during reeling should be sufficient to prevent the pipe from being stored slack, which can damage the pipe during subsequent unreeling. The parameters important to consider in selecting storage reels for flexible pipe include the following.

a) The drum radius should meet or exceed the storage MBR requirements of the flexible pipe.

b) The size of the reel should accommodate the length of flexible pipe, including end fittings and accessories.

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c) The structure of the reel should be capable of safely supporting the mass of the flexible pipe and its contents.

d) Reel dimensions, structural design and construction should account for the loads induced by the vessel motions and the flexible pipe tension during installation and recovery if the reel is to be used for offshore installation.

10.5.2.2 In the fabrication of reels, all surfaces in contact with the flexible pipe should be free of any sharp edge, burr or cut that can damage the flexible pipe. This also applies to partitions when used to subdivide reels into separate sections.

10.5.3 Baskets

Baskets or carousels rotated around a vertical axis are frequently used for the storage of flexible pipe in very long lengths. Baskets are normally used only for storage and are not capable of supporting any significant tension in the flexible pipe. Therefore, a tensioning system is generally required for installation of flexible pipe from a basket. Design parameters and fabrication requirements are otherwise similar to those of reels.

10.5.4 Crates/pallets

Crates or pallets are commonly used for storage of flexible pipes in short lengths, either straight or coiled. If stored in coil, the storage MBR criteria for the flexible pipe should be met. The flexible pipe should be tightly secured to the crate or pallet to prevent damage due to abrasion. The crate or pallet should contain no sharp edge, burr or cut which can damage the pipe.

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11 Handling, transportation, and installation

11.1 General

Clause 11 provides guidelines and recommendations for handling, transportation and installation of flexible pipe systems. In 11.4, the general installation considerations are addressed and sample installation procedures and final commissioning are described.

11.2 Handling

11.2.1 General

11.2.1.1 The precautions listed in 11.2.1.2 to 11.2.1.4 should be taken during handling and transportation of flexible pipe to prevent damage.

11.2.1.2 Precautions should be taken to ensure that the flexible pipe is not damaged by dragging on the floor or against sharp edges of the handling equipment or by unacceptable torsional/bending loading as a result of improper procedures when it is transferred from reel (or basket) to reel (or basket).

11.2.1.3 The flexible pipe should be securely fastened to its supporting reel, basket or crate. The end fittings usually require additional fastening by means of wire ropes, fibre slings, bands, adjustable lever hoists or clamps, as well as protection with a soft packaging material, in order to protect adjacent pipe layers and to take up any creep or subsequent motion.

11.2.1.4 Handling and lifting appliances used for flexible pipes both onshore and offshore, whether temporary or permanent, include items such as the following:

a) cranes and A-frames;

b) reels, carousels, baskets and strip-out pallets;

c) lifting frames and cradles;

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d) caterpillars/tensioners;

e) pulling heads;

f) winches;

g) load cells;

h) chutes and bend limiters;

i) spreader beams and bars;

j) Tirfor lifting machines and “come-alongs”;

k) lifting ropes, slings and webbing straps;

l) Chinese fingers;

m) control lines;

n) shackles;

o) sheaves;

p) caribina hooks;

q) lifting eyes.

All handling equipment should be treated as given in the following recommendations together with additional best offshore working practices:

— used in accordance with the rules and regulations of relevant international or national standards;

NOTE Certification requirements can apply.

— protected from damage and deterioration while not in use;

— inspected for signs of damage and deterioration prior to use;

— designed and specified for dynamic applications when intended for offshore use.

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11.2.2 Steel pipe-lay tensioners and equipment

11.2.2.1 If steel pipe-lay tensioning equipment or another type of equipment that is not specifically designed to handle flexible pipe is used for the installation of flexible pipes, it should be documented by detailed calculation that the crushing loads on the pipe do not exceed the design requirements of ISO 13628-2 and ISO 13628-10. The tensioner compression force should also be shown to be sufficient to resist the tension in the pipe.

11.2.2.2 As a principle, the calculations should be verified by trials of either the actual equipment or a shoe and loading configuration that consistently simulates the actual equipment used, and it should be verified that the relevant installation loads are simulated or validated by representative testing or use of the equipment.

11.2.3 Reels, carousels, baskets, and strip-out pallets

Support and drive frames, shoes, cradles and bobbins forming a part of an assembly should be designed and certified for offshore dynamic applications, including lifting both individually and as an assembly, if appropriate. Potential damage or collapse of pipes on reels and carousels because of excess overlying weight should be

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assessed where relevant. The drive facility should be fitted with the following facilities when used for installation reels and carousels:

a) fully controllable braking;

b) manual override for automatic tensioning devices;

c) back tensioning facility, e.g. for re-reeling.

11.2.4 Overboarding chutes — Rotating and fixed

11.2.4.1 Fixed or rotating bend limiters (such as arches and chutes) employed as installation or handling aids should be designed as recommended by the flexible-pipe manufacturer in accordance with relevant International Standards or national standards. All such equipment should be maintained in good condition. Surfaces that come into contact with the flexible pipe should not be corroded or abrasive and should be free from sharp edges. Wetting of the chute may be used in some cases to reduce the friction with the pipe.

11.2.4.2 A larger-diameter roller or conveyor, sheave or another type of equipment should be used in place of an overboarding chute when tensions or other installation parameters are such that an overboarding chute can damage any structural or component part of a flexible pipe. Alternatively, the vertical lay system can be employed. A stinger constituting a number of small rollers is generally not acceptable.

11.2.5 Chinese fingers

Chinese fingers, if used, should be selected with due consideration for the flexible-pipe materials, and acceptance for the selected design should be obtained from the flexible-pipe manufacturer. Chinese fingers should have a suitable finish to prevent pipe-cover damage when used for flexible-pipe installations.

11.3 Transportation

11.3.1 General

11.3.1.1 In 11.3, any movement of a partially or fully manufactured product that is not a normal part of the manufacturing procedure is included. The transportation facility should be selected to minimize handling and opportunity for damage. Use of craneage, if required, should be fully certified and rated in accordance with the lift requirements.

11.3.1.2 The manufacturer and purchaser should satisfy themselves of the validity of travel authorization prior to transportation. Due regard should be given to all rules and regulations imposed by relevant countries en route if transportation involves international travel.

11.3.2 Load-out

11.3.2.1 Load-out covers the period immediately prior to lifting or transferring flexible pipes on board a vessel up to and immediately after the vessel leaves the quay side. All flexible pipes should be visually inspected prior to and during load-out. Such inspection should be carried out by the manufacturer, purchaser, and installation or transport representatives, where employed. The inspection should be documented fully and signed off by the above parties.

11.3.2.2 All flexible pipes should be packed and handled in accordance with the requirements of ISO 13628-2 and ISO 13628-10, and further protected against deck activities where necessary. Such protection and packaging should remain in place during load-out. The transportation vessel should not be permitted to leave the quay-side until the purchaser has issued a load-out acceptance certificate, unless otherwise agreed by the manufacturer and purchaser.

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11.3.3 Sea fastenings

Sea fastenings should be designed for the final transported mass in a dynamic environment appropriate for the transportation vessel and the sailing route. All sea fastenings should be fully certified in accordance with the appropriate design code prior to sail-away. All designs should be approved by the purchaser prior to load-out.

11.3.4 Reeled flexible pipe

11.3.4.1 Reeled flexible pipe in this context covers flexible pipe that is on a reel, carrousel or basket. Flexible pipes should not be placed on a reel so that end fittings or other attachments induce unacceptable local loading in the pipe structure. End fittings or attachments that are not wrapped and packed should not be over-wrapped with unprotected pipe.

11.3.4.2 Masses should be accurately monitored and recorded during lifting, either with load cells certified in accordance with established practice, or crane gauges, where such gauges have been individually certified. The reel should be fixed to prevent rotation prior to lifting in a drive or support frame. The reel should clearly identify that the pipe is full of fluid and the effect of the fluid mass on the total mass, if relevant.

11.3.5 Coiled flexible pipe

Coiled flexible pipe covers all pipes loaded out and secured on deck in coiled condition, either packaged or unpackaged. The flexible pipes should be coiled so that removal of storage straps does not result in uncontrolled release. Coiled flexible pipes should be suitably sea-fastened prior to sail-away. Deck location should be such that potential hazards are minimized during over-boarding.

11.3.6 Uncoiled flexible pipe

11.3.6.1 Uncoiled flexible pipe covers all flexible pipes secured on deck, but neither reeled nor coiled. The flexible pipes should be provided with suitable protection from dragging over dockside surfaces.

11.3.6.2 The flexible pipes should be located on deck within reach of the deck crane or lifting facility, so that dragging across the deck and lifting around objects during subsequent installation is minimized. The flexible pipes should be suitably sea-fastened and provided with protection from normal deck activities prior to sail-away.

11.4 Installation

11.4.1 Installation analysis

11.4.1.1 The installation analysis should take into account contingency scenarios. Dynamic installation analyses should be used to define the maximum sea-state and current profile suitable for deck and installation activities on the particular vessel. The loads applied in the analyses should be for the maximum defined sea-state for the planned activities.

11.4.1.2 The installation load cases should check that minimum and maximum tensioner loads do not violate the pipe design criteria if tensioners are used. The maximum load (with pipe hang-off tension) should be checked for potential collapse of the pipe, while the minimum tensioner load, F_{min}, required to hold the pipe should be greater than the force required to prevent the pipe slipping, defined as given in Equation (9):

$$F_{min} = \text{maximum}\left(\frac{\gamma_{max}}{\mu_1}, \frac{\gamma_{max}}{\mu_2}\right) \quad (9)$$

where

γ_{max} is the maximum tension in the pipe;

μ_1 is the friction coefficient between pipe outer sheath and tensioner pads;

μ_2 is the friction coefficient between pipe outer sheath and underlying armour layer.

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11.4.2 Monitoring

The subsea activities should be constantly monitored using diver- and/or ROV-mounted cameras as approved by the client and installation contractor. The monitor recordings should be stored for review of subsea activities after installation has finished. The recordings should identify all visible markings, confirm lay patterns and configurations, and status of bolted flanges, connectors, bend restrictors, bend stiffeners and buoyancy modules. All recordings should be stored with a log and uniquely marked for storage and retrieval.

11.4.3 Installation of reeled flexible pipes

Deployment reels should be placed directly in line with overboard chutes whenever possible. The use of rollers, single-point attachments or sheaves should not induce unacceptable loads on the flexible-pipe structure. Pipe deflection units may be used provided the MBR criterion is met. Single-point contacts should be minimized. Detailed calculations should be carried out to ensure that no unacceptable loads are induced at any contact point.

11.4.4 Installation of carouselled flexible pipes

The recommendations in 11.4.3 also apply to flexible pipes on carousels.

11.4.5 Installation of coiled flexible pipes

Storage straps should be replaced by temporary deployment rigging prior to deployment of coils overboard unless the storage straps can be used for installation. The flexible pipe should be coiled on a rotating pallet and the strip-out rigging should have a suitable swivel, when possible. The crane should slowly raise the pipe to a vertical position, allowing it to release any inherent twist through the swivel. Divers should not use sharp tools for removal of temporary-deployment rigging.

11.4.6 Installation of uncoiled flexible pipes

Uncoiled flexible pipes should be lifted overboard with a crane using a multiple-point lift. Care should be taken to ensure that no damage is caused to the flexible pipe or end fittings if overboarding chutes and winches are used. The pipe can also be laid out straight on the deck and picked up by one end. The installation procedures should ensure that the MBR criteria are not exceeded in this case.

11.4.7 Deployment and tie-in

11.4.7.1 Loads and deformations during deployment should be within allowable limits. Bend radii should be monitored during installation or the installation method and laying parameters defined to ensure the MBR criteria are not exceeded, for example, by monitoring the seabed touchdown point with an ROV and using a transponder to maintain a minimum layback distance, thereby ensuring the configuration does not exceed the MBR criteria. Pull-in wires (or weak links if used) should be such that they break before damage is sustained to the flexible pipe as a result of excessive tension, if feasible. Flexible pipes should not be over-tensioned during deployment through a steel pipe or J-tube, while accounting for the maximum friction force from the pull-in. Back-tension is required during these operations.

11.4.7.2 The tie-in sequence should be arranged such that minimal inhibited fluid is lost after blind flanges are removed, unless flooding with inhibited water is carried out immediately after tie-in. In general, flexible pipes should not be laid around obstacles such that natural movement is restricted. This can be acceptable, however, if the procedures, equipment and flexible pipe are designed for the application. The use of scour mats should be considered in preference to physical restriction if scour is considered a problem.

11.4.7.3 It is recommended that flowlines be connected to their termination points (wellhead, manifold) at right angles to the main lay direction. This allows excess lengths and expansions of the line to be absorbed in the final loop at the connection point. This final loop may also be used if there is an underestimation of the flowline length.

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11.4.8 Trenching and burial

A pipe-tracking facility should be incorporated to facilitate route confirmation at a later date if an installed flexible pipe is expected to become buried in soft seabed conditions. Suitable sand-bagging or some such method should be provided to support a flexible pipe over sharp edges or corners in the event that the MBR criteria might be violated or if the outer sheath cover might be damaged if the pipe enters a trench in hard seabed conditions or passes over a boulder within the trench.

11.4.9 Vessel and equipment

11.4.9.1 The vessel and equipment should be in good condition and working order and be checked prior to vessel mobilization. All measurement equipment, particularly for measuring load, should be calibrated. All lifting equipment should have suitable certification.

11.4.9.2 The installation procedures and control systems should be sufficient to ensure control of the tension in the pipe if pipe tension is to be distributed among tensioners, reel drives and carousel drives.

11.4.9.3 Typically, the vessel spread should include the following equipment for monitoring the flexible pipe during installation:

a) ROV for configuration;

b) tension-measuring equipment for maximum top tension;

c) departure-angle-measuring equipment;

d) compression-load measurement for caterpillar tensioners.

11.4.10 Installation procedures

11.4.10.1 General

11.4.10.1.1 The installation procedure employed for each flexible pipe is dependent on the system configuration and the particularities of the system components. A horizontal installation using an overboarding chute is shown schematically in Figure 30. Vertical installation can also be used, as shown schematically in Figure 31.

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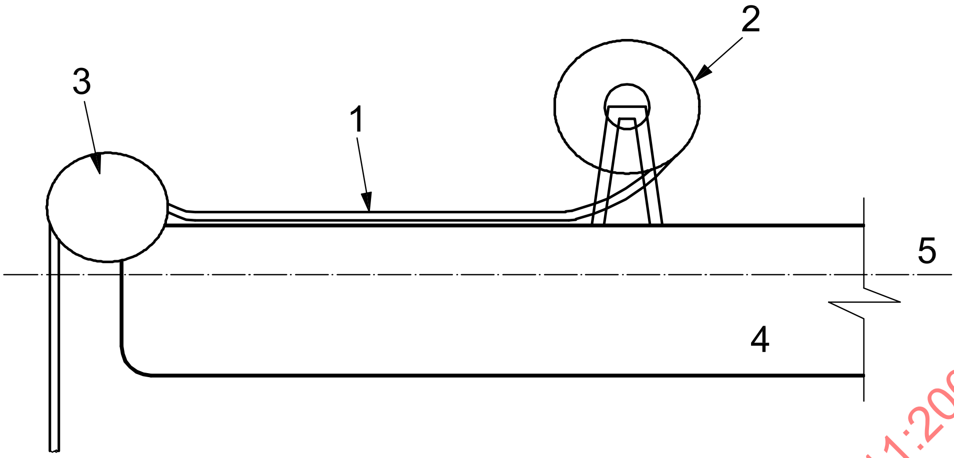
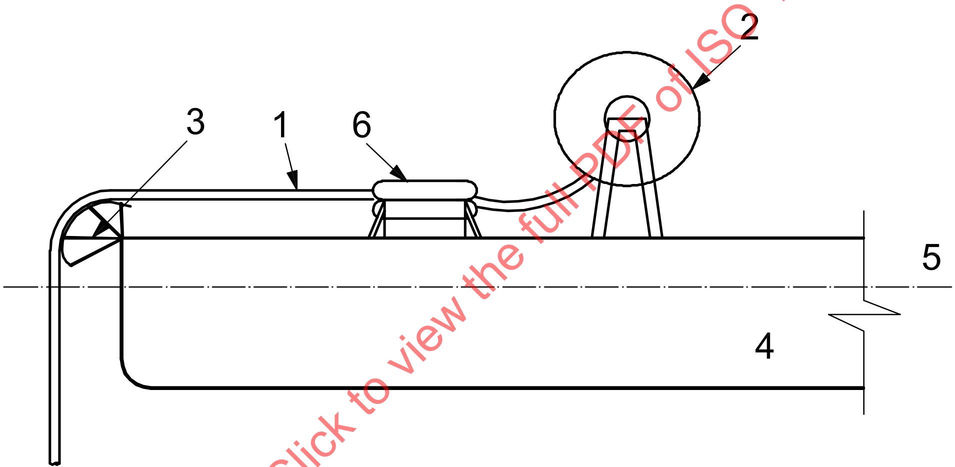


a) **Low tension** [a] ($\gamma < 20$ kN)



b) **High tension** [b] ($\gamma > 20$ kN)

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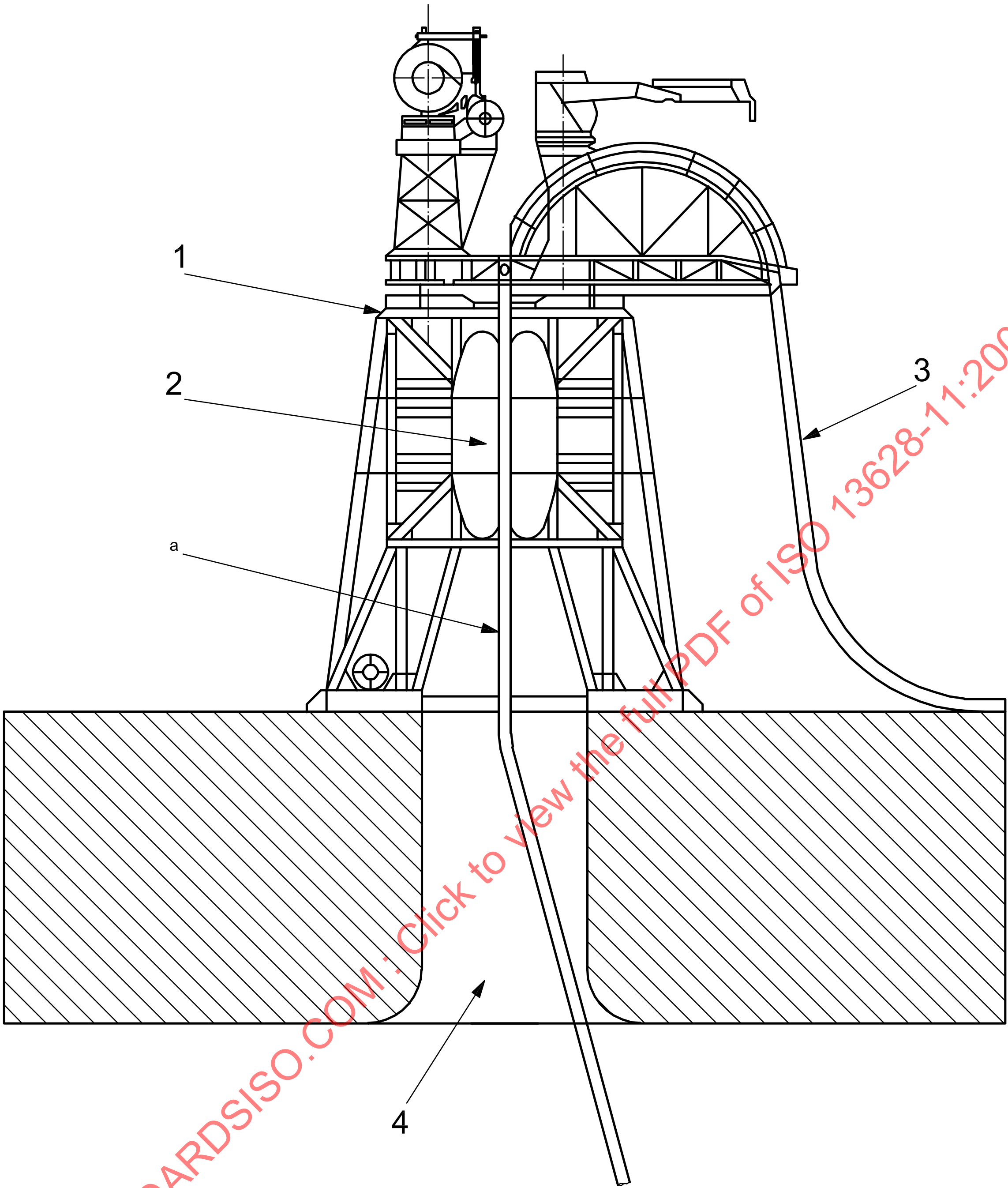
Key

1 flexible pipe
2 installation reel
3 laying chute
4 installation vessel
5 MWL
6 tensioners

a For low-tension systems, holdback tension is provided by the installation reel or a winch.
b For high-tension systems, the pipe is kept slack behind the tensioners.

Figure 30 — Schematic of horizontal lay installation



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Key

1 installation derrick
2 caterpillar tensioners
3 flexible pipe
4 vessel moonpool

[a] Buoyancy modules, anodes etc. fitted at this point.

Figure 31 — Schematic of vertical lay installation

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11.4.10.1.2 The flexible pipes can be installed either flooded, free-flooding or empty. The manufacturer and installation contractor should determine the installation conditions. Some pipes can require flooded or free-flooding installation to prevent collapse of the pipe or to ensure the stability of the installed line. The suitability of the carcass material (for rough-bore structures) should be confirmed with the manufacturer in this case.

11.4.10.1.3 In selecting the installation strategy, it is necessary to address the issues that can influence the schedule and risks, include the following:

a) pre-installation of risers prior to hook-up;

b) number and size of ancillary components, including buoyancy, to be installed;

c) types of base, if any, to be used and anchoring system (gravity, pile or suction);

d) tension in line;

e) tie-in systems, such as riser/flowline connections;

f) maximum environmental conditions (installation window);

g) interfaces with installation of other systems, such as mooring lines;

h) diver-assisted or diverless operations;

i) installation-vessel requirements, including number, size and mobilization or demobilization costs;

j) trenching or protection requirements;

k) installation of bundles or multiple lines;

l) subsea versus topside operations;

m) identification of components or equipment installed onshore to minimize offshore operations;

n) ROV operations;

o) allowable installation tolerances.

11.4.10.2 Flowlines

Figure 32 shows a typical installation procedure for a flexible flowline. The flowline is attached to a pile or clump weight in the vicinity of the start flowline base and is laid out along the seabed towards the end flowline base. The final portion of the flowline is laid out in an overlength shape. Inflatable buoyancy units may then be attached to the flowline ends, which are then winched into the flowline bases for connection. Figure 33 illustrates an example installation of a flexible flowline through a J-tube. For a J-tube pull-in, a pre-installed sealing plug can be used to seal the J-tube at the lower bellmouth to prevent loss of corrosion inhibitors.

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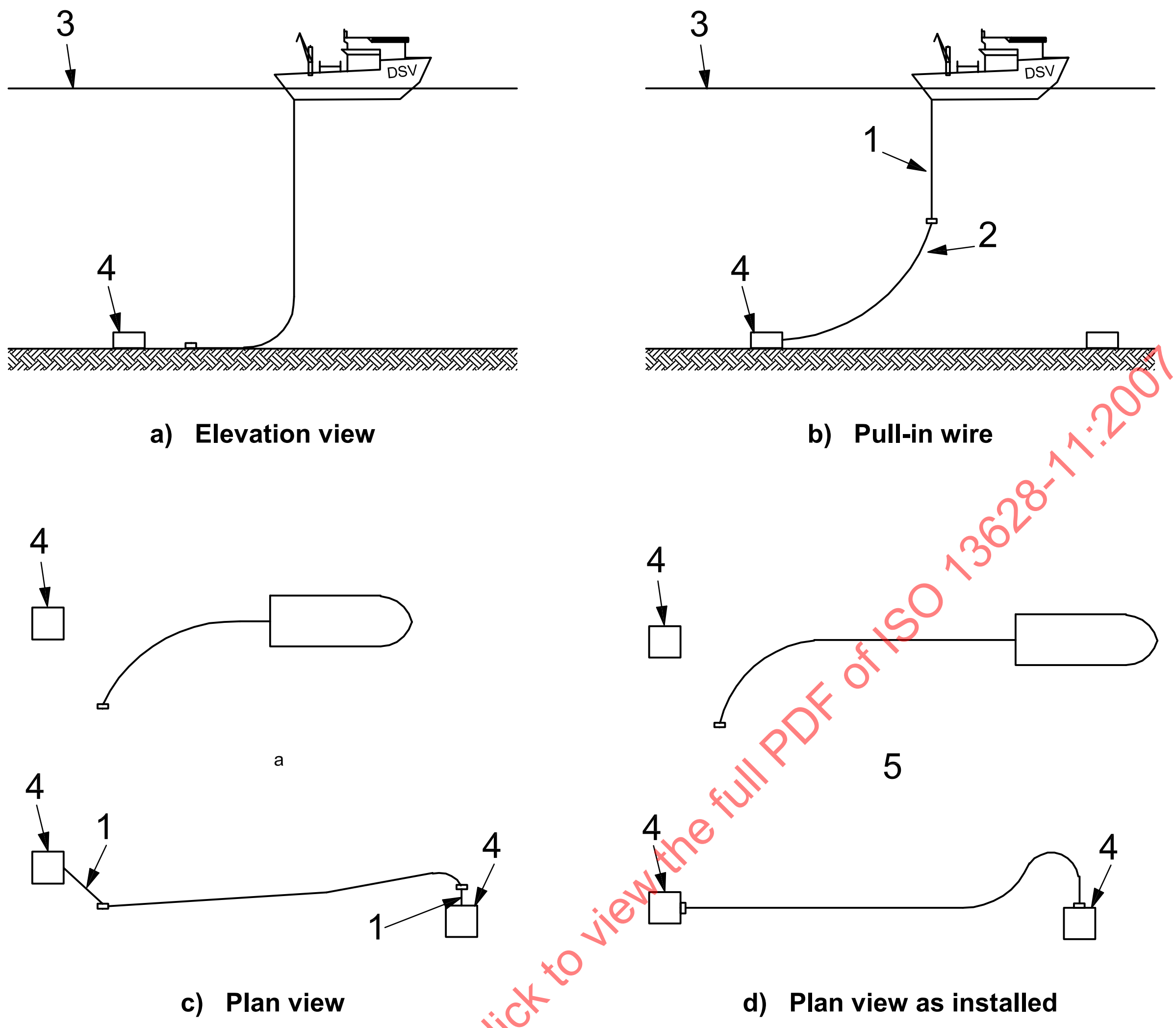

Key

1 pull-in wire
2 flexible pipe
3 MWL
4 flowline base
5 layout pipe

[a] Overboard first flange to seabed.

Figure 32 — Typical flowline installation procedure

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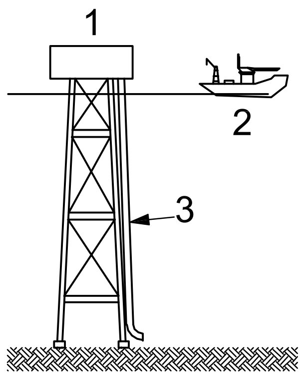
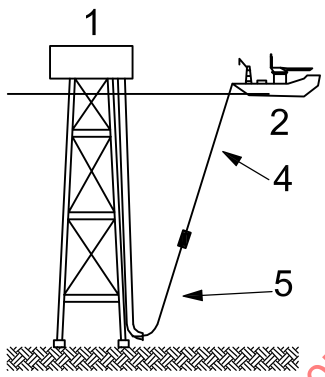
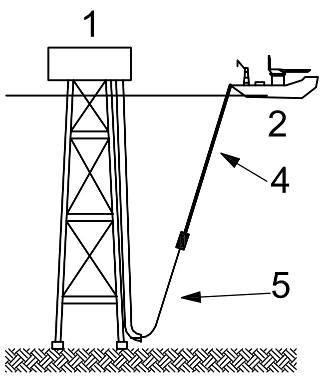


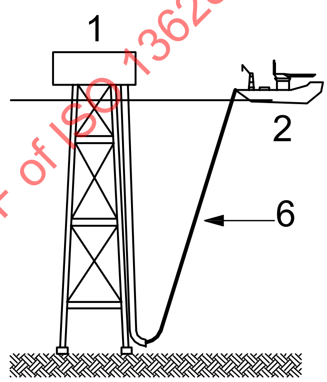
a) The installation vessel moves up to the platform



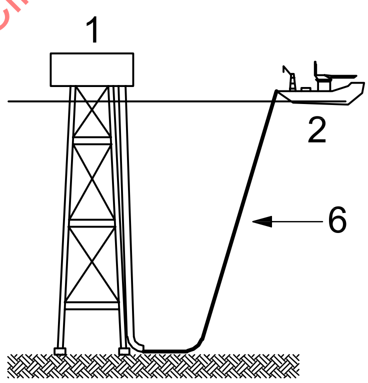
b) The pre-installed messenger line, followed by a pull-in wire, is transferred to the vessel from the platform



c) The pull-in wire is attached to the end of the flexible pipe and the pull-in operation begins



d) When the end of the flexible pipe reaches the top of the J-tube, the end fittings are attached to a hang-off structure



e) The installation of the flexible pipe is then continued in a lay-away operation

Key

1 platform

2 installation vessel

3 J-tube

4 messenger line

5 pull-in wire

6 flexible pipe

Figure 33 — Schematic of J-tube pull-in operation

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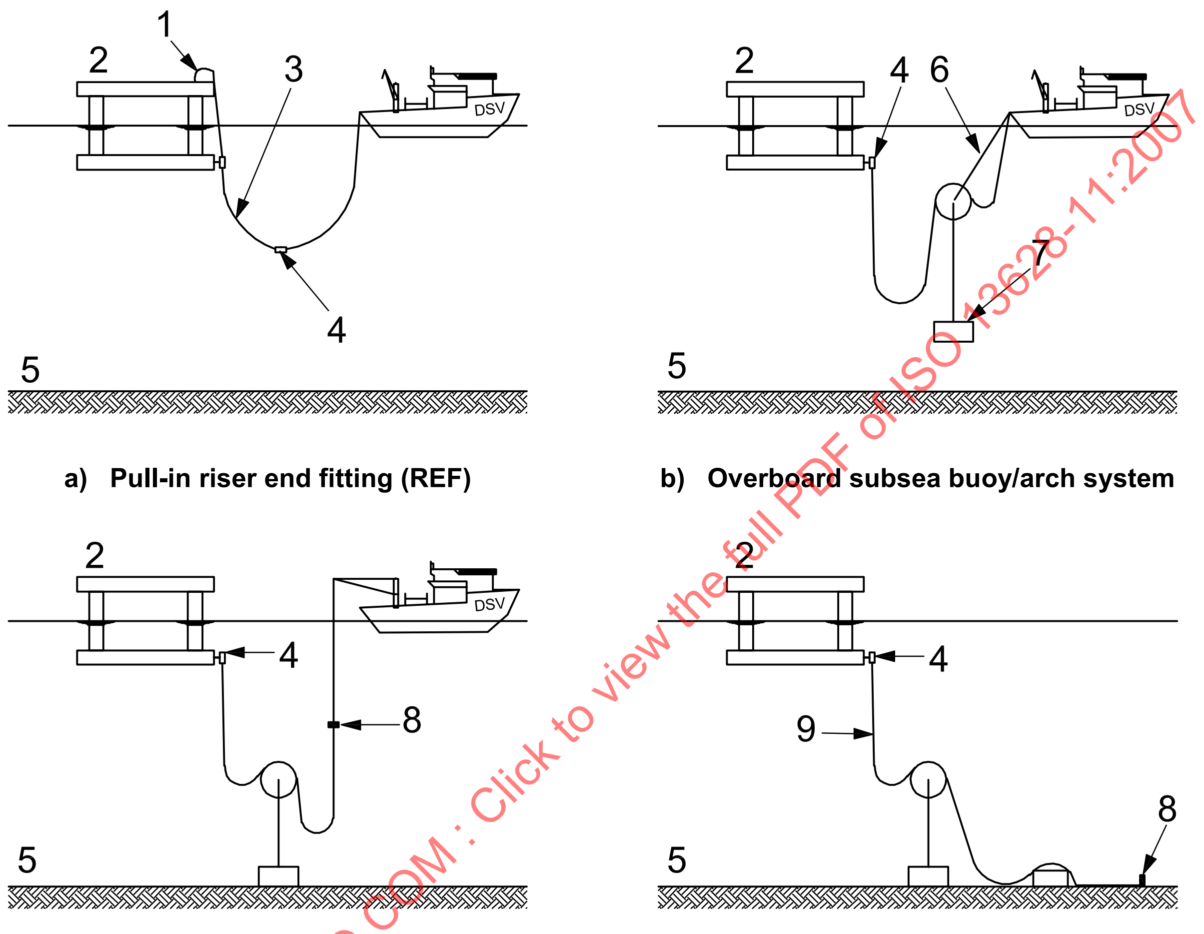
11.4.10.3 Riser configurations

Figures 34 to 38 illustrate typical lay systems and installation procedures for flexible riser configurations for lazy-S, steep-S, lazy wave, steep wave and free-hanging catenary configurations. These figures show the flexible pipe being installed with the first end connected to the vessel. This method does not necessarily suit all applications and can be reversed. The vessel is represented schematically as a semi-submersible but this is of no consequence with regard to the actual installation.



a) Pull-in riser end fitting (REF)

b) Overboard subsea buoy/arch system

c) Overboard riser lower-end flange

d) System as-installed

Key

1 pull-in winch
2 FPS
3 pull-in wire
4 riser end fitting (REF)
5 seabed
6 layout wire
7 clump weight
8 riser flange
9 flexible riser

NOTE 1 The above procedure is based on connecting to the FPS firstly and then laying away from the FPS. The procedure can also be reversed.

NOTE 2 The horizontal lay procedure can be replaced with a vertical lay procedure.

NOTE 3 Many installers prefer to handle flexibles, buoys and clump weights separately.

Figure 34 — Typical lazy-S riser installation procedure

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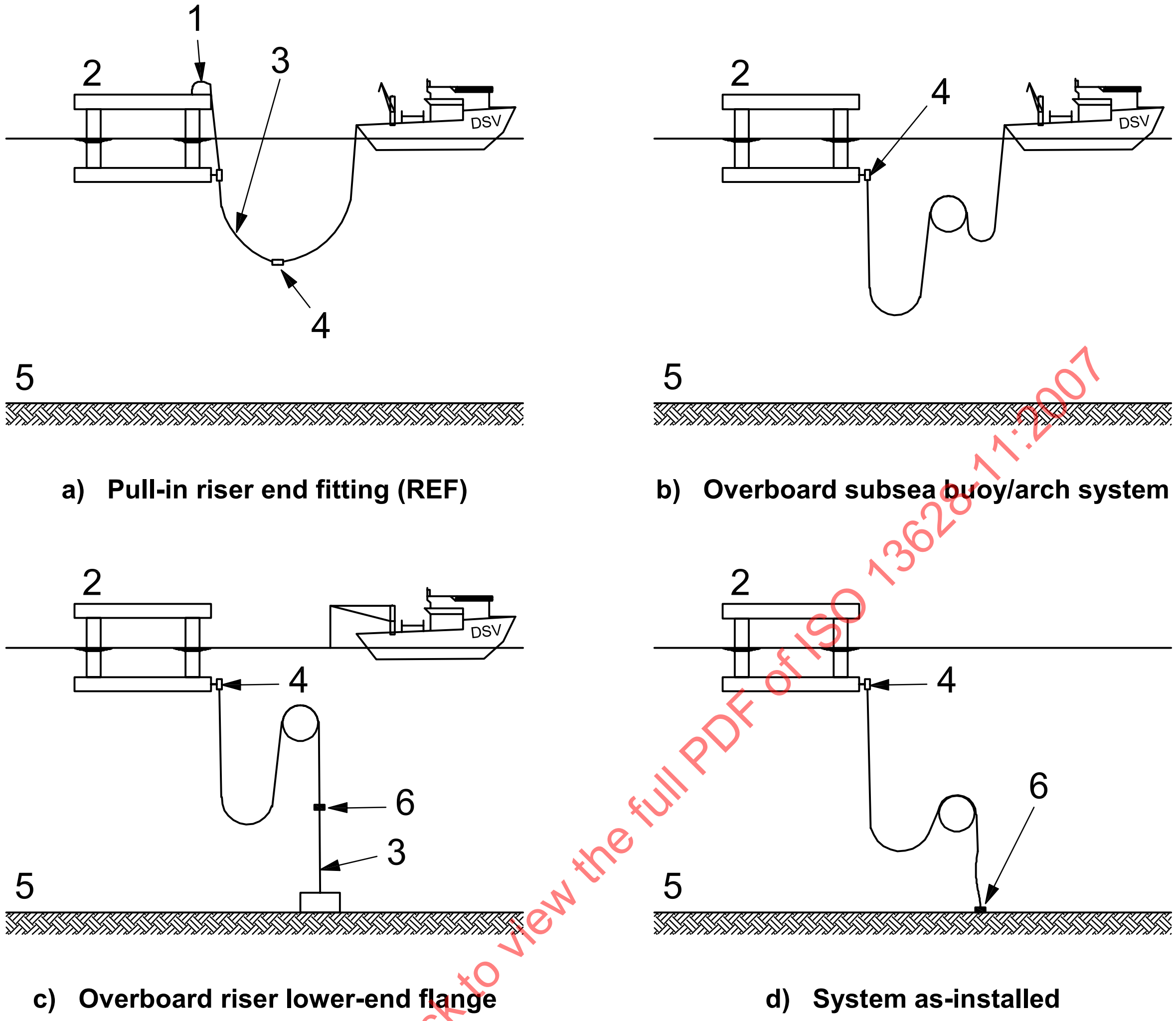

Key

1 pull-in winch
2 FPS
3 pull-in wire
4 REF
5 seabed
6 riser flange

NOTE 1 This procedure is based on connecting to the FPS first, then laying away from the FPS. The procedure can be reversed.

NOTE 2 The horizontal lay procedure can be replaced with a vertical lay procedure.

NOTE 3 Many installers prefer to handle flexibles, buoys, and clump weights separately.

Figure 35 — Typical steep-S riser installation procedure

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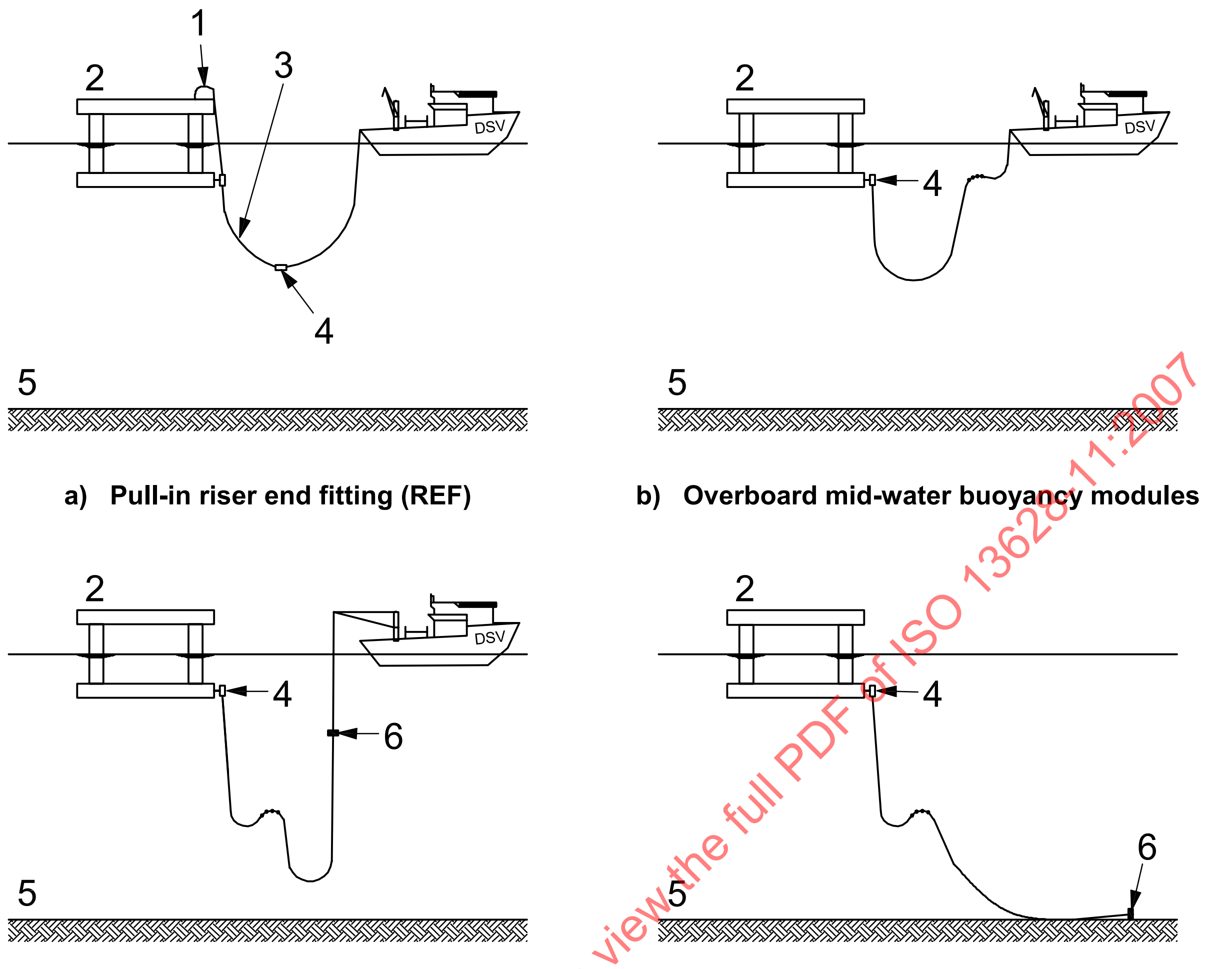

a) **Pull-in riser end fitting (REF)**

b) **Overboard mid-water buoyancy modules**

c) **Overboard riser lower-end flange**

d) **System as-installed**

Key

1 pull-in winch
2 FPS
3 pull-in wire
4 REF
5 seabed
6 riser flange

NOTE 1 This procedure is based on connecting to the FPS first, then laying away from the FPS. The procedure can be reversed.

NOTE 2 The horizontal lay procedure can be replaced with a vertical lay procedure.

Figure 36 — Typical lazy-wave riser installation procedure

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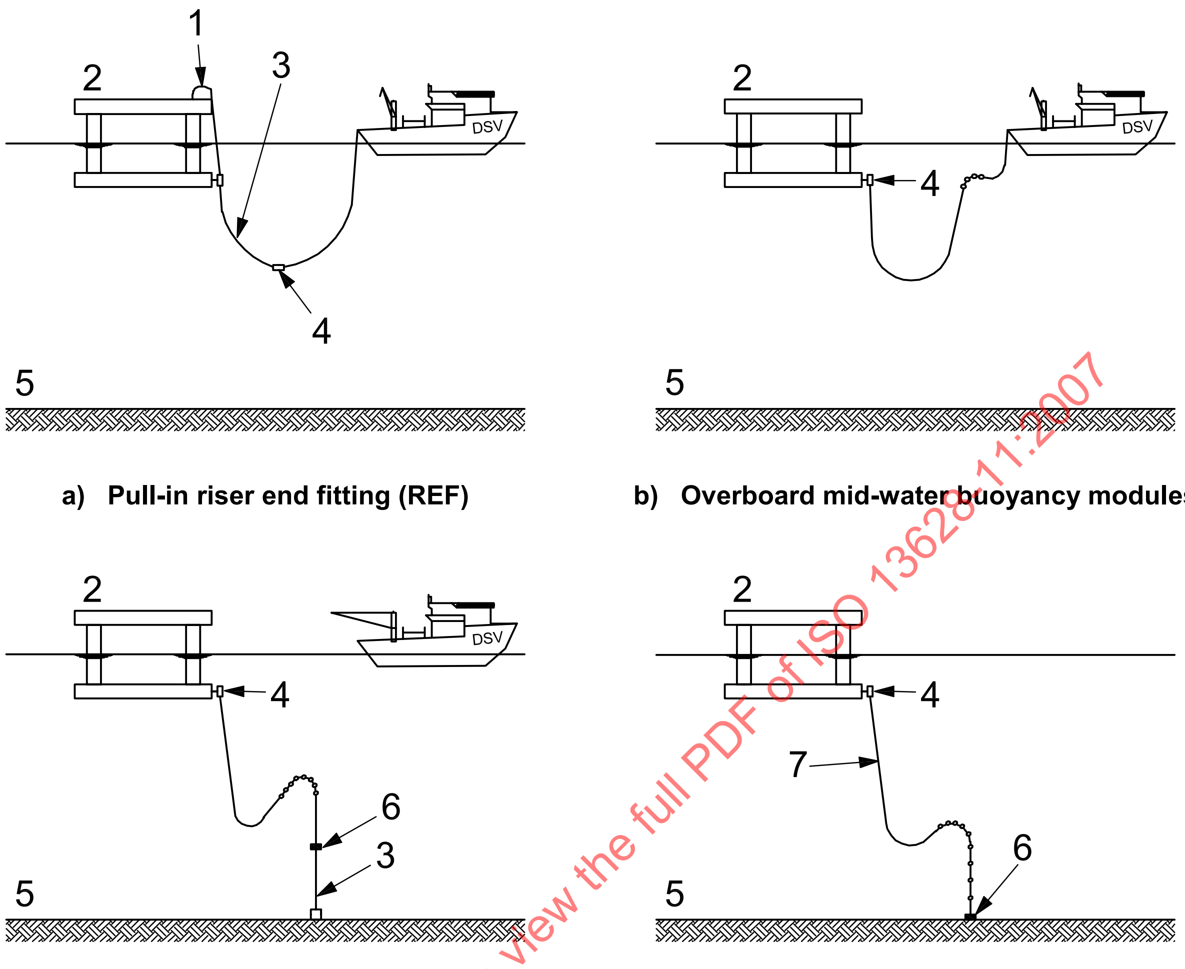

a) **Pull-in riser end fitting (REF)**

b) **Overboard mid-water buoyancy modules**

c) **Overboard riser lower-end flange**

d) **System as-installed**

Key

1 pull-in winch
2 FPS
3 pull-in wire
4 REF
5 seabed
6 riser flange
7 flexible riser

NOTE 1 This procedure is based on connecting to the FPS first, then laying away from the FPS. The procedure can be reversed.

NOTE 2 The horizontal lay procedure can be replaced with a vertical lay procedure.

Figure 37 — Typical steep-wave riser installation procedure

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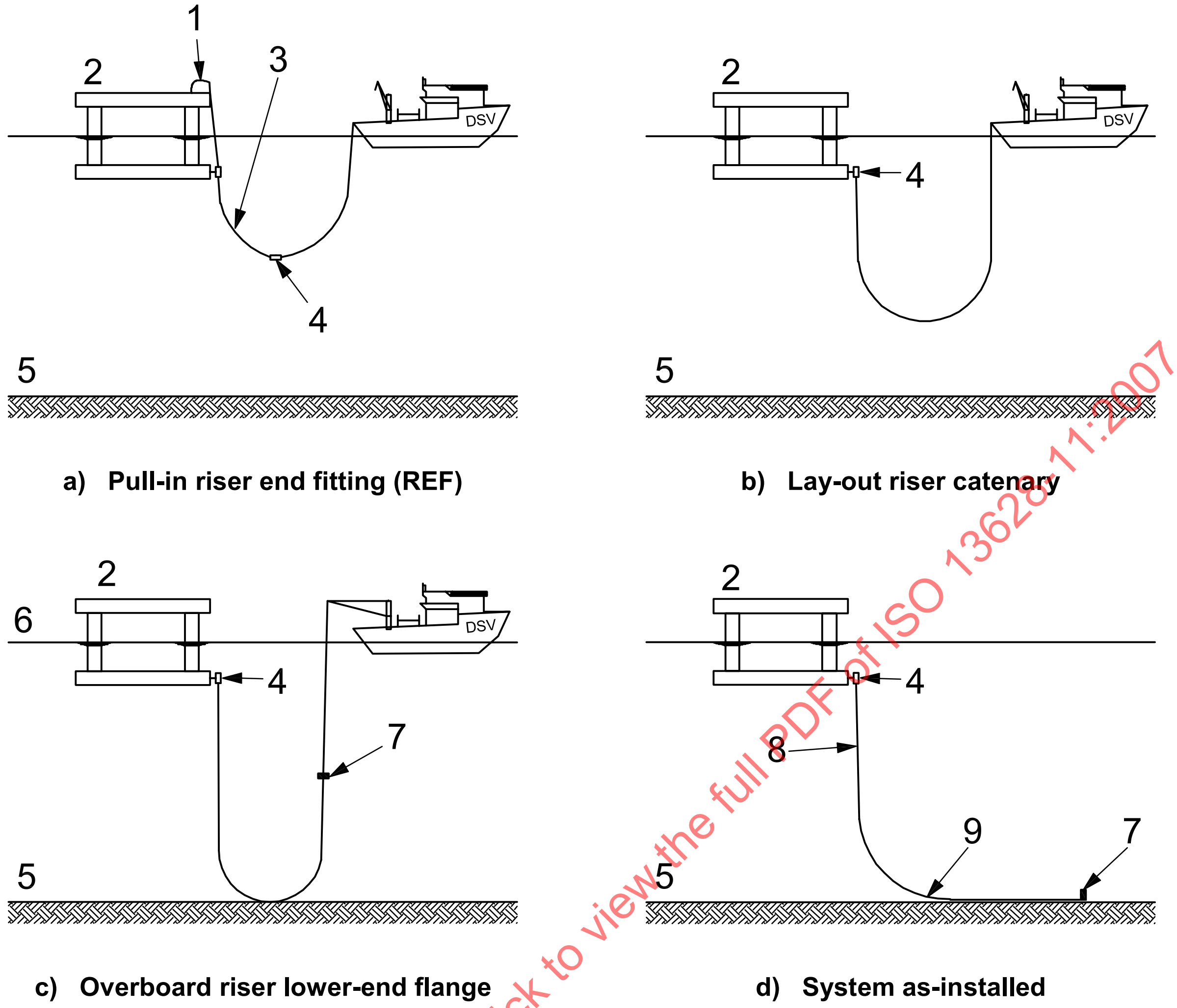

Key

1 pull-in winch
2 FPS
3 pull-in wire
4 REF
5 seabed
6 MSL
7 riser flange
8 flexible riser
9 touchdown point

NOTE 1 This procedure is based on connecting to the FPS first, then laying away from the FPS. The procedure can be reversed.

NOTE 2 The horizontal lay procedure can be replaced with a vertical lay procedure.

Figure 38 — Typical free-hanging catenary installation procedure

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11.4.11 Diverless and diver-assisted installation

The selection of diver-assisted or diverless installation depends on a number of factors, including the following:

a) safety aspects;

b) water depth;

c) regulatory requirements or guidelines;

d) available space for tie-in operations (if a large number of risers are to be connected to a turret, there can be insufficient space for divers);

e) economic factors (diverless tie-in equipment can have significant costs);

f) environmental conditions;

g) equipment reliability (technical risks);

h) schedule requirements (for example, diverless operations can be much quicker).

11.5 Pre-commissioning and commissioning

11.5.1 Introduction

11.5.1.1 This process involves the testing and monitoring of flexible pipes after tie-in and completion of the full system, of which the flexible riser and/or flexible flowlines are an integral part. Damage should be repaired and the commissioning should be restarted if the flexible pipe incurs damage during the commissioning period. The pipe manufacturer and the purchaser should decide, through consultation, if the pipe is repairable.

11.5.1.2 The purchaser should provide the test specification. The manufacturer's recommendations on testing should be taken into account and the testing should be carried out prior to any backfilling.

11.5.2 Pigging

11.5.2.1 The guidelines in 11.5.1.2 should be implemented if commissioning requires pigging of the flexible pipe. Metallic brushes should not be used in flexible pipes without a metallic carcass layer. Metallic brushes may be used if the internal liner comprises a steel carcass, provided the materials are compatible and the brush does not damage the carcass. Metallic scrapers should not be used.

11.5.2.2 Gauges may be used, provided the discs are designed such that any obstruction protruding within the gauged diameter are indicated by a permanent deformation. The gauge plate should be approved by the flexible pipe manufacturer (see ISO 13628-2 and ISO 13628-10).

11.5.2.3 Articulated pigs should only be used if the natural mass of the pipe or installed, imposed bend radius is sufficiently large to accommodate the segment lengths in the pig assembly. Foam pigs should be used for pipes without a metallic carcass layer if possible, but other types of pig may be used, subject to acceptance by the flexible-pipe manufacturer.

11.5.3 Hydrostatic pressure test

11.5.3.1 General

11.5.3.1.1 The hydrostatic test may be performed separately on the flexible pipe or as a system test if the flexible pipe is part of the total system. The pipe system may include manifolds, trees, valve assemblies, couplings, seals, etc. All components in the system should be verified as being capable of withstanding the maximum test pressure. The installation test procedure should be as given in ISO 13628-2 and ISO 13628-10 (hydrostatic pressure test), where relevant.

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11.5.3.1.2 The hydrostatic test should take into account the following recommendations.

a) Only a leak test (with a pressure recommended at 1,1 times the design pressure) is necessary if the flexible pipe is installed without the occurrence of any suspected damage, because a structural-integrity test will have already been performed.

b) A structural-integrity test (with a pressure recommended at 1,25 times the design pressure) can be required if the pipe has been damaged, repaired, end fittings replaced, retrieved and re-installed without a FAT hydrotest, or other such occurrence that can be considered relevant.

c) The hold period for the test should be 24 h, unless otherwise recommended (see 11.5.3.5).

d) Regulatory-authority requirements can exceed the recommended test pressures in a) and b) and should be checked with the relevant authorities.

e) The flexible-pipe design should be checked against allowable criteria for the pressure-test load case, including loads from maximum test pressure (which are between 1,04 and 1,1 times nominal as specified in 11.5.3.3), functional loads (including mass and buoyancy of pipe, contents and attachments), relevant environmental loads and any appropriate accidental loads.

11.5.3.1.3 The hydrostatic test procedure should identify the following, as and where applicable:

a) pre-test pigging requirements;

b) fill-medium details;

c) pressurization and depressurization rates;

d) stabilization criteria;

e) pressure-isolation details;

f) entrapped-air assessment;

g) permissible unidentifiable pressure loss;

h) pressure-variation calculation method;

i) visual-inspection details;

j) data-recording details;

k) inspection requirements;

l) acceptance criteria.

11.5.3.1.4 All annulus vents in unbonded pipes should be opened in end fittings that are not immersed in seawater during the test. The hydrostatic pressure test comprises the following main tasks:

a) test of instrumentation and connections;

b) pressurization of the line;

c) stabilization period;

d) hold period;

e) depressurization.

11.5.3.1.5 Recommendations for these tasks and acceptance criteria, measuring equipment and test records are given in 11.5.3.2 to 11.5.3.9.

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11.5.3.2 Test of instrumentation and connections

A pressure test should be performed on the test equipment and connections at a pressure not less than 104 % of the nominal test pressure of the flexible pipe. The duration of this test is 0,5 h.

11.5.3.3 Pressurization

Pressurization of the pipe should be carried out at a steady and controlled rate specified by the manufacturer. Too high a rate can lead to excess stabilization periods. A typical maximum rate is 18 MPa/h (180 bar/h). The pressure should be raised to a value no greater than 110 % of the nominal test pressure.

NOTE Different manufacturers specify factors between 104 % and 110 % of the nominal test pressure; any factor within this range is suitable, so long as it is documented and used consistently throughout design and test activities.

The air content should not exceed 0,5 % for smooth-bore pipes and 1,0 % for rough-bore pipes. Venting at the pipe ends should be performed and pressurization recommenced if the air content exceeds the above values.

11.5.3.4 Stabilization

The stabilization period should last for 10 h after the end of pressurization. This stabilization period may be extended if significant pressure drops are still occurring after the first 10 h, because of the stabilization process or thermal stabilization in the flexible pipe. The period may also be reduced if the line is stabilized. Stabilization is defined as a pressure change over 1 h of less than 1 % of the test pressure. During stabilization, the pressure curve should be recorded, and a log of pressure and subsea and test fluid temperatures should be maintained (every 0,5 h for pressure readings and every 2 h for temperature readings).

11.5.3.5 Hold period

11.5.3.5.1 The 24 h hold period may start when the stabilization period is completed. A log of pressure and subsea and test fluid temperature readings should be taken at 0,5 h intervals during the hold period. The pressure shall be greater than or equal to the nominal test pressure for the hold period. There shall be no unaccountable pressure drop during the test. The maximum pressure drop during the hold period should not exceed 4 % of the nominal test pressure.

11.5.3.5.2 The hold period for a leak test may be reduced to 6 h if all of the flexible pipe, including both end fittings, can be visually inspected for leakage during the test.

11.5.3.5.3 The line should be repressurized if the pressure falls below the test pressure once the test has commenced. In such a case, the hold period is considered as recommencing from this point.

11.5.3.6 Depressurization

The depressurization of the pipe should be performed at a steady and controlled rate. The maximum depressurization rate should be defined by the manufacturer. Pipe failure can be caused by depressurization at too high a rate. A typical maximum rate is 108 MPa/h (1 080 bar/h).

11.5.3.7 Qualitative acceptance criteria

11.5.3.7.1 The following acceptance criteria are recommended as a minimum.

a) The test pressure is maintained for the period specified in 11.5.3.5.

b) The test pipe does not undergo unintended or major changes in shape or configuration under pressure.

c) The pipe does not leak.

11.5.3.7.2 Leaks through all components in the pipe system should be evaluated if the pressure loss is such that a leak is suspected, because the leak can be from valves, seals, etc., rather than from the pipe itself.

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11.5.3.8 Measurement equipment

Measurement equipment used for pressure testing should be calibrated at least every 6 months. Equipment should be maintained in good order and used only for the purpose for which each item has been designed and intended. Equipment used should be listed with all relevant details in the test documentation and should be calibrated to within the following levels of accuracy:

a) hydrostatic pressure gauges: 0,0 % to 0,5 %;

b) dead-weight testers: 0,0 % to 0,1 %;

c) pressure-chart recorders: ± 0,5 %;

d) all other measurement equipment: ± 1,0 %.

11.5.3.9 Test records

11.5.3.9.1 It is recommended that the following test records be maintained:

a) date and time;

b) location, condition and situation details;

c) test and safety personnel;

d) fill-medium details;

e) all equipment and certification details;

f) pressure recorder charts showing continuous recordings;

g) periodic pressure readings, every 30 min as a minimum;

h) periodic ambient temperature readings, every 30 min as a minimum;

i) periodic fill-medium temperature readings, every 30 min as a minimum;

j) visual observations.

11.5.3.9.2 The test records should be signed by the appropriate personnel and filed for reference.

11.5.3.9.3 A post-commissioning survey should be carried out and recorded on video tape to verify that the flexible pipe system is installed as designed.

11.5.4 Drying of pipe

11.5.4.1 There can be stringent requirements on the amount of water that can be left in a flexible pipe after the hydrostatic pressure test in some cases. An example of this is gas-export flexible risers tied in to major export lines, which have stringent requirements on the dryness of the gas. A rough-bore pipe is required for the riser. With this construction, the interlocking carcass layer forms a large trap for water, which, subsequent to a hydrotest, might violate the gas-dryness requirements. Vacuum drying of the flexible riser is potentially a very costly and time-consuming operation on the critical path of a project.

11.5.4.2 A special valve skid can be developed for the seabed end to allow dry installation and tie-in. In addition, the factory hydrotest of the riser can be performed with glycol instead of water, and the riser pressurized with nitrogen during transportation and installation to ensure dryness.

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12 Retrieval and reuse

12.1 General

12.1.1 Clause 12 addresses the retrieval of flexible pipe and reuse at an alternative location. Recommendations are provided for the inspection and test requirements for the pipe prior to reuse. Note that the retrieval recommendations for pipe that is intended to be reused also apply to pipe that is intended to be retrieved and scrapped.

12.1.2 Consideration should also be given to the recommendations in 12.2 for a pipe that is intended to be retrieved for repair purposes and re-installed after repair.

12.2 Retrieval

12.2.1 General — Bonded and unbonded pipe

12.2.1.1 A flexible pipe can be retrieved because of the cessation of its usefulness at a particular location or because of damage to the pipe. The retrieval operation is essentially the reverse of installation. A pre-survey to assess the condition of the pipe should be carried out to highlight any potential problems, such as the following:

a) pipe burial: jetting can be necessary to unbury the pipe to avoid kinking the pipe during recovery;

b) pipe crossings and adjacent lines: to ensure these are not damaged by retrieval operations;

c) hard marine growth: can cut through the outer sheath as the pipe comes in contact with layover arches, bending shoes, tensioners, etc.

12.2.1.2 A procedure for pipe retrieval should be prepared to preserve the pipe integrity during the operation. The same conditions considered in the global and local analysis of the original installation should be used for the pipe retrieval operation (such as pipe flooded or empty, restrictions because of environmental conditions, equipment-imposed loads and configurations considered), as applicable.

12.2.1.3 Local environmental laws and regulations should also be considered. Special care regarding pipe-fluid spillages should be taken to avoid pollution. The potential for hazardous elements in the pipe, such as radioactive materials, mercuric compounds, etc., should be evaluated and appropriate safety procedures and equipment specified. Pipe flushing with inhibited seawater and cleaning can be necessary prior to disconnection and retrieval.

12.2.1.4 Risks involving personnel should be a subject of special review. A hazard identification and operability-type study should be performed for all operations. Paraffin plugging is a major safety and environmental hazard. Pipe recovery is possibly not safe if the occurrence of paraffin plugging is a possibility.

12.2.1.5 Procedures for pipe retrieval should foresee how the pipe will be identified. Proper visual identification (through ROV, for example) should be used for this purpose. Buried pipe requires special procedures to avoid possible damage to the pipe or other subsea equipment from trawler equipment used for unburying the pipe.

12.2.1.6 All limitations of the pipe during installation and handling (such as MBR, maximum allowable torsion, maximum crushing load and tension and winding/unwinding and storage recommendations) should be respected during the retrieval procedure to avoid damage or failure of the pipe. Consideration should be given to the pipe's aged condition (reduced structural capacity) when specifying retrieval criteria.

12.2.1.7 The tensions experienced by the pipe are greater during retrieval than installation because of friction on the overboarding chute. Voiding the pipe can be necessary prior to retrieval, depending on the tension and riser configuration.

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12.2.1.8 The recovery operation may be simulated using suitable software. The simulation should take into account relevant factors (such as sea-state, current profile, vessel motions) and possible restrictions to recovery, including burial material (soil, clay or rocks), protection mats and structures.

12.2.1.9 Loads, deformations and abrasions of the pipe should be monitored at all times during pipe retrieval. The pipe should be inspected during recovery. Any damage should be identified clearly on the pipe outer sheath by means of suitable markings. The manufacturer should be consulted for cleaning and storage procedures.

12.2.2 Unbonded pipe

12.2.2.1 The potential for corrosive or toxic fluids in the pipe annulus should be evaluated. Any vent ports or valves containing such fluids in the end fittings should be immediately plugged on retrieval of the pipe until these fluids can be safely discharged. One possibility for discharging the fluids is to pump air or nitrogen into one end fitting and allow release at the other end fitting.

12.2.2.2 Special care should be taken during retrieval to avoid bursting the outer sheath because of excess differential pressure between the annulus and exterior of the pipe. Excess differential pressure can also cause loosening of the outer sheath and can result in problems (including damage to the sheath) if the pipe is retrieved using tensioners or if Chinese fingers are used (compression created might not be sufficient to take tension load through friction). The retrieval rate should be controlled to allow such excess pressure to be bled off at the end fitting vent valve during retrieval. The pressure-release system should be controlled to ensure the safety of personnel if the annulus contains toxic fluids.

12.2.2.3 The allowable retrieval rate should be calculated based on the condition of the gas-relief system. Gas-relief valves that have not been operational for a substantial period can become stuck because of scale deposition, marine growth, corrosion, etc. Clogged valves should be freed prior to recovery of the pipe, if feasible. Consideration can be given to drilling burst discs in the outer sheath prior to recovery to safeguard the integrity of the outer sheath.

12.2.3 Bonded pipe

12.2.3.1 For float/sink-type bonded pipes that float when empty (full of air), the pipeline should be retrieved by floating it to the surface and then heaving it onto a reel from the surface of the water. The manufacturer should be consulted for de-watering and pigging procedures and limitations.

12.2.3.2 Care should be taken during reeling of bonded pipelines that consist of multiple lengths to protect the adjacent pipe layers from damage due to contact with an end fitting. The manufacturer should be consulted for packing recommendations related to his particular end fitting.

12.2.3.3 Care should be taken during retrieval of smooth-bore (collapsible), bonded pipes to avoid capturing excessive twist on the reel. Consideration should be given to maintaining a nominal pressure in the pipe bore during retrieval to control twist. Full twists captured on the reel should be relieved by transpooling the pipe under internal pressure. If the pipe floats when full of air, the twist can also be relieved by pulling the pipe off the retrieval reel onto the water surface, pressurizing it with air, then heaving it back onto the reel off the surface of the water. The pipe should not be stored or reused in the twisted condition.

12.2.3.4 Smooth-bore, bonded pipe can exhibit high elongation due to tension, particularly when the pipe is unpressurized. Care should be taken during retrieval to minimize the amount of elongation that is captured on the reel. The pipe should be transpooled, under internal pressure, to relieve the elongation before the pipe is stored or reused if excessive elongation is captured on the reel. Alternatively, if the pipe floats when full of air, the pipe can be pulled off the retrieval reel onto the water surface, pressurized with air, then heaved back on to the reel off the surface of the water.

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12.3 Reuse

12.3.1 General

12.3.1.1 As a minimum, the following stages are recommended for the process of reusing a flexible pipe in a new application:

a) documentation;

b) pipe evaluation;

c) pipe retrieval;

d) inspection and repair;

e) test requirements;

f) installation.

12.3.1.2 Clause 11 contains guidelines on installation and 12.2 contains guidelines on pipe retrieval. The remaining stages in the process are addressed in 12.3.2 to 12.3.5. A retrieved pipe designed for static applications should not be reused for a dynamic application. Stages a) and b) of 12.3.1.1 should be performed prior to pipe retrieval to determine if it is feasible to reuse the pipe.

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12.3.2 Documentation

12.3.2.1 The user should maintain a detailed record of previous use so that it is possible to accurately evaluate the feasibility of reusing the pipe. The record should specify water depth, production-fluid characteristics, installation date, length in service, operating pressure and temperature and any unanticipated events that can affect the pipe function.

12.3.2.2 Any events that can have damaged the pipe and any previous repairs to the pipe should also be documented and held as evidence of the pipe's service history. In addition, records of all previous inspections and monitoring operations relating to the pipe should be maintained.

12.3.3 Pipe evaluation

12.3.3.1 General

12.3.3.1.1 When a pipe is under evaluation for reuse, the new design conditions should be defined using the purchasing guidelines in ISO 13628-2 and ISO 13628-10. The flexible pipe for reuse should comply with the pipe-structure design criteria specified in ISO 13628-2 and ISO 13628-10 for the new design conditions.

12.3.3.1.2 A general review should be carried out, prior to pipe reuse, considering the pipe-design characteristics, the new conditions of use, the remaining pipe service life and all previous conditions that can have affected its characteristics. The evaluation should also address any accidental damage found from the pipe inspection after retrieval. The effect of corrosive fluids on the structural layers of the pipe should be evaluated in the calculation of the remaining service life. In addition, the aged state and remaining life of the liner or internal pressure sheath/liner polymer/elastomer material should be evaluated.

12.3.3.1.3 Pipe verification and assessment for reuse are addressed in 12.3.3.2 to 12.3.3.4 for the following reuse conditions:

a) similar use;

b) new conditions;

c) special cases.

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12.3.3.2 Evaluation for similar use

12.3.3.2.1 The pipe is intended for reuse in conditions similar to the original application in this case. It does not include situations in which the pipe was subjected to abnormal occurrences, damage or other events that can have significantly reduced the service life. The following information is necessary for the evaluation:

a) new conditions of use (see ISO 13628-2 and ISO 13628-10), including identification of any major changes in the application (H_2S or CO_2 levels);

b) remaining service life;

c) original data specified by the manufacturer, including pipe capacity (data sheet and design report).

12.3.3.2.2 An inspection of the pipe for damage should be sufficient to approve the pipe for reuse if the new conditions of use (including installation and retrieval equipment and procedure and environmental and operational conditions) are easily identified as equivalent or less critical than the original conditions or original design criteria, and if the remaining service life is greater than the life required for the new location.

12.3.3.2.3 Attention should be given to the procedures and equipment used for installation and retrieval, particularly for deep-water applications where installation conditions can be critical. The installation loads should be confirmed to be less than the original installation, or, alternatively, a new analysis should be performed to confirm that the pipe meets the design requirements specified in ISO 13628-2, ISO 13628-10 and Clause 5.

12.3.3.3 Evaluation for new conditions of use

12.3.3.3.1 The following information shall be assessed if the new conditions of use are not similar to the original ones, or if the evaluation carried out according to 12.3.3.2 is inconclusive:

a) global and cross-section analyses (considering new installation equipment, new operational conditions, new application, etc.);

b) results of prototype tests, as available (short- and long-term tests).

12.3.3.3.2 The liner or internal pressure sheath of flexible pipe for reuse should be suitable for the new transported-fluid conditions, considering aspects such as chemical compatibility, temperature, gas permeation and ageing. Ageing models and methods for determination of elastomer or polymer residual life should be used in the analysis with appropriate safety margins where available.

12.3.3.3.3 The metallic materials should be qualified for SSC and HIC resistance in the new design conditions if sour conditions are foreseen. Elastomer, polymer and metallic-layer thickness reduction as a result of fretting or abrasion, which can have occurred during previous use, shall be properly evaluated.

12.3.3.4 Evaluation of special cases

12.3.3.4.1 Additional analysis can be necessary if the pipe is subjected to abnormal occurrences, damage, critical stresses or other events that can have significantly reduced the service life of the pipe. In such situations, the following can be required:

a) special local analyses;

b) new prototype tests;

c) records of abnormal operation, such as occurrences when the pipe was submitted to conditions beyond those considered by the original design (extreme loads or temperatures);

d) records of defects or condition detected from inspection during operation or after retrieval (such as damage, corrosion or ageing);

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e) records of former conditions of long-term pipe storage;

f) tests for material qualification (ageing tests, compatibility tests, SSC/HIC NACE qualification tests).

12.3.3.4.2 Special local analyses can be useful for evaluating damage, such as wire rupture, corrosion, wear, etc. New prototype tests may be performed to confirm some specific characteristic required for reuse of the pipe in new conditions (if new installation equipment applies high stress to the pipe).

12.3.3.4.3 Results of qualification tests on materials (see ISO 13628-2 and ISO 13628-10) can be useful for evaluating their remaining life when exposed to operational fluid or to environmental conditions. New tests can be necessary if data are not available. See ISO 13628-2 and ISO 13628-10 for test procedures and criteria.

12.3.3.4.4 Qualified methods for the pipe and system design should be available to carry out the global and local analysis. Operators can use their own methods or those of a manufacturer or a third party to carry out the pipe assessment. In all cases, the programmes and methods used should be validated as required by ISO 13628-2 and ISO 13628-10.

12.3.3.4.5 Special attention should be given to calculating the pipe remaining life. Safety margins should be the same as specified in ISO 13628-2 and ISO 13628-10. Information concerning long-term performance of materials under the original use conditions is essential for taking any decision about pipe reuse. Sources of data that can be useful for this purpose include operational experience with materials and pipes, results of long-term tests performed for material qualification, prototype testing (destructive testing of samples from retrieved pipe), inspection of retrieved pipes, suitably qualified non-destructive testing monitoring techniques and calibrated models for calculating service life, both theoretically and with tests.

12.3.4 Inspection and repair

12.3.4.1 General

Manufacturer's technical personnel should be involved in any inspection and/or repair operation.

12.3.4.2 Unbonded pipe

12.3.4.2.1 Rapid corrosion of exposed pipe armour can occur when it is subjected to the atmosphere as a result of damage (caused, for instance, during the pipe retrieval). It is, therefore, recommended that such areas be immediately protected by using special anti-corrosion products and by covering them with tape or bandage if they cannot be immediately repaired.

12.3.4.2.2 An inspection should assess the degree of corrosion that has taken place and evaluate the corrosion that can be present in areas of damaged outer sheath that allow the ingress of water. Corrosion can both reduce the armour load capacity and adversely affect its wear characteristics. Areas of the pipe where burst discs were located during the pipe's previous operation are an example of a pipe section where significant corrosive damage can occur. Acceptance tests (see 12.3.5) and local analysis should be performed to evaluate if the damage is critical.

12.3.4.2.3 It can be convenient to cut out critical damage in a localized area and install end fittings on the extremities of remaining sections to make their reuse feasible. Special attention should be given to the interface between the pipe and the bend stiffener/restrictor, where damage and corrosion are likely to appear.

12.3.4.2.4 Qualified procedures and personnel should be used for outer-sheath repair. The procedures should guarantee the minimum required pipe-performance properties. The qualification of repair procedures should include tests that confirm pipe characteristics. The long-term degradation of the repaired area should also be considered. As an alternative to outer-sheath repair, it can be more convenient to strip off the whole layer and re-extrude a new outer sheath.

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12.3.4.2.5 End fittings should be subjected to detailed inspection. The corrosion-protection system should be evaluated for all components (end-fitting body, bolts, nuts). The gasket seat should be checked against the design standard for the required surface finish. It should be decided whether regrooving by machining is feasible or whether the flange should be replaced if the face does not meet the requirements. Replacing the flange can possibly require replacement of the end fitting, as it might not be possible to weld on a new flange. Relief valves should be tested and recalibrated or replaced.

12.3.4.2.6 The long-term degradation of plastic components of end fittings should be evaluated. The service life of resins and gaskets should be obtained from the pipe supplier.

12.3.4.2.7 The new end fittings should be assembled using a procedure approved by the pipe supplier or other competent body if the end fittings are removed.

12.3.4.3 Bonded pipe

12.3.4.3.1 The exterior surface of the pipe should be thoroughly cleaned and inspected during or after retrieval.

12.3.4.3.2 Rapid corrosion of exposed reinforcing plies can occur if the cover layer of a bonded flexible pipe is damaged (for instance, during pipe retrieval). It is, therefore, recommended that the area be immediately protected by applying anti-corrosion product(s) and covering with a temporary, impermeable layer.

12.3.4.3.3 All areas of cover damage should be inspected for corrosion. Corrosion can produce rapid degradation in the filament-wire cables typically used in bonded flexible pipe. Acceptance tests and local analysis should be performed to determine if the corrosion damage is critical.

12.3.4.3.4 Cutting out the damage and installing new end fittings at the cut ends of the remaining sections can be possible if the damage in a localized area is determined to be critical. New end fittings should be installed by qualified personnel using qualified procedures. Bonded flexible pipes with built-in end fittings may use temporary repair fittings but, in general, this type of pipe cannot be permanently re-terminated.

12.3.4.3.5 Qualified procedures and personnel should be used for all cover repairs. The repair-procedure qualification should include tests that confirm pipe characteristics. Long-term degradation of the repaired area should also be considered.

12.3.4.3.6 End fittings should be subjected to detailed inspection. The corrosion-protection system should be evaluated for all components (end-fitting body, bolts, nuts). The gasket seat should be checked against the design standard for the required surface finish. The decision should be made whether regrooving by machining is feasible or whether the flange should be replaced if the face does not meet the requirements. Replacing the flange can require replacement of the end fitting, as it might not be possible to weld on a new flange.

12.3.4.3.7 The long-term degradation of plastic components of end fittings should be evaluated. The service life of resins and gaskets should be obtained from the pipe supplier.

12.3.4.3.8 The interface between the built-in nipple and the liner layer should be visually inspected using a mirror or borescope for bonded pipes with built-in end fittings. Any evidence of delamination of the liner layer, linear movement (slippage) between the nipple and liner or seepage of oil into the nipple-liner interface should be thoroughly evaluated to determine if it is critical.

12.3.5 Test requirements

12.3.5.1 After a pipe is prepared for reuse, it should be subjected to the factory tests specified in ISO 13628-2 or ISO 13628-10 or as required by the user (such as a hydrostatic test, gauge test or electric continuity test). The hydrostatic test pressure should be in accordance with FAT requirements in ISO 13628-2. The design pressure should be reduced to 0,67 times the test pressure if the test pressure is reduced.

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12.3.5.2 Pipe flushing and corrosion protection for storage can be necessary after the pressure test. Other tests or inspection methods (see Clause 11) can be used to check for defects in the pipe, such as material loss by corrosion or cracks or flaws in the structural layers. The pipe should be subjected to further analysis, as recommended in 12.3.3.4, if abnormalities are identified.

12.3.5.3 Re-installation and commissioning of the pipe should take into consideration the recommendations of 11.4 and 11.5.

13 Integrity and condition monitoring

13.1 General

Clause 13 provides guidelines and recommendations on integrity and condition monitoring, including potential pipe defects, for unbonded flexible pipes. In general, Clause 13 does not apply to bonded flexible pipes.

13.2 General philosophy

13.2.1 Inspection/monitoring philosophy

13.2.1.1 A detailed integrity and condition-monitoring programme should be established, based on an evaluation of the failure modes to which flexible pipe are exposed and the risk attributed to failure from each source.

13.2.1.2 A monitoring system designed to operate throughout the field design life, or for a reduced period on one or more dynamic risers or flowlines for research or operational use, is possibly required. These issues should be resolved fully and a field philosophy completed prior to design commencement. The monitoring and inspection philosophy should be identified in the project design premise.

13.2.2 General

The inspection and monitoring programme should typically include all applications of flexible pipe and their ancillary components.

13.2.3 Objectives

The objectives of an in-service integrity and condition monitoring programme should include the following:

a) detection of possible degradation at a sufficiently early stage to allow for remedial action and, thereby

   1) protect against accidents or loss of life,

   2) protect against environmental pollution,

   3) avoid downtime,

   4) minimize the risk of economic loss arising from pipe system degradation or damage to field equipment;

b) demonstration of continued fitness for purpose;

c) compliance with all relevant statutory and regulatory requirements;

d) provision of a record of service data, which can be required when considering future reuse.

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13.2.4 Establishment of an inspection/monitoring programme

13.2.4.1 Potential modes of failure should be identified for the specific design and application of the flexible pipe. The pipe system's functional and operational requirements should be taken into account when assessing potential failure modes.

13.2.4.2 A risk analysis should seek to quantify the risk attributed to each failure mode, typically as a function of the probability and consequence of failure. The establishment of an inspection and monitoring strategy should relate the degree of required monitoring or inspection to the calculated level of risk.

13.2.4.3 Available direct or indirect methods to inspect/access the pipe should be evaluated for their suitability for the intended flowline or riser application. Furthermore, adequate provision for facilitating pipe monitoring should be made in the design of the pipe system and associated topside and subsea facilities. In this respect, topside piping should be designed to allow access for internal inspection tools. This area of flexible pipe technology is continually evolving, and the pipe and pipe-system design should consider the likelihood that some developing methods will become standard practice in the future.

13.2.4.4 The requirements for a baseline survey should be considered for each of the methods that is selected as part of the integrity and condition monitoring programme. Provision should be made for any such baseline survey before the pipe is brought into service, and records should be held for the full life of the flexible pipe system.

13.2.4.5 Integrity monitoring should begin at the factory with thorough inspection, quality control and documentation of the manufacturing process. It is necessary to plan installation operations thoroughly to avoid damage caused by handling equipment. Special care shall be taken with the first baseline visual inspection after installation to document minor anomalies or damage that may indicate undetected problems and the necessity for more frequent monitoring.

13.2.5 Inspection and monitoring programme review

The inspection and monitoring programme should be subjected to regular, documented review throughout the service life of the flexible-pipe field system. This review should reconsider the methods and frequency of review based on the results of inspection or monitoring, experience of this or similar systems or additional knowledge of flexible-pipe behaviour. Documented records of the review process should be retained for the service life of the field system, or the service life of each flexible pipe in the field system if any pipes are reused.

13.3 Failure modes and potential pipe defects

13.3.1 A flexible-pipe failure mode describes one possible process by which a flexible pipe can fail. A single failure mode typically represents a succession of pipe defects that have the potential to culminate in pipe failure. The identification of relevant failure modes should be based on a detailed knowledge of flexible-pipe behaviour.

13.3.2 Tables 30 to 32 identify potential defects that apply to the integrity of flexible pipe systems. Each defect is numbered and the likely cause and consequence of the defect has been identified.

13.3.3 Tables 30 and 31 relate to riser and flowline applications, respectively, individually classifying defects in each layer of pipe. Table 32 applies to defects associated with system components and pipe attachments and damage that can affect the condition or integrity of the flexible pipe itself.

13.3.4 These tables should be reviewed during the selection of the integrity and condition monitoring programme. The review allows identification of critical components in the pipe system and potentially critical defects, thereby facilitating a better definition of the requirement and relevancy of available monitoring methods.

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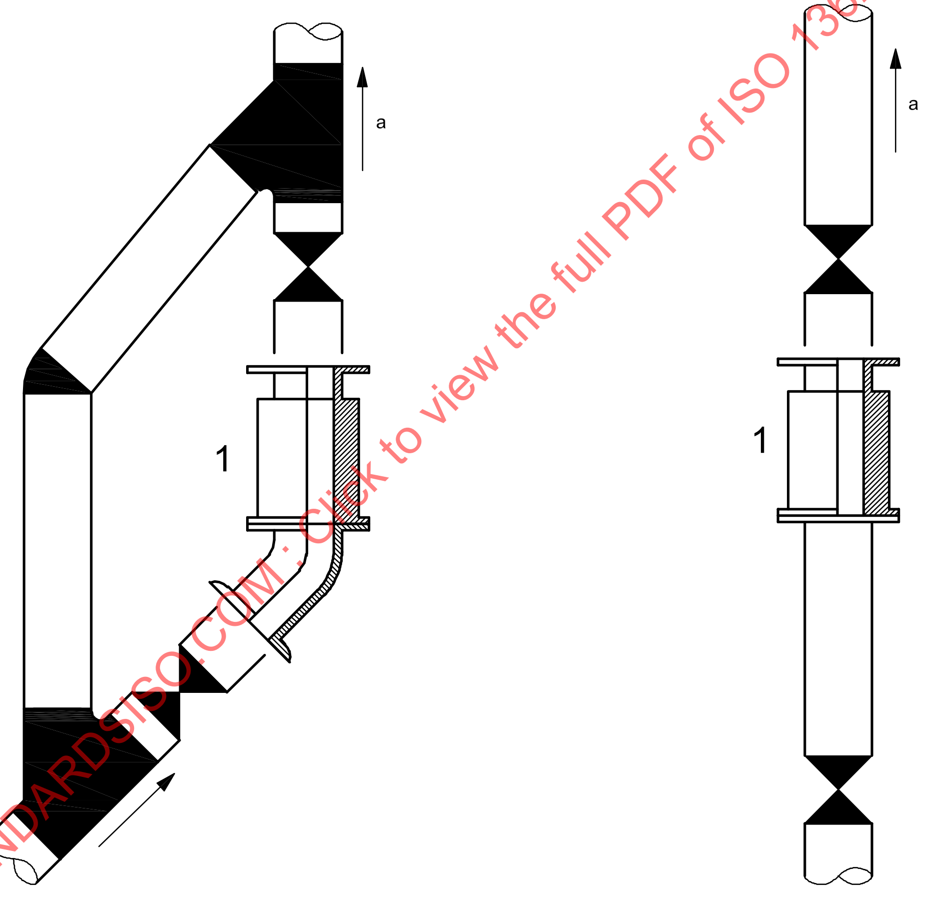
13.4 Monitoring methods

13.4.1 Table 33 lists current methods available for the monitoring of flexible pipes in service. Visual inspection and periodic pressure testing have been, to date, the most common forms of in-service monitoring used for the demonstration of continued fitness for purpose.

13.4.2 Non-destructive testing of pipes in service includes direct intrusive and non-intrusive techniques that have been field demonstrated and suitably qualified as measurement methods.

13.4.3 The ageing of non-metallic components and the corrosion or erosion of metallic components can be monitored by installation in the flow path of short test pipes or coupons placed in coupon sampling traps. The test material can be retrieved and destructively or non-destructively tested at pre-defined intervals throughout the service life of the component. Figure 39 shows a removable, rigid, test-pipe arrangement (in series or in parallel with the flow), which uses a mock-up of the internal layers of flexible pipe. It allows gas venting through a pressure-relief valve.



a) In parallel

b) In series

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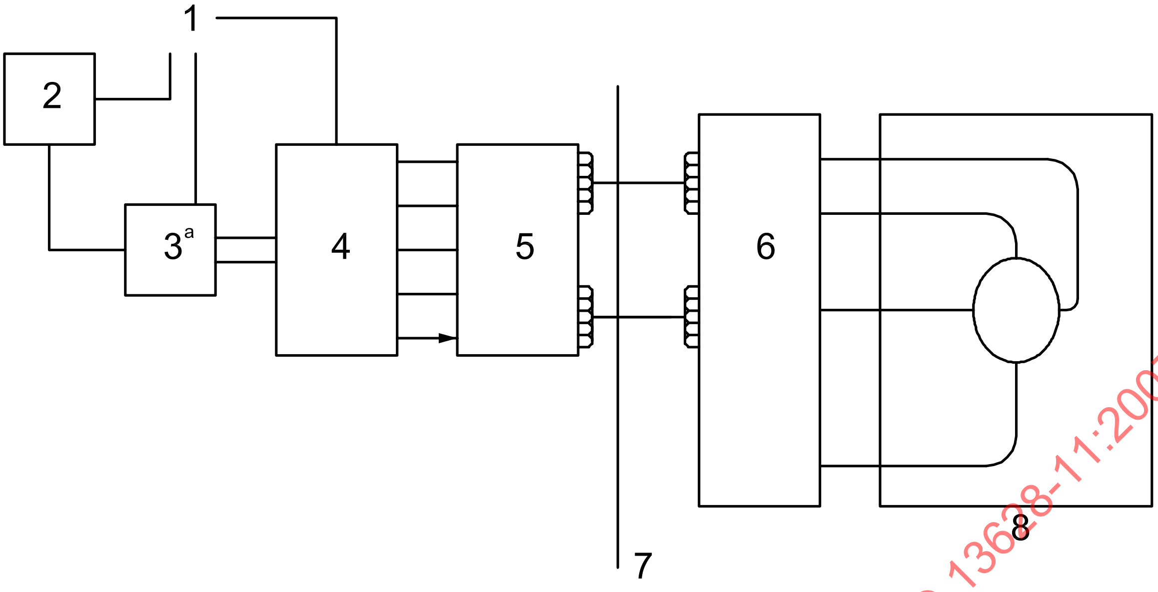
Key

1 test pipe

a Flow direction.

Figure 39 — Schematic of possible test pipe arrangements

13.4.4 Dielectric sensing of the internal pressure sheath should be used only if qualified for the material and for the temperature and pressure ranges applicable to the service conditions. Figure 40 is a schematic representation of the measurement method applied to topside internal-pressure-sheath monitoring.



Key

1 alternate current supply
2 IBM-compatible personal computer
3 LCR meter
4 multiplexer
5 distribution board
6 junction box
7 weather-deck hazardous area
8 sensor spool piece in product flow

[a] An LCR meter measures inductance (L), capacitance (C), and resistance or impedance (R).

Figure 40 — Schematic of topside dielectric-sensing layout and instrumentation for thermoplastic monitoring

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13.4.5 Gas-diffusion monitoring of a flexible-riser annulus measures the composition of the gas sampled through a vent valve at the pipe-end fitting, typically at the riser top. The objective is to relate the results to the potential for metallic-layer corrosion (including SSC and HIC) or the aged condition of the internal pressure sheath, which can provide an early warning of severe deterioration before the integrity of the pipe is affected.

13.4.6 Load, deformation and environmental monitoring include methods that involve the measurement of the following:

a) pipe tension;

b) deflection;

c) torsion;

d) bending;

e) internal product composition;

f) internal pressure and temperature;

g) vessel motions and environmental conditions.

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