
**Petroleum, petrochemical and natural gas
industries — Composite repairs for
pipework — Qualification and design,
installation, testing and inspection**

*Industries du pétrole, de la pétrochimie et du gaz naturel — Réparations
en matériau composite pour canalisations — Conformité aux exigences
de performance et conception, installation, essai et inspection*

STANDARDSISO.COM : Click to view the full PDF of ISO/TS 24817:2006



PDF disclaimer

This PDF file may contain embedded typefaces. In accordance with Adobe's licensing policy, this file may be printed or viewed but shall not be edited unless the typefaces which are embedded are licensed to and installed on the computer performing the editing. In downloading this file, parties accept therein the responsibility of not infringing Adobe's licensing policy. The ISO Central Secretariat accepts no liability in this area.

Adobe is a trademark of Adobe Systems Incorporated.

Details of the software products used to create this PDF file can be found in the General Info relative to the file; the PDF-creation parameters were optimized for printing. Every care has been taken to ensure that the file is suitable for use by ISO member bodies. In the unlikely event that a problem relating to it is found, please inform the Central Secretariat at the address given below.

STANDARDSISO.COM : Click to view the full PDF of ISO/TS 24817:2006

© ISO 2006

All rights reserved. Unless otherwise specified, no part of this publication may be reproduced or utilized in any form or by any means, electronic or mechanical, including photocopying and microfilm, without permission in writing from either ISO at the address below or ISO's member body in the country of the requester.

ISO copyright office
Case postale 56 • CH-1211 Geneva 20
Tel. + 41 22 749 01 11
Fax + 41 22 749 09 47
E-mail copyright@iso.org
Web www.iso.org

Published in Switzerland

Contents

Page

Foreword.....	v
Introduction	vi
1 Scope	1
2 Normative references	1
3 Terms and definitions	2
4 Symbols and abbreviated terms	5
4.1 Symbols	5
4.2 Abbreviated terms	8
5 Applications	8
6 Qualification and design	10
6.1 Risk assessment	10
6.2 Repair class	11
6.3 Repair lifetime	11
6.4 Required data	11
6.5 Design methodology	14
6.6 Requalification	35
7 Installation	35
7.1 General	35
7.2 Materials of construction	36
7.3 Storage conditions	36
7.4 Method statements	36
7.5 Installer qualifications	37
7.6 Installation guidance	37
7.7 Live repairs	38
7.8 Repair of clamps, piping components, tanks or vessels	38
7.9 Environmental considerations	38
8 Testing and inspection	39
8.1 General	39
8.2 Allowable defects for the repair system	39
8.3 Repair of defects within the repair system	41
8.4 Inspection methods	41
8.5 Repair system maintenance and replacement strategy	41
9 System testing	42
10 Future modifications	42
11 Decommissioning	42
Annex A (normative) Design data sheet	43
Annex B (normative) Qualification data	46
Annex C (normative) Short-term pipe spool survival test	48
Annex D (normative) Measurement of γ_{LCL} for through-wall defect calculation	50
Annex E (normative) Measurement of performance test data	53
Annex F (normative) Measurement of impact performance	56
Annex G (normative) Measurement of the degradation factor	57

Annex H (informative) Axial extent of repair look-up table	59
Annex I (normative) Installer qualification	61
Annex J (normative) Installation requirements and guidance	64
Bibliography	67

STANDARDSISO.COM : Click to view the full PDF of ISO/TS 24817:2006

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.

In other circumstances, particularly when there is an urgent market requirement for such documents, a technical committee may decide to publish other types of normative document:

- an ISO Publicly Available Specification (ISO/PAS) represents an agreement between technical experts in an ISO working group and is accepted for publication if it is approved by more than 50 % of the members of the parent committee casting a vote;
- an ISO Technical Specification (ISO/TS) represents an agreement between the members of a technical committee and is accepted for publication if it is approved by 2/3 of the members of the committee casting a vote.

An ISO/PAS or ISO/TS is reviewed after three years in order to decide whether it will be confirmed for a further three years, revised to become an International Standard, or withdrawn. If the ISO/PAS or ISO/TS is confirmed, it is reviewed again after a further three years, at which time it must either be transformed into an International Standard or be withdrawn.

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/TS 24817 was prepared by Technical Committee ISO/TC 67, *Materials, equipment and offshore structures for petroleum, petrochemical and natural gas industries*, Subcommittee SC 6, *Processing equipment and systems*.

Introduction

The objective of ISO/TS 24817 is to ensure that composite repairs to pipework when qualified, designed, installed and inspected using ISO/TS 24817 will meet the specified performance requirements. Composite repairs are designed for use in oil and natural gas industry processing and utility service applications. The main users of this Technical Specification will be owners of the pipework, design contractors, suppliers contracted to deliver the repairs, certifying authorities, installation contractors and maintenance contractors.

STANDARDSISO.COM : Click to view the full PDF of ISO/TS 24817:2006

Petroleum, petrochemical and natural gas industries — Composite repairs for pipework — Qualification and design, installation, testing and inspection

1 Scope

This Technical Specification gives requirements and recommendations for the qualification and design, installation, testing and inspection for the external application of composite repairs to corroded or damaged pipework used in the petroleum, petrochemical and natural gas industries.

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 75-3, *Plastics — Determination of temperature of deflection under load — Part 3: High-strength thermosetting laminates and long-fibre-reinforced plastics*

ISO 527-1, *Plastics — Determination of tensile properties — Part 1: General principles*

ISO 527-4, *Plastics — Determination of tensile properties — Part 4: Test conditions for isotropic and orthotropic fibre-reinforced plastic composites*

ISO 868, *Plastics and ebonite — Determination of indentation hardness by means of a durometer (Shore hardness)*

ISO 10952, *Plastics piping systems — Glass-reinforced thermosetting plastics (GRP) pipes and fittings — Determination of resistance to chemical attack on the inside of a section in deflected condition*

ISO 11357-2, *Plastics — Differential scanning calorimetry (DSC) — Part 2: Determination of glass transition temperature*

ISO 11359-2, *Plastics — Thermomechanical analysis (TMA) — Part 2: Determination of coefficient of linear thermal expansion and glass transition temperature*

ISO 14692 (all parts), *Petroleum and natural gas industries — Glass-reinforced plastics (GRP) piping*

ANSI/API RP 579, *Recommended Practice for Fitness-for-Service*

ASME B31G, *Manual for Determining the Remaining Strength of Corroded Pipelines: a Supplement to B31, Code for Pressure Piping*

ASTM C581, *Standard Practice for Determining Chemical Resistance of Thermosetting Resins Used in Glass-Fibre-Reinforced Structures Intended for Liquid Service*

ASTM D543, *Standard Practices for Evaluating the Resistance of Plastics to Chemical Reagents*

ASTM D696, *Standard Test Method for Coefficient of Linear Thermal Expansion of Plastics Between – 30 °C and 30 °C with a Vitreous Silica Dilatometer*

ASTM D1598, *Standard Test Method for Time-to-Failure of Plastic Pipe Under Constant Internal Pressure*

ASTM D1599, *Standard Test Method for Resistance to Short-Time Hydraulic Failure Pressure of Plastic Pipe, Tubing, and Fittings*

ASTM D2583, *Standard Test Method for Indentation Hardness of Rigid Plastics by Means of a Barcol Impressor*

ASTM D2992, *Standard Practice for Obtaining Hydrostatic or Pressure Design Basis for “Fiberglass” (Glass-Fiber-Reinforced Thermosetting-Resin) Pipe and Fittings*

ASTM D3039, *Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials*

ASTM D3165, *Standard Test Method for Strength Properties of Adhesives in Shear by Tension Loading of Single-Lap-Joint Laminated Assemblies*

ASTM D3681, *Standard Test Method for Chemical Resistance of “Fiberglass” (Glass-Fiber-Reinforced Thermosetting-Resin) Pipe in a Deflected Condition*

ASTM D5379/D5379M-05, *Standard Test Method for Shear Properties of Composite Materials by the V-Notched Beam Method*

ASTM D6604, *Standard Practice for Glass Transition Temperatures of Hydrocarbon Resins by Differential Scanning Calorimetry*

ASTM E831, *Standard Test Method for Linear Thermal Expansion of Solid Materials by Thermomechanical Analysis*

ASTM E1640, *Standard Test Method for Assignment of the Glass Transition Temperature by Dynamic Mechanical Analysis*

ASTM E2092, *Standard Test Method for Distortion Temperature in Three-Point Bending by Thermomechanical Analysis*

ASTM G8, *Standard Test Methods for Cathodic Disbonding of Pipeline Coatings*

BS 7910, *Guide to methods for assessing the acceptability of flaws in metallic structures*

EN 59, *Glass reinforced plastics — Measurement of hardness by means of a Barcol impressor (BS 2782-10: Method 1001, Methods of testing plastics. Glass reinforced plastics. Measurement of hardness by means of a Barcol impressor)*

EN 1465, *Adhesives — Determination of tensile lap shear strength of rigid-to-rigid bonded assemblies*

3 Terms and definitions

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

3.1

anisotropic

exhibiting different physical properties in different directions

3.2

Barcol hardness

measure of surface hardness using a surface impressor

3.3**composite**

thermoset resin system that is reinforced by fibres

3.4**cure****curing**

setting of a thermosetting resin system, such as polyester or epoxy, by an irreversible chemical reaction

3.5**delamination**

separation of layers within a repair laminate or between a repair laminate and the substrate

3.6**differential scanning calorimetry****DSC**

method of determining the glass transition temperature of a thermosetting resin

3.7**glass transition temperature**

temperature at which a resin undergoes a marked change in physical properties

3.8**hardener**

component added to a thermosetting resin to effect cure

3.9**heat distortion temperature****HDT**

temperature at which a standard test bar deflects by a specified amount under a given load

3.10**in-fill material**

material used to repair external surface imperfections prior to the application of the composite laminate

3.11**laminate****repair laminate**

that part of a repair system that is the composite

NOTE

Most composites considered in this Technical Specification are composed of discrete lamina or layers which are wrapped or stacked one on top of the other. This stacked construction is the laminate.

3.12**leak**

condition of a substrate wall that can allow the contents to make contact with, and act directly upon, the (composite) repair laminate

NOTE

This does not refer to a fluid leaking through a hole or breach in the substrate.

3.13**occasional load**

load that occurs rarely and during a short time

NOTE

Occasional loads typically occur less than 10 times in the life of the component and each load duration is less than 30 min.

3.14**owner**

organization that owns or operates the substrate to be repaired

**3.15
pipeline**

pipe with components subject to the same design conditions used to transport fluids between plants

NOTE Components may include, for example, bends, flanges, valves.

**3.16
pipework**

interconnected piping subject to the same set or sets of design conditions

**3.17
piping
piping system**

assemblies of piping components used to convey fluids within a plant

NOTE Components may include pipe, fittings, flanges, gaskets, bolting, valves. A piping system is often above ground but sometimes buried.

**3.18
ply**
single wrap or layer (lamina) of a repair laminate

**3.19
post cure**
additional elevated-temperature cure

**3.20
qualification application procedure**
application procedure used to apply the repair system for the qualification tests

**3.21
qualification test temperature**
test temperature at which qualification testing of the repair system is performed

**3.22
reinforcement**
fibre embedded in the resin system

NOTE Possible fibre materials include aramid, carbon, glass, polyester or similar materials. Reinforcement results in mechanical properties superior to those of the base resin.

**3.23
repair system**
system comprised of the substrate, composite material (repair laminate), filler material, adhesive and including surface preparation and installation methods used for repair of pipework

**3.24
repair system supplier**
company that supplies and installs the repair system

**3.25
resin system**
all of the components that make up the matrix portion of a composite

NOTE Often this includes a resin, filler(s), pigment, mechanical property modifiers and catalyst or hardener.

**3.26
risk**
term describing an event encompassing what can happen (scenario), its likelihood (probability) and its level or degree of damage (consequences)

3.27**substrate**

surface on which a repair is carried out

NOTE The surface may belong to original pipework, a pipework component, pipeline, tank or vessel.

3.28**Shore hardness**

measure of surface hardness using a surface impressor or durometer

3.29**thermoset resin system**

resin system that cannot be resoftened following polymerization

4 Symbols and abbreviated terms**4.1 Symbols**

α_a	repair laminate thermal expansion coefficient, axial direction, expressed in millimetres per millimetre degree Celsius
α_c	thermal expansion coefficient of the repair laminate for either the axial or circumferential directions
α_s	thermal expansion coefficient of substrate
c	crack length
D	external diameter
D_a	external attachment equivalent diameter
D_b	external branch, tee, nozzle diameter
D_d	external diameter end dome
D_r	external reducer diameter (smaller diameter)
d	diameter (or diameter of the equivalent circle) of the through-wall defect
ΔT	difference between operation and installation temperatures
E_c	tensile modulus of the composite laminate in the circumferential direction
E_a	tensile modulus of the composite laminate in axial direction
E_{ac}	combined tensile modulus $\sqrt{E_a E_c}$
E_s	tensile modulus of substrate
ε_c	circumferential design strain
ε_{c0}	allowable circumferential strain
ε_a	axial design strain
ε_{a0}	allowable axial strain

ε_t	thermal strain
$\varepsilon_{\text{short}}$	short-term failure strain of the composite laminate
F_{ax}	applied axial load
F_{eq}	equivalent axial load
F_{sh}	applied shear load
f_c	service factor for cyclic fatigue
f_D	degradation factor for the long-term performance of repairs to through-wall defects
f_{leak}	service factor for repairs to through-wall defects
f_{perf}	service factor for performance data
$f_{\text{th,overlay}}$	repair thickness increase factor for reduced available overlap length
$f_{\text{th,stress}}$	repair thickness increase factor for piping system or vessel component
f_{T1}	temperature de-rating factor for composite allowable strains
f_{T2}	temperature de-rating factor for through-wall defect repair design
ϕ	angle subtended by axial slot
G	shear modulus of the composite laminate
γ	toughness parameter (energy release rate) for the composite steel interface
γ_{LCL}	95 % confidence limit of energy release rate
h	burial depth
I	second moment of area
l	total axial extent of repair
$l_{\text{available}}$	available landing area (axial extent) of undamaged substrate
l_{over}	axial extent of design thickness of repair
l_{defect}	axial length of defect
l_{taper}	axial length of taper
N	number of cycles
M_{ax}	applied axial moment
M_{to}	applied torsional moment
n	number of observed data points
n_W	number of wraps or layers of repair laminate
p	design internal pressure

p_{after}	internal pressure after repair system is applied
p_e	external design pressure
p_{eq}	equivalent design pressure
$p_{\text{ext,soil}}$	external soil pressure
p_{live}	internal pressure within the substrate during application of the repair
p_{min}	minimum (internal pressure) load (or stress) of the load cycle
p_{max}	maximum (internal pressure) load (or stress) of the load cycle
p_{mthp}	medium-term hydrostatic test pressure
p_s	maximum allowable working pressure (MAWP)
p_{sthp}	short-term hydrostatic test pressure
p_0	initial test pressure
\dot{p}	fixed linear increase in test pressure
q	tensile stress
R_c	cyclic loading severity, defined as: $R_c = \frac{p_{\text{min}}}{p_{\text{max}}}$
s	allowable stress of the substrate material
s_a	measured yield stress of substrate or mill certification yield stress
s_{lt}	lower confidence limit of the long-term stress determined by performance testing
T_d	design temperature
T_g	glass transition temperature
T_m	maximum operating temperature of repair system
T_{amb}	ambient temperature
T_{test}	qualification test temperature
t	wall thickness of substrate
t_{lifetime}	design lifetime
t_{layer}	thickness of an individual wrap or layer of repair laminate
t_b	wall thickness of branch, tee
t_f	wall thickness of flange
t_{design}	design thickness of repair laminate
t_{min}	minimum thickness of repair laminate
t_s	minimum remaining substrate wall thickness

τ	lap shear strength
ν	Poisson's ratio for the repair laminate
w	(axial) width of circumferential slot defect
W_{soilg}	specific weight of soil

4.2 Abbreviated terms

ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
API	American Petroleum Institute
AWWA	American Water Works Association
BS (BSI)	British Standards Institute
CFRP	carbon-fibre-reinforced plastic
COSHH	regulations for control of substances hazardous to health
CSWIP	certification scheme for welding inspection personnel
DSC	differential scanning calorimetry
FRP	fibre-reinforced plastic
GRP	glass-reinforced plastic
HDT	heat distortion temperature
MAWP	maximum allowable working pressure
MSDS	materials safety data sheet
NDT	non-destructive testing
OSHA	Occupational Safety and Health Act
PCC	post-construction committee
SMYS	specified minimum yield strength

5 Applications

The qualification and design, installation, testing and inspection procedures for repair systems in this Technical Specification cover situations involving the repair of damage commonly encountered in oil, gas and utility pipework systems. The procedures are also applicable to the repair of pipelines, caissons, storage tanks and vessels with appropriate consideration.

Procedures in this Technical Specification cover the repair of metallic and GRP pipework, pipework components, pipelines originally designed in accordance with a variety of standards, including ISO 15649, ISO 13623, ISO 14692, ASME B31.1, ASME B31.3, ASME B31.4, ASME B31.8 and BS 8010.

Repair systems are applied to achieve a satisfactory level of structural integrity.

The following repair situations are addressed:

- external corrosion, where the defect is or is not through-wall; in this case the application of a repair system will usually arrest further deterioration;
- external damage such as dents, gouges and fretting (at supports);
- internal corrosion, erosion, where the defect is or is not through-wall; in this case corrosion and/or erosion can continue after application of a repair system, and therefore the design of the repair system shall take this into account;
- structural strengthening in local areas.

As a general guide, Table 1 summarizes the types of defect that can be repaired using repair systems.

Table 1 — Guide to generic defect types

Type of defect	Applicability of repair system
General wall thinning	Y ^a
Local wall thinning	Y
Pitting	Y
Gouges	R ^b
Blisters	Y
Laminations	Y
Circumferential cracks	Y
Longitudinal cracks	R
Through-wall penetration	Y
^a Y implies generally appropriate. ^b R implies can be used, but requires extra consideration.	

Services that are covered within the scope of this Technical Specification include all services normally found on an oil and gas production or processing installation. These include:

- utility fluid, diesel, seawater, air;
- chemicals (liquids);
- production fluids, including liquid hydrocarbons, gaseous hydrocarbons and gas condensates.

The upper pressure and temperature limits are dependent on the type of damage being repaired and the type of repair system being used. These limits are determined from the qualification testing results presented in Clause 6.

The lower temperature limit is dependent on the type of repair laminate being used. This limit is determined by the design requirements presented in Clause 6. The lower pressure limit, e.g. vacuum conditions, is determined by the design requirements presented in 6.5.9.7.

The composite materials constituting the repair laminate considered within this Technical Specification are typically those with aramid (AFRP), carbon (CFRP), glass (GRP) or polyester (or similar material) reinforcement in a polyester, vinyl ester, epoxy or polyurethane matrix. Other fibre and matrix types are also permissible.

6 Qualification and design

6.1 Risk assessment

A risk assessment associated with both the defect and the repair method shall be completed by the owner prior to application of the repair system.

The following factors shall be considered within the risk assessment:

- assessment of the nature and location of the defects;
- design and operating conditions for the substrate and contents (including pressure, temperature, sizes and combinations thereof);
- repair lifetime (see 6.3);
- geometry of the substrate being repaired;
- hazards associated with system service;
- availability of personnel with the necessary skills;
- ease with which it is practicable to execute surface preparation operations;
- performance under upset and major incident situations, including impact, abrasion, fire, explosion, collision and environmental loading;
- operational measures, including (if relevant) permits, gas testing and fire protection requirements to ensure safety in the vicinity of the repair area;
- failure modes;
- inspectability (both visual and non-destructive);
- repair system materials.

For clarification, the risk assessment is not intended as a means to predetermine that the repair method is the appropriate strategy or remedial action, but rather to assess the risks associated with applying the repair method.

The information and data describing any hazards shall be included in the method statement (7.4) to be used on site.

Since the application of these repair systems typically changes the mode of failure from rupture of the substrate to a leak, the consequences of failure will therefore be reduced.

The objective of the assessment shall be to establish the class of the repair (6.2), which determines the detail of the design method (6.5) to be carried out, together with the requirements for supporting documentation. This also determines the design margin or factor of safety to be used in the design.

Guidance on performing a risk assessment can be obtained from Reference [36].

6.2 Repair class

Each repair shall be allocated to a particular class following completion of the risk assessment. Repair classes are defined in Table 2.

Class 1 repairs cover design pressures up to 1 MPa (10 bar) and design temperatures up to 40 °C and are appropriate to the majority of the utility service systems. This class is intended for those systems that do not relate directly to personnel safety or safety-critical systems.

Class 2 repairs cover design pressures up to 2 MPa (20 bar) and design temperatures up to 100 °C but exclude hydrocarbons. This class is appropriate to those systems that have specific safety-related functions.

Class 3 repairs cover all fluid types and pressures up to the qualified upper pressure limit. This class is appropriate for systems transporting produced fluids.

Applications in which the service conditions are more onerous or not included in the above, shall be designated as Class 3.

Table 2 — Repair class

Repair class	Typical service	Design pressure	Design temperature
Class 1	Low specification duties, e.g. static head, drains, cooling medium, sea (service) water, diesel and other utility hydrocarbons	< 1 MPa	< 40 °C
Class 2	Fire water/deluge systems	< 2 MPa	< 100 °C
Class 3	Produced water and hydrocarbons, flammable fluids, gas systems Class 3 also covers operating conditions more onerous than described.	Qualified upper limit	Qualified upper limit

6.3 Repair lifetime

The lifetime (in years) of the repair system shall be defined in the repair data sheet, Annex A. It may be limited by the defect type and service conditions, e.g. internal corrosion.

The minimum lifetime of the repair shall be 2 years.

Short lifetimes (2 years) are intended to apply to those situations where the repair is required to survive until the next shutdown.

Long lifetimes (up to 20 years) are intended to apply to those situations where the repair is required to reinstate the substrate to its original design lifetime or to extend its design life for a specified period.

Once the lifetime of the repair has expired, the owner shall either remove or revalidate the repair system.

6.4 Required data

6.4.1 Background

The following data shall be supplied for each repair application. The detail to which these requirements are fulfilled is determined by the output of the risk assessment. Original equipment design data, maintenance and operational histories shall be provided by the owner and material qualification data shall be provided by the repair system supplier. The availability of relevant data shall feature as part of the risk assessment.

6.4.2 Original equipment design data

Original equipment design data are required, consisting of:

- a) piping line lists or other documentation showing process design conditions and a description of the piping class, including material specification, wall thickness, and pressure and temperature ratings;
- b) piping isometric drawings and, if appropriate, the output of a piping flexibility calculation;
- c) specification of all operating mechanical loads not included in the above, including upset conditions;
- d) original design calculations.

6.4.3 Maintenance and operational histories

Maintenance and operational histories are required, consisting of:

- a) documentation of any changes in service conditions, including pressure, temperature, internal fluids and corrosion rate;
- b) past service conditions;
- c) summary of all alterations and past repairs local to the substrate of concern;
- d) inspection reports detailing the nature and extent of damage to be repaired.

6.4.4 Service condition data

Service condition data are required, consisting of:

- a) lifetime requirements/expectation of the repair system life;
- b) required design and operating pressures (internal and external)/temperatures;
- c) expected future service conditions;
- d) if applicable, MAWP as calculated according to the requirements of ASME B31G, API RP 579, BS 7910 or another applicable standard. This shall be carried out taking into account the current position and any possible further degradation in the future.

An example of a design data sheet is presented in Annex A.

6.4.5 Repair system qualification data

The documentation and qualification data related to repair systems that shall be provided by suppliers are shown in Table 3.

Details of the qualification data to be provided by the suppliers are given in Annex B.

Table 3 — Documentation and data requirements

Documentation requirement	Class 1	Class 2	Class 3
Material documentation and data	✓	✓	✓
Design capability		✓	✓
Surface preparation documentation	✓	✓	✓
Short-term test data	✓	✓	✓
Long-term test data		✓	✓

Clarification of the terms used in Table 3 is as follows:

a) Material documentation and data

This shall include a statement of the resins and reinforcements used and any standards to which they are supplied. Basic data on material compatibility with the working environment shall also be available. It shall be ensured that any chemical interaction between the resin (and associated curing agents) and substrate will not cause further degradation of the substrate. Also attention shall be given to CFRP laminates and the potential for bimetallic (galvanic) corrosion of the substrate.

b) Design capability

Suppliers who offer a repair option for Class 2 and 3 repairs shall provide design calculations with supporting data.

c) Surface preparation

The durability of a bonded assembly under applied load is determined to a large extent by the quality of the surface preparation used. Details of the surface preparation procedure and how it is to be implemented shall be provided.

d) Short-term test data

These shall include tensile strength and modulus in both the hoop and axial directions and the strength of the (adhesive) bond between the repair laminate and the substrate.

e) Long-term test data

These shall include the strength of the adhesive bond between the repair laminate and substrate and optionally the ultimate tensile strain of the repair laminate. Long-term is defined as greater than or equal to 1 000 h.

Table 4 lists the data required to comply with Class 3 requirements. Annex B contains the full details of the qualification data requirements.

Table 4 — Qualification test requirements

	Material property	Test method
Mechanical properties	Young's modulus	ISO 527-1, ISO 527-4 (or ASTM D3039)
	Poisson's ratio	ISO 527-1, ISO 527-4 (or ASTM D3039)
	Shear modulus	ASTM D5379
	Thermal expansion coefficient	ISO 11359-2 (or ASTM D696)
	Glass transition temperature of resin or heat distortion temperature of resin	ISO 11357-2 (or ISO 75-3, ASTM D6604, ASTM E1640, ASTM E831), ASTM E2092
	Barcol or Shore hardness	ISO 868 or EN 59 (or ASTM D2583)
Adhesion strength	Lap shear	EN 1465 (or ASTM D3165)
Performance data	Long-term strength (optional)	Annex E
	Energy release rate (optional)	Annex D
	Short-term pipe spool survival test (optional)	Annex C

6.5 Design methodology

6.5.1 Overview

There are two design cases.

a) Defect type A design case

The defect is within the substrate, not through-wall and not expected to become through-wall within the lifetime of the repair system, requiring structural reinforcement only. One of the following three design methods shall be used:

- 1) include allowance for the substrate (see 6.5.4);
- 2) exclude allowance for the substrate (see 6.5.5);
- 3) long-term performance test data (see 6.5.6).

b) Defect type B design case

The substrate requires structural reinforcement and sealing of through-wall defects (leaks). For substrates with active internal corrosion, the repair laminate shall be designed on the assumption that a through-wall defect will occur if the remaining wall thickness at the end of service life is expected to be less than 1 mm. Both of the following design methods shall be used:

- 1) the design method in 6.5.7;
- 2) the design method for the Defect type A design case.

The greater repair thickness from the Defect type A design case or the design method in 6.5.7 shall be taken as the repair laminate thickness, t_{design} .

Subclauses 6.5.9 and 6.5.10 shall be considered for each design case and applied where appropriate, with the largest thickness being taken as the repair laminate thickness, t_{design} .

6.5.2 Environmental compatibility

The suitability for use of the repair system in the service environment shall be based on the following considerations. The service environment is the environment that contacts the repair laminate. It may be either the external or internal environment.

The qualification of the repair system (6.4.5) demonstrates that the repair system is compatible with aqueous and hydrocarbon environments at the qualification test temperature. In general, thermoset resins are compatible with a wide range of environments, but consideration shall be given when the environment is strongly acidic (pH < 3,5), strongly alkaline (pH > 11) or is a strong solvent, e.g. methanol, toluene in concentration greater than 25 %.

Resistance to UV degradation and weathering (where appropriate) shall be provided by data from the resin supplier.

When the environmental compatibility of the repair system is unknown, then the repair system supplier shall provide one of the following to demonstrate compatibility:

- environmental compatibility data or experience of previous applications from the resin supplier, demonstrating that the environment is no more aggressive than aqueous or hydrocarbon environments at the design temperature;

- if no compatibility data from the resin supplier are available, then specific environmental testing is required. One of the following test procedures – ISO 10952, ASTM D543, ASTM C581, ASTM D3681 or equivalent – comparing the exposure of the specific environment and aqueous environment to the repair laminate at the design temperature shall be performed. The repair system shall be considered compatible to the specific environment if the test results from the specific environment are no worse than for the aqueous environment.

When erosion is the cause of the degradation process of the substrate and the repair laminate is in contact with the eroding medium, then the repair laminate can suffer material loss. The repair system supplier shall calculate the survival of the repair system for the specified repair lifetime assuming a conservative estimate of the loss of laminate material. Alternatively, a metal plate can be placed over the affected area prior to application of the repair laminate to minimize material loss (of the laminate).

6.5.3 Design temperature effects

For a design temperature, T_d , greater than 40 °C, the repair system shall not be used at a temperature higher than the glass transition temperature (T_g) less 30 °C. For repair systems for which a T_g cannot be measured, the repair system shall not be used above the HDT less 20 °C. For repair systems which do not exhibit a clear transition point, i.e. a significant reduction in mechanical properties at elevated temperatures, then an upper temperature limit, T_m , shall be defined (or quoted) by the repair supplier.

For a repair system where the defect within the substrate is not through-wall, the temperature limit can be relaxed to T_g less 20 °C or HDT less 15 °C. T_g or HDT shall be measured in accordance with Table 4.

Table 5 summarizes the upper temperature limit of the repair.

Table 5 — Service temperature limits for repair systems

	Defect type B limit T_m	Defect type A limit T_m
T_g measured	$T_g - 30$ °C	$T_g - 20$ °C
HDT measured	HDT - 20 °C	HDT - 15 °C

For design temperatures ≤ 40 °C (and Class 1 and Class 2 repairs), adequate cure of the field-applied repair laminate or adhesive shall be demonstrated by Barcol or Shore hardness testing. For these conditions, no acceptance criteria linked to T_g or HDT are stipulated. Adequate cure is defined as a measured hardness value, and shall be no less than 90 % of the minimum obtained from repair system qualification in accordance with Table 4.

The temperature de-rating factor, f_{T1} , to account for elevated design temperature application used in Equation (8) is given in Table 6, where T_m is the upper temperature limit for the system (as defined in Table 5), in degrees Celsius.

Table 6 — Temperature de-rating factor for composite allowable strains, f_{T1}

Design temperature T_d °C	Temperature factor f_{T1}
$T_d = T_m$	0,70
$T_m - 20$	0,75
$T_m - 40$	0,85
$T_m - 50$	0,90
$T_m - 60$	1,00

Factors for intermediate temperatures shall be obtained by interpolation.

The additional requirements for repairs to through-wall defects are qualified through performance testing. To allow for higher design temperatures than the qualification test temperature, Table 7 defines the temperature de-rating factor, f_{T2} , that shall be applied to Equations (11), (12) and (13), where T_{amb} is the ambient test temperature, in degrees Celsius, and T_{test} is the qualification test temperature, in degrees Celsius.

Table 7 — Temperature de-rating factor for through-wall defects (type B defect), f_{T2}

Temperature °C	Temperature factor f_{T2}
$T_d - (T_{test} - T_{amb}) = T_m$	0,70
$T_d - (T_{test} - T_{amb}) = T_m - 20$	0,75
$T_d - (T_{test} - T_{amb}) = T_m - 40$	0,85
$T_d - (T_{test} - T_{amb}) = T_m - 50$	0,90
$T_d - (T_{test} - T_{amb}) = T_m - 60$	1,00

For Table 7 to be appropriate, the same post-curing regime between qualification test sample preparation and in-service application shall apply.

The split in requirement for service temperatures at 40 °C is to ensure consistency with ASME PCC-2 [11].

6.5.4 Design based on substrate-allowable stress (defect type A)

Use of the design method in this subclause is appropriate if the contribution of the substrate is to be included in the calculation for load-carrying capability.

For piping systems, Equations (1) and (2) shall be used. In the derivation of these equations it is assumed that the repair thickness is limited by the allowable stress in the substrate.

In the circumferential direction, the minimum repair laminate thickness, t_{min} (expressed in millimetres), due to internal pressure is given by Equation (1):

$$t_{min,c} = \frac{D}{2s} \cdot \left(\frac{E_s}{E_c} \right) \cdot (p_{eq} - p_s) \tag{1}$$

In the axial direction, the minimum repair laminate thickness, t_{min} (expressed in millimetres), due to internal pressure, bending and axial thrust is given by Equation (2):

$$t_{min,a} = \frac{D}{2s} \left(\frac{E_s}{E_a} \right) \cdot \left(\frac{2F_{eq}}{\pi D^2} - p_s \right) \tag{2}$$

where

E_a is the axial modulus of the repair laminate, expressed in megapascals;

E_c is the circumferential modulus of the repair laminate, expressed in megapascals;

E_s is the modulus of substrate, expressed in megapascals;

D is the external diameter, expressed in millimetres;

F_{eq} is the equivalent axial load, expressed in newtons [see Equation (3)];

- s is the allowable stress of the substrate material, expressed in megapascals;
- p_{eq} is the equivalent internal pressure, expressed in megapascals [see Equation (3)],
- p_s is the MAWP, expressed in megapascals.

In Equation (2), the contribution of F_{eq} shall be taken as positive.

p_{eq} and F_{eq} are defined as:

$$p_{\text{eq}} = p \left[1 + \frac{16}{(\pi D^2 p)^2} \left(F_{\text{sh}} + \frac{2}{D} M_{\text{to}} \right)^2 \right] \quad (3)$$

$$F_{\text{eq}} = \frac{\pi}{4} p D^2 + \sqrt{F_{\text{ax}}^2 + 4F_{\text{sh}}^2} + \frac{4}{D} \sqrt{M_{\text{ax}}^2 + M_{\text{to}}^2}$$

where

- p is the internal design pressure, expressed in megapascals;
- F_{sh} is the applied shear load, expressed in newtons;
- M_{to} is the applied torsional moment, expressed in newton millimetres;
- F_{ax} is the applied axial load, expressed in newtons;
- M_{ax} is the applied axial moment, expressed in newton millimetres.

The design repair thickness, t_{design} (expressed in millimetres), shall be the maximum value of $t_{\text{min,c}}$ and $t_{\text{min,a}}$ determined from Equations (1) and (2).

If the purpose of the repair system is to strengthen an undamaged section to carry additional bending or other axial loads, the value of F_{eq} shall be taken to be the increased total axial load requirement, and the value of p_s shall be the original MAWP.

For pipelines, Equation (4) or Equation (5) shall be used. In the derivation of these equations it is assumed that the repair thickness is limited by the allowable strain of the repair laminate (see 6.5.5). Only hoop loading is considered in determining the minimum wall thickness of the repair laminate.

In the circumferential direction, the minimum repair laminate thickness, t_{min} (expressed in millimetres), due to internal pressure is given by Equation (4):

$$\varepsilon_c = \frac{p_{\text{eq}} D}{2E_c t_{\text{min}}} - s \frac{t_s}{E_c t_{\text{min}}} - \frac{p_{\text{live}} D}{2(E_c t_{\text{min}} + E_s t_s)} \quad (4)$$

where

- p_{live} is the internal pressure during repair installation, expressed in megapascals;
- ε_c is the allowable repair laminate circumferential strain, expressed in millimetres per millimetre;
- t_s is the minimum remaining substrate wall thickness, expressed in millimetres.

If the repair is applied at zero internal pressure, i.e. $p_{\text{live}} = 0$, then Equation (4) can be rearranged to give:

$$t_{\text{min}} = \frac{1}{\varepsilon_c E_c} \left(\frac{p_{\text{eq}} D}{2} - s t_s \right) \quad (5)$$

The design repair thickness, t_{design} , shall be taken as the value determined from either Equation (4) or Equation (5).

Equations (1) to (5) are valid for repair thickness $t_{\text{design}} < \frac{D}{6}$

The assumptions made in deriving Equations (4) and (5) are that the substrate is elastic and only contributes to the load-sharing up to the allowable stress (of the substrate).

6.5.5 Design based on repair laminate allowable strains (defect type A)

Use of the design method in this subclause is appropriate if the contribution of the substrate is to be ignored in the calculation for load-carrying capability and if short-term material properties are to be used.

In the circumferential direction, the minimum repair laminate thickness, t_{min} (expressed in millimetres), due to internal pressure, bending and axial thrust is given by:

$$t_{\text{min,c}} = \frac{1}{\varepsilon_c} \left(\frac{p_{\text{eq}} D}{2} \frac{1}{E_c} - \frac{F_{\text{eq}} \nu}{\pi D E_c} \right) \quad (6)$$

In Equation (6) the contribution of F_{eq} shall be taken as negative.

In the axial direction, the minimum repair laminate thickness, t_{min} (expressed in millimetres), due to internal pressure, bending and axial thrust, is given by:

$$t_{\text{min,a}} = \frac{1}{\varepsilon_a} \left(\frac{F_{\text{eq}}}{\pi D} \frac{1}{E_a} - \frac{p_{\text{eq}} D}{2} \frac{\nu}{E_c} \right) \quad (7)$$

where

E_a is the axial modulus of the repair laminate, expressed in megapascals;

E_c is the circumferential modulus of the repair laminate, expressed in megapascals;

D is the external diameter of test spool, expressed in millimetres;

F_{eq} is the equivalent axial load, expressed in newtons [see Equation (3)];

p_{eq} is the equivalent internal pressure, expressed in megapascals [see Equation (3)];

ν is the Poisson's ratio of the repair laminate (see Annex B for definition);

ε_a is the allowable repair laminate axial strain, expressed in millimetres per millimetre;

ε_c is the allowable repair laminate circumferential strain, expressed in millimetres per millimetre.

In Equation (7) the contribution of F_{eq} shall be taken as positive.

The design repair thickness, t_{design} , shall be the maximum value of $t_{\text{min,c}}$ and $t_{\text{min,a}}$ determined from Equations (6) and (7).

Equations (6) and (7) are valid for repair thickness $t_{\text{design}} < \frac{D}{6}$

For occasional loads (short-duration loads), Class 1 minimum repair-lifetime (2 year) strains shall be used; see Table 8.

The allowable strains presented in Table 8 shall only be used if the short-term strain to failure of the repair laminate is greater than 1 %, otherwise performance data from 6.5.6 shall be used. The short-term strain to failure can be derived from the test carried out to determine the tensile properties of the laminate (Table 4).

The thermal expansion coefficient for a repair laminate is different from that of the substrate, resulting in the generation of thermal stresses within the repair laminate when the design temperature is different from the installation temperature. This effect shall be considered in the design assessment by subtracting the thermally induced strains from the allowable strains. The temperature factor, f_{T1} , shall be applied to the allowable strain before subtraction. The allowable repair laminate thermal strains in the circumferential and axial directions, ε_c and ε_a , shall be calculated by:

$$\begin{aligned} \varepsilon_c &= f_{T1}\varepsilon_{c0} - |\Delta T(\alpha_s - \alpha_c)| \\ \varepsilon_a &= f_{T1}\varepsilon_{a0} - |\Delta T(\alpha_s - \alpha_a)| \end{aligned} \tag{8}$$

where

ε_{a0} is the allowable repair laminate axial strain (no temperature effect, see Table 8), expressed in millimetres per millimetre;

ε_{c0} is the allowable repair laminate circumferential strain (no temperature effect, see Table 8), expressed in millimetres per millimetre;

f_{T1} is the temperature de-rating factor, see Table 6;

α_a is the repair laminate thermal expansion coefficient, axial direction, expressed in millimetres per millimetre degree Celsius;

α_c is the repair laminate thermal expansion coefficient, circumferential direction, expressed in millimetres per millimetre degree Celsius;

α_s is the substrate thermal expansion coefficient, expressed in millimetres per millimetre degree Celsius;

ΔT is the difference between design and installation temperatures, expressed in degrees Celsius.

Table 8 — Allowable strains for composite laminates as a function of repair lifetime

Modulus	Allowable strain			Allowable strain			Allowable strain		
	Class 1			Class 2			Class 3		
	%			%			%		
Repair lifetime years	2	10	20	2	10	20	2	10	20
For $E_a > 0,5 E_c$									
– ε_{c0}	0,40	0,32	0,25	0,35	0,30	0,25	0,30	0,27	0,25
– ε_{a0}	0,40	0,32	0,25	0,35	0,30	0,25	0,30	0,27	0,25
For $E_a < 0,5 E_c$									
– ε_{c0}	0,40	0,32	0,25	0,35	0,30	0,25	0,30	0,27	0,25
– ε_{a0}	0,25	0,16	0,10	0,10	0,10	0,10	0,10	0,10	0,10

Table 8 is used in the following manner. For example, for a Class 2 repair design lifetime of 8 years with ($E_a < 0,5 E_c$), the allowable strains can be either extrapolated or taken from the next highest repair lifetime, i.e. 10 years, implying the allowable circumferential and axial strains are 0,3 % and 0,1 % respectively.

The values in Table 8 include a service factor for safety equivalent to 0,67.

6.5.6 Design based on repair-allowable stresses determined by performance testing (defect type A)

Use of the design method in this subclause is appropriate if performance-based test data are available.

Annex E provides three methods for the determination of long-term failure stress (or strain) of the repair laminate.

If allowance for the substrate is not to be included, then Equation (9) shall be used.

In the circumferential direction, the minimum repair laminate thickness, t_{min} (expressed in millimetres), due to internal pressure, bending and axial thrust, is given by:

$$t_{min} = \frac{1}{f_{perf} \cdot s_{lt}} \left(\frac{p_{eq} D}{2} - \frac{\nu F_{eq}}{\pi D} \right) \tag{9}$$

In Equation (9) the contribution of F_{eq} shall be taken as negative.

For axial stresses due to internal pressure, bending and axial thrust, the minimum repair laminate thickness, t_{min} (expressed in millimetres), is given by Equation (2) or Equation (7) as appropriate.

The design repair laminate thickness, t_{design} , shall be the greater of the values determined.

If allowance for the substrate is to be included, then Equation (10) shall be used.

For hoop stresses due to internal pressure, the design repair laminate thickness, t_{design} , is given by:

$$t_{design} = \left(\frac{1}{f_{perf} \cdot s_{lt}} \right) \left(\frac{p_{eq} D}{2} - s t_s \right) \tag{10}$$

where

- F_{eq} is the equivalent axial load, expressed in newtons [see Equation (3)];
- p_{eq} is the equivalent internal pressure, expressed in megapascals [see Equation (3)];
- D is the external diameter of test spool, expressed in millimetres;
- s is the allowable stress of the substrate material, expressed in megapascals;
- t_s is the minimum remaining substrate wall thickness, expressed in millimetres;
- s_{lt} is the lower confidence limit of the long-term stress, expressed in megapascals (see Annex E);
- f_{perf} is the service de-rating factor; see Table 9.

Table 9 — Service factor, f_{perf} , for performance data of repair systems

Service factor	Class 1			Class 2			Class 3		
	2	10	20	2	10	20	2	10	20
Repair lifetime, years	2	10	20	2	10	20	2	10	20
1 000 h data	0,83	0,65	0,5	0,67	0,58	0,5	0,6	0,55	0,5
Design life data	1	0,83	0,67	0,83	0,75	0,67	0,75	0,71	0,67

6.5.7 Design of repairs for through-wall defects (defect type B)

A defect within a substrate shall be considered through-wall if the wall thickness at any point of the affected area is determined to be less than 1 mm at the end of its life.

Use of the design method in this subclause is appropriate if the defect within the substrate is through-wall or deemed to become through-wall at the end of its life. The requirements of this subclause are in addition to those described in 6.5.4, 6.5.5 or 6.5.6.

For a circular or near-circular defect, the minimum thickness for a repair laminate, t_{\min} (expressed in millimetres), shall be calculated using:

$$p = f_{T2} f_{\text{leak}} \sqrt{\left\{ \frac{0,001 \gamma_{\text{LCL}}}{(1-\nu^2) \left\{ \frac{3}{512 t_{\min}^3} d^4 + \frac{1}{\pi} d \right\} + \frac{3}{64 G t_{\min}} d^2} \right\}} \quad (11)$$

where

E_{ac} is the combined tensile modulus $\sqrt{E_a E_c}$, expressed in megapascals;

G is the shear modulus of the repair laminate, expressed in megapascals;

p is the design internal pressure, expressed in megapascals;

ν is the Poisson's ratio of the repair laminate (see Annex B for definition);

d is the diameter of defect, expressed in millimetres;

t_{\min} is the thickness of repair laminate, expressed in millimetres;

γ_{LCL} is the 95 % lower confidence limit of energy release rate, expressed in joules per square metre (see Annex D);

f_{T2} is the temperature de-rating factor; see Table 7;

f_{leak} is the service de-rating factor; see Equation (15).

Where the design incorporates a plug to allow the repair of a live line, the procedure described shall be used. The tests carried out to determine the value of γ_{LCL} (Annex D) shall be conducted on the whole assembly, including any plug arrangement.

Equation (11) is valid for defect sizes $d \leq \sqrt{6Dt}$

where

D is the substrate external diameter, expressed in millimetres;

t is the substrate wall thickness, expressed in millimetres.

For non-circular defects that have an aspect ratio < 5 , Equation (11) shall be used, where the value of d (effective defect diameter) is selected such that it contains the defect.

For a circumferential slot type defect, the minimum thickness for a repair laminate, t_{min} , expressed in millimetres, is calculated using the smallest value of repair thickness calculated from both Equation (12) and Equation (13):

$$p = f_{T2} f_{leak} \left\{ \frac{0,001 \gamma_{LCL}}{\frac{(1-\nu^2)}{E_{ac}} \left[\frac{1}{24 t_{min}^3} w^4 + \frac{\pi}{4} w \right] + \frac{3}{16 G t_{min}} \frac{\left(\frac{4}{5} + \frac{\nu}{2}\right)}{(1+\nu)} w^2} \right\} \quad (12)$$

$$p = \frac{f_{T2} f_{leak}}{D} \sqrt{0,008 E_{ac} t_{min} \gamma_{LCL}} \quad (13)$$

where w is the axial width of the slot, expressed in millimetres.

For an axial slot type defect having a circumferential width of the slot $w = \phi D/2$, expressed in millimetres, the minimum thickness for a repair laminate, t_{min} , expressed in millimetres, is calculated using Equation (14):

$$p = f_{T2} f_{leak} \left\{ \frac{0,001 \gamma_{LCL}}{\frac{(1-\nu^2)}{E_{ac}} \left[\frac{\pi D}{8} \phi + \frac{D^4}{384 t_{min}^3} \phi^4 + \frac{D^4 \left(\frac{E}{4G} + 2\right)}{11520 t_{min}^3} \phi^6 \right]} \right\} \quad (14)$$

where the limit on the applicability of Equation (14) is given by $\phi < 1$, where ϕ is the angle subtended by the axial slot, expressed in radians.

The value of the service factor, f_{leak} , shall be set to:

Class 1	Class 2	Class 3
$f_{leak} = 0,83 \times 10^{-0,0208 8(t_{lifetime}-1)}$	$f_{leak} = 0,75 \times 10^{-0,018 56(t_{lifetime}-1)}$	$f_{leak} = 0,666 \times 10^{-0,015 84(t_{lifetime}-1)}$

where $t_{lifetime}$ is the design lifetime, expressed in years.

If long-term performance test data are available in accordance with Annex E, then the service factor, f_{leak} , shall be calculated using:

Class 1	Class 2	Class 3
$f_{leak} = 0,83 f_D$	$f_{leak} = 0,75 f_D$	$f_{leak} = 0,666 f_D$

where f_D is the degradation factor [defined in Annex G, Equation (G.4)].

The design repair thickness, t_{design} , shall be the maximum value of the minimum repair thickness determined from one of Equations (11), (12), (13) or (14), iteratively, and the design repair thickness derived as in 6.5.4, 6.5.5 or 6.5.6.

In some circumstances it may not be possible to prepare the substrate completely adjacent to the repair. Often a protective metal plate is used to protect the damaged substrate during surface preparation, e.g. grit blasting. In these circumstances, the defect area shall be taken as the unprepared substrate surface area (including metal plate plus any fairing material) and not the size of the actual defect.

6.5.8 Axial extent of repair

The design thickness of the repair laminate shall extend beyond the damaged region in the substrate by the larger of 50 mm or l_{over} expressed in millimetres, where l_{over} is given by Equation (17) or Equation (18):

For slot type defects:

$$l_{\text{over}} = 2\sqrt{Dt} \quad (17)$$

For circular type defects:

$$l_{\text{over}} = 4d \quad \text{where} \quad d < 0,5\sqrt{Dt} \quad (18)$$

where

d is the diameter of defect, expressed in millimetres;

D is the external diameter of substrate, expressed in millimetres;

t is the thickness of substrate, expressed in millimetres.

If the equality in Equation (18) is not satisfied, then Equation (17) shall be used. Annex H presents a look-up table of axial extent of repair as a function of both diameter and defect size.

The total axial length of the repair, l (expressed in millimetres), is given by Equation (19):

$$l = 2l_{\text{over}} + l_{\text{defect}} + 2l_{\text{taper}} \quad (19)$$

The ends of the repair laminate shall be tapered if axial loads are present. These axial loads can result solely from end effects due to internal pressure, or can result from system loads such as bending or thermal expansion. A minimum taper of approximately 5:1 is recommended.

To check that the axial extent of the repair, l_{over} , is sufficient to ensure that the applied axial load can be transferred from the substrate to the repair, Equation (20) shall be satisfied:

$$l_{\text{over}} > \frac{E_a \varepsilon_a t_{\text{min,a}}}{\tau} \quad (20)$$

where

E_a is the axial modulus of repair laminate, expressed in megapascals;

ε_a is the allowable axial strain of repair system, expressed in millimetres per millimetre;

$t_{\text{min,a}}$ is the minimum thickness of repair laminate for axial applied loads, expressed in millimetres [see either Equation (2) or Equation (7)];

τ is the lap shear strength, expressed in megapascals (see Annex B).

If the geometry of the section to be repaired is such that it is not possible to achieve the required axial extent of overlay, l_{over} , including required taper length, the following shall apply. The following shall be treated as a special design case and the analysis shall be completed prior to application of the repair system.

To account for the limited axial extent (i.e. less than 50 mm) of available substrate ($l_{\text{available}}$), the design repair thickness, t_{design} , determined from 6.5.4, 6.5.5, 6.5.6 or 6.5.7 shall be increased by the repair thickness increase factor, $f_{\text{th,overlay}}$, defined as:

$$f_{\text{th,overlay}} = \left(\frac{l_{\text{over}}}{l_{\text{available}}} \right)^{2/3} \quad (21)$$

where $t_{\text{design}} = f_{\text{th,overlay}} t_{\text{design,original}}$.

A detailed engineering stress analysis of the adhesive layer, demonstrating that the axial load can be transmitted between the repair and the substrate, shall be performed. The analysis shall also demonstrate that the average principal stress (averaged over the stressed part of the adhesive layer) is less than three times the average principal stress value from lap shear test data (see Table 4).

The minimum axial extent of available overlay length that repairs can be applied to is defined as either

- a) $l_{\text{available}}$ shall be at least 25 mm, or
- b) $f_{\text{th,overlay}}$ shall be no greater than 2,5 mm.

If there is limited axial extent of available substrate, it will not be possible to taper the repair laminate. For this case, the transition between the repair laminate and the restraining substrate, e.g. flange face, shall be as smooth as possible to minimize stress concentrations. However, where possible the repair laminate should always be tapered, particularly when axial loads are present, in order to minimize edge stresses within the repair laminate.

The total axial extent of the repair for reduced axial extent is therefore as given below:

For one-sided reduced axial extent:

$$l = l_{\text{over}} + l_{\text{defect}} + l_{\text{taper}} + l_{\text{available}}$$

For two-sided reduced axial extent:

$$l = l_{\text{defect}} + l_{\text{available,1}} + l_{\text{available,2}} \quad (22)$$

where the larger of the two values of $f_{\text{th,overlay}}$ is taken to determine the design thickness of the repair, Equation (21).

When applying repairs over components, e.g. flanges, clamps, etc., to achieve the appropriate axial length of repair, the axial profile of the repair shall be as smooth as is practically possible to reduce sharp changes in diameter, thus minimizing local stress concentrations. This may result in a thickening of the repair to ensure a smooth axial profile.

When applying repairs up to raised faces, the transition from the repair to the raised face shall be contoured to avoid sharp changes in directions.

6.5.9 Optional design considerations

6.5.9.1 Impact

The repair system supplier shall demonstrate that the repair to a through-wall defect (type B defect) is capable of withstanding a low-velocity 5 J impact representative of a dropped tool. The demonstration test shall be carried out in accordance with the procedure described in Annex F.

6.5.9.2 Cyclic loading

Cyclic loading is not necessarily limited to internal pressure loads. Thermal and other cyclic loads shall also be considered when assessing cyclic severity.

If the predicted number of pressure or other loading cycles is less than 7 000 over the design life, then cyclic loading shall not be considered (in accordance with ISO 14692).

If the predicted number of pressure or other loading cycles exceeds 7 000 over the design life, then cyclic loading shall be considered.

If the predicted number of pressure or other loading cycles exceeds 10^8 over the design life, then in Equations (24) and (25) N shall be set to 10^8 .

For 6.5.4 and 6.5.5, the composite allowable strain in both circumferential and axial directions, ε_c and ε_a , (see Table 8), shall be de-rated by the factor, f_c , i.e.:

$$\begin{aligned}\varepsilon_c &= f_c \varepsilon_{c,\text{non-cyclic}} \\ \varepsilon_a &= f_c \varepsilon_{a,\text{non-cyclic}}\end{aligned}\quad (23)$$

where

$\varepsilon_{a,\text{non-cyclic}}$, $\varepsilon_{c,\text{non-cyclic}}$, are the allowable strains in the axial and circumferential directions [as defined in Equation (8)] prior to de-rating for cyclic loading, expressed in millimetres per millimetre;

f_c is given by:

$$f_c = \sqrt{\left(R_c^2 + \frac{1}{2,888 \log_{10} N - 7,108} (1 - R_c^2) \right)} \quad (24)$$

where

R_c is the cyclic loading severity, defined as the ratio of minimum pressure to maximum pressure:

$$R_c = \frac{p_{\min}}{p_{\max}}$$

N is the number of loading cycles.

For 6.5.7, the service factor, f_{leak} , in Equations (11), (12), (13) or (14) shall be replaced by:

$$f_{\text{leak}} = 0,333 \sqrt{\left(R_c^2 + \frac{1}{2,888 \log_{10} N - 7,108} (1 - R_c^2) \right)} \quad (25)$$

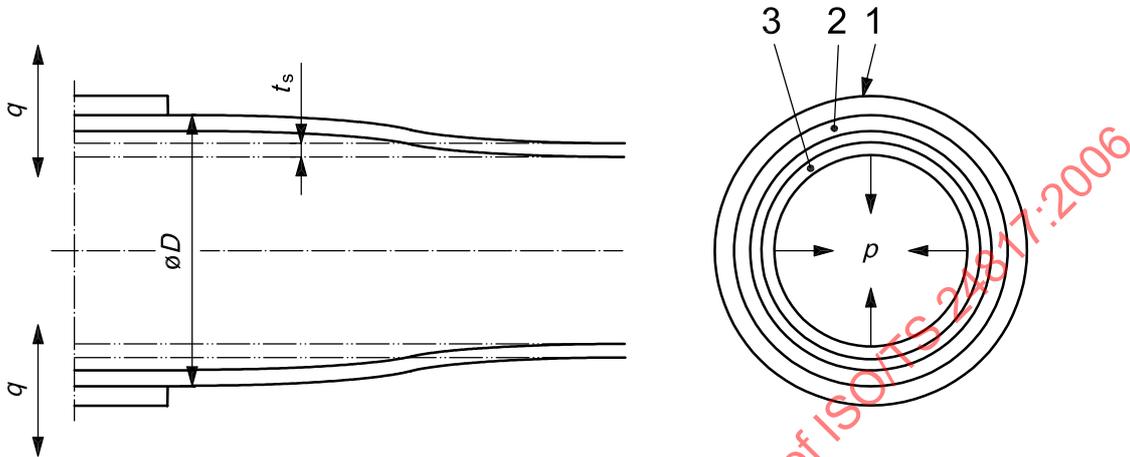
Equations (24) and (25) are intended primarily for cyclic internal pressure loading, but may be applied with caution to axial and thermal loads provided they remain tensile, i.e. the equations are not applicable for reversible loading.

6.5.9.3 Live repairs

If repairs are applied to substrates under live conditions, then the strength- and fracture-toughness of the bond at the interface between the repair laminate and substrate shall be assessed for the specific case during operation when the internal pressure, p_{after} , after the repair system is applied is less than the internal pressure, p_{live} , within the substrate during application of the repair, i.e. $p_{\text{after}} < p_{\text{live}}$.

To assess the strength of the bond of the repair interface, the tensile stress acting on the bond, q (expressed in megapascals), shall be compared to the minimum bond strength defined in Annex B (lap shear strength).

Figure 1 schematically describes the key variables, where, q is the tensile pressure acting on the interface between the repair and the steel substrate when the pipe is depressurised. This tensile stress is due to the fact that the steel contracts more than the composite.



Key

- 1 repair
- 2 pipe before repair (live)
- 3 pipe after repair
- p is the design internal pressure
- q is the tensile pressure (stress) on the interface
- D is the external pipe diameter
- t_s is the minimum remaining substrate wall thickness

Figure 1 — Schematic diagram of live repair

The tensile stress, q (expressed in megapascals), acting on the interface is given by Equation (26):

$$q = (p_{\text{live}} - p_{\text{after}}) \left(1 - \frac{E_s t_s}{(E_s t_s + E_c t_{\text{design}})} \right) + (\alpha_c - \alpha_s)(T_{\text{live}} - T_{\text{after}}) \frac{2E_c t_{\text{design}}}{D} \quad (26)$$

where

- p_{live} is the internal pressure when repair is applied, expressed in megapascals;
- p_{after} is the internal pressure after repair is applied, expressed in megapascals;
- E_c is the circumferential tensile modulus of repair laminate, expressed in megapascals;
- t_{design} is the thickness of repair laminate, expressed in millimetres;
- α_c is the repair laminate thermal expansion coefficient, circumferential direction, expressed in millimetres per millimetre degree Celsius;
- α_s is the substrate thermal expansion coefficient, expressed in millimetres per millimetre degree Celsius;

T_{live} is the temperature when repair is applied, expressed in degrees Celsius;

T_{after} is the temperature after repair is applied, expressed in degrees Celsius;

D is the external diameter of substrate, expressed in millimetres.

The value of q shall be less than the lap shear strength, see Annex B.

6.5.9.4 Fire performance

The requirements for fire performance shall be identified in the risk assessment. Flame spread and smoke generation shall also be considered in the assessment. Due account shall be taken of the response of the repair system. In many cases additional fire protection is not necessary, as the substrate may still be able to perform satisfactorily during the short duration of a fire event. However, conduction from the metal substrate can cause the temperature of the repair laminate to exceed its glass transition temperature, limiting the fire performance of the repair system.

Strategies for achieving fire performance include the following:

- application of additional repair material such that enough basic composite will remain intact for the duration of the fire event;
- application of intumescent external coatings;
- application of intumescent and other energy-absorbent materials within the repair laminate;
- use of resin formulations with specific fire-retardant properties.

Further guidance on the design and testing of composites for fire performance is contained in ISO 14692.

Further guidance on the fire test performance properties of repair laminates, smoke index, flame spread index and fuel contribution index is contained in ASTM E84.

6.5.9.5 Cathodic disbondment

For repairs to substrates that are cathodically protected, it may be required to demonstrate that the repair will not disbond due to the cathodic protection system.

ASTM G8 shall be used to demonstrate that the repair system is not susceptible to disbondment under an imposed electrical current.

6.5.9.6 Electrical conductivity

For repairs to metallic substrates, it is likely that the properties of the substrate will satisfy electrical conductivity requirements.

If the substrate is insulating, e.g. composed of FRP, and electrical conductivity requirements are specified, the electrical conductivity properties of the repair system shall be measured to ensure that the original characteristics of the substrate are restored.

Electrical conductivity testing shall be carried out in accordance with ISO 14692.

6.5.9.7 External loads

The minimum repair thickness, t_{\min} (expressed in millimetres), to resist external pressure or vacuum applied to the repair system is given by:

$$t_{\min} = D \left[\frac{3(1-\nu^2)p_e}{2E_c} \right]^{1/3} \tag{27}$$

The minimum repair thickness, t_{\min} (expressed in millimetres), to resist soil loads to prevent collapse of a buried repaired substrate is given by:

$$t_{\min} = D \left[\frac{3(1-\nu^2)p_{\text{ext,soil}}}{2E_c} \right]^{1/3} \tag{28}$$

where $p_{\text{ext,soil}} = \frac{4}{\pi D} \left[D\left(h + \frac{D}{2}\right) - \frac{\pi D^2}{8} + \frac{1}{3}\left(h + \frac{D}{2}\right)^2 \right] W_{\text{soilg}}$

where

- p_e is the external or vacuum pressure, expressed in megapascals;
- $p_{\text{ext,soil}}$ is the external soil pressure, expressed in megapascals;
- ν is the Poisson's ratio of the repair laminate (see Annex B for definition);
- D is the external diameter of substrate, expressed in millimetres;
- E_c is the circumferential tensile modulus of repair laminate, expressed in megapascals;
- h is the burial depth (to centreline), expressed in millimetres;
- W_{soilg} is the specific weight of soil, expressed in megapascals per millimetre.

The design repair thickness, t_{design} , shall be the maximum value of the minimum repair thickness determined from Equation (27) or Equation (28) and the design repair thickness derived in 6.5.1.

Further guidance on trench back-fill and other loadings can be obtained from ISO 14692.

6.5.10 Repair of other components

The repair system supplier shall demonstrate that the performance of the repair system to components other than straight pipe sections complies with design through pressure testing.

A single test for each component, identical to one of those described in Annex D (same diameter, wall thickness and one selected defect size), shall be performed. The repair system shall be considered qualified if the failure pressure of the test is greater than or equal to the failure pressure of the equivalent pipe section.

6.5.10.1 Clamps and other repair systems

Clamps are generally applied over defects much smaller than themselves. The clamp protrudes or stands off a set height from the pipework. The size of the effective defect is a function of the geometry of the clamp or repair system. Often the outer surface of the clamp is not smooth, e.g. bolts, etc., implying it may not be possible to achieve a large enough outer surface area for adequate bonding.

If good bonding between the repair laminate and the full outer surface of the clamp can be demonstrated, the effective size of the defect is a fully circumferential defect at each end of the clamp of axial extent 1,5 times the stand-off height. Either Equation (12) or Equation (13) shall be used to calculate, iteratively, the minimum repair thickness, t_{\min} (expressed in millimetres).

If good bonding between the repair laminate and the clamp surface cannot be demonstrated, the effective size of the fully circumferential defect is the axial extent of the clamp plus an axial distance of three times the stand-off distance. Equation (13) shall be used to calculate the minimum repair thickness, t_{\min} (expressed in millimetres).

The same principle as outlined for clamps shall also apply to the repair of existing repair systems.

If it can be demonstrated that the repair is still bonded to the substrate, then the defect size is taken as 1,5 times the thickness of the existing repair and either Equation (12) or Equation (13) shall be used to calculate the minimum repair thickness, t_{\min} (expressed in millimetres).

If it cannot be demonstrated that the existing repair is bonded to the substrate, then the size of the defect is the total axial extent of the existing repair (axial extent of repair plus taper length), and Equation (13) shall be used to calculate the minimum repair thickness, t_{\min} (expressed in millimetres).

The axial profile of the repair laminate should be as smooth as possible in the transition from the main pipe body to the component causing the protuberance.

The axial length of the repair to either clamps or existing repairs shall be calculated using Equation (17).

6.5.10.2 Patches

Repair patches are used when it is impractical for the repair to encompass the full circumference of the component. Typically these components are limited to large diameter (greater than 600 mm) pipework, pipelines or vessels.

The thickness of the repairs shall be calculated according to either 6.5.4 or 6.5.5.

The extent of the patch repair shall be the same in both the axial and circumferential directions. The axial extent of the repair shall be calculated according to 6.5.8.

6.5.10.3 Piping system components

The following piping system components are considered:

- bends;
- tees;
- reducers;
- flanges.

The repair design procedure for each piping system component is a comparative approach based on the equivalent straight pipe component (same diameter and thickness). The repair design process is to calculate the thickness of the repair for an equivalent straight pipe section followed by a further calculation of a multiplicative factor, called the repair thickness increase factor, which accounts for the stress intensification due to the geometry of the component.

The first step in the design approach is to calculate the thickness of the repair for the equivalent pipe section of the component as described in 6.5.1, $t_{\text{design, straight pipe}}$ (expressed in millimetres). This repair thickness includes both the repair strength calculation (6.5.4 or 6.5.5) as well as the leak sealing calculation (6.5.7), if appropriate. The second step is to calculate the repair thickness increase factor based on the stress intensity factor corresponding to the piping system component, $f_{\text{th, stress}}$.

The design repair thickness, $t_{\text{design,component}}$ (expressed in millimetres), is given by Equation (29):

$$t_{\text{design, component}} = t_{\text{design, straight pipe}} f_{\text{th, stress}} \tag{29}$$

Table 10 presents repair thickness increase factors, $f_{\text{th, stress}}$, for each piping component.

The axial length of the repair shall be calculated from either Equation (17) or Equation (18).

For tees, the main diameter is defined as that pipe that contains the defect. This pipe diameter shall be used to calculate the repair thickness from the equivalent straight pipe section. The repair thickness increase factor is then applied to this repair thickness.

Table 10 — Repair thickness increase factors for piping system components

Piping system component	Repair thickness increase factor $f_{\text{th, stress}}$	Comment and limits
Bend	1,2	
Tee	$1,4 \left(\frac{1}{2} \left[\frac{D_b}{t_b} \right]^2 \frac{t}{D} \right)^{0,25}$	Minimum value, $f_{\text{th, stress}} = 1,2$ Maximum value, $f_{\text{th, stress}} = 3$ For explanation of symbols, see Figure 2, Diagram 1 where D = external diameter of main pipe (mm) t = wall thickness of main pipe (mm) D_b = external diameter of branch pipe (mm) t_b = wall thickness of branch pipe (mm)
Flange	$1 + 0,064 \left(1 - \frac{t}{t_f} \right)$	$t_f > t$ For explanation of symbols, see Figure 2, Diagram 2 where t = wall thickness of main pipe (mm) t_f = wall thickness of flange (mm)
Reducer	$1 + 0,064 \left(1 - \frac{D_r^2}{D^2} \right)$	$D > D_r$ For explanation of symbols, see Figure 2, Diagram 3 where D = external diameter of main pipe (mm) D_r = external diameter of reducer (mm)

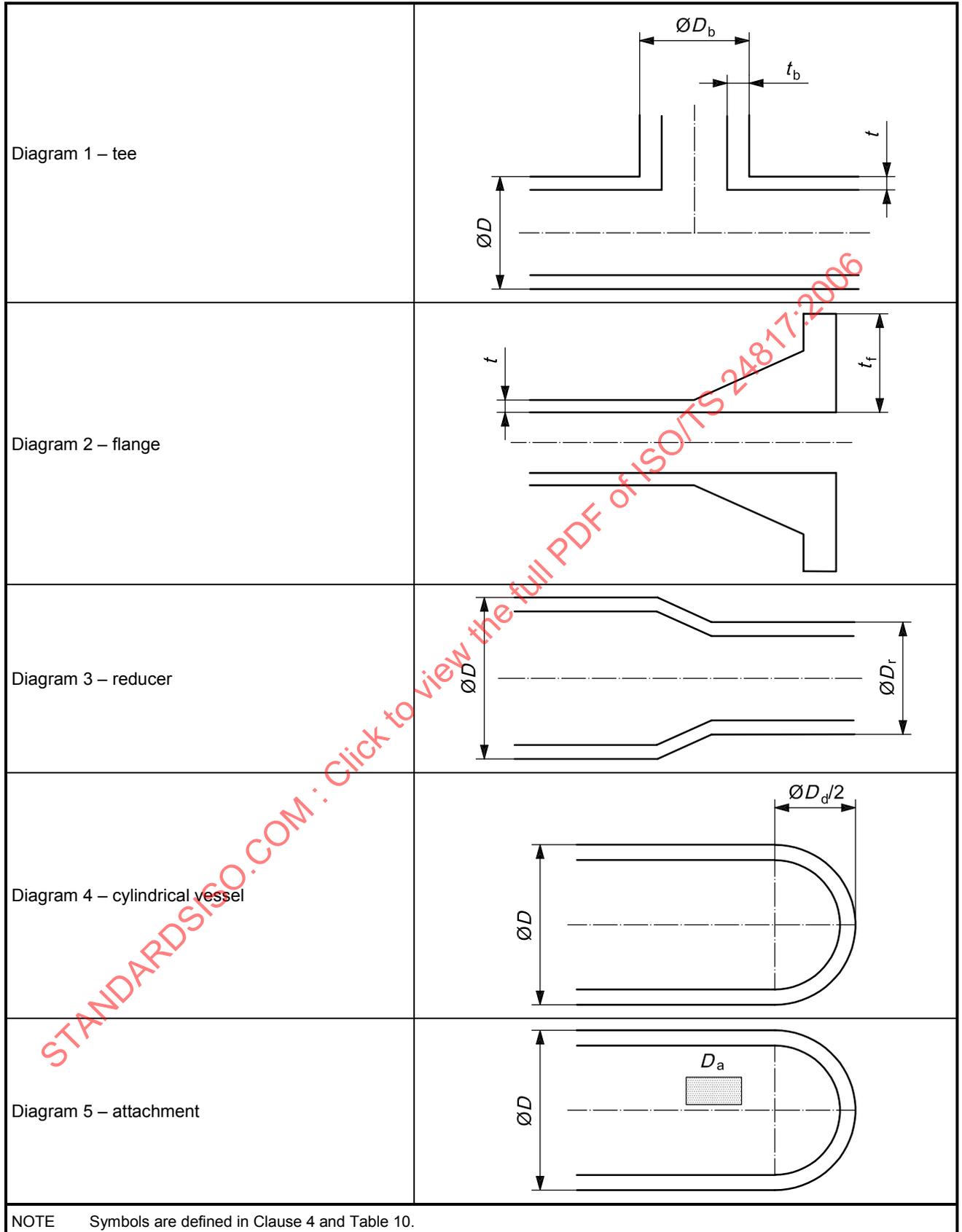


Figure 2 — Schematic diagrams of components

The axial length of repair shall be based on the (larger) dimension of the piping system component and applies to the axial length of repair along both the main body and the branch (where appropriate).

For the repair of tees, the maximum allowable design pressure, p (expressed in megapascals), for the repair laminate design thickness, $t_{\text{design,component}}$ (expressed in millimetres), shall be restricted to:

$$p \leq \frac{2E_c \varepsilon_c t_{\text{design,component}}}{D + D_b} \quad (30)$$

where

ε_c is the circumferential allowable design strain;

D is the external diameter of main body, expressed in millimetres;

D_b is the external diameter of branch, expressed in millimetres;

E_c is the circumferential tensile modulus of repair laminate, expressed in megapascals.

6.5.10.4 Tank and vessel components

The following tank and vessel components are considered:

a) cylindrical vessels:

- end dome, main body connection;
- supports/saddles/rigid attachments;
- tees/nozzles;

b) spherical vessels:

- supports/saddles/rigid attachments;
- tees/nozzles.

For tanks and vessels, there are currently few applications, implying less validation of the proposed empirical rules for the design of the repair system.

The repair design procedure for each vessel component is the same as that described in 6.5.10.3. Table 11 and Table 12 present repair thickness increase factors for cylindrical and spherical tank and vessel components respectively.

The axial length of the repair shall be calculated from either Equation (17) or Equation (18).

Table 11 — Repair thickness increase factors for cylindrical vessel components

Cylindrical vessel component	Repair thickness increase factor $f_{th, stress}$	Comment and limits
End dome, main body connection	$1 + 0,032 \frac{D^2}{D_d^2}$	$D > D_d$ For explanation of symbols see Figure 2, Diagram 4 where D = external diameter of main body (mm) D_d = external diameter of end dome (mm)
Supports, saddles, rigid attachments	$1 + \frac{\pi D_a^2}{2Dt} (K_3 + K_4)$ <p>where</p> $K_3 = 0,22 \cos\left(\frac{\log_{10} C_{rt} - C_{al}}{2}\right)$ $K_4 = 1,8 \left(1 - 0,4 C_{ha}^{0,5}\right) \times \cos\left(\frac{\log_{10} C_{rt}}{2}\right) \times (-\log_{10} C_{al})^{0,3}$	$C_{ha} = \frac{C_h}{C_a}, \quad C_{rt} = 128 \frac{D}{t} \left(\frac{C_a}{D}\right)^2$ $C_{al} = \frac{2C_a}{l}, \quad D_a = 2,35 \sqrt{C_a C_h}$ <p>Minimum value, $f_{th, stress} = 1,2$ Maximum value, $f_{th, stress} = 3$ For explanation of symbols see Figure 2, Diagram 4 where D = external diameter of main body (mm) t = wall thickness of main body (mm) C_a = axial extent of attachment (mm) C_h = hoop extent of attachment (mm) l = length of cylinder (mm)</p>
Teas, nozzles	$\frac{5,522}{(1,2 + t_r)} \rho^{0,45}$ <p>where</p> $\rho = \frac{D_b}{\sqrt{2Dt}}, \quad t_r = \frac{t_b}{t}$	<p>Minimum value, $f_{th, stress} = 1,2$ Maximum value, $f_{th, stress} = 3$ For explanation of symbols see Figure 2, Diagram 1 where D = external diameter of main body (mm) t = wall thickness of main body (mm) D_b = external diameter of tee (mm) t_b = wall thickness of tee (mm)</p>

Table 12 — Repair thickness increase factors for spherical vessel components

Spherical vessel component	Repair thickness increase factor $f_{th, stress}$	Comment
Supports, saddles, rigid attachments	$1 + \frac{\pi D_a^2}{Dt} (K_3 + K_4)$ <p>where</p> $K_3 = 0,38 \exp \left(-2,3 \left[\frac{1,287 D_a}{\sqrt{Dt}} \right]^{0,25} \right)$ $K_4 = 1,2 \exp \left(-2,2 \left[\frac{1,287 D_a}{\sqrt{Dt}} \right]^{0,5} \right)$	<p>Minimum value, $f_{th, stress} = 1,2$</p> <p>Maximum value, $f_{th, stress} = 3$</p> <p>For explanation of symbols see Figure 2, Diagram 5</p> <p>where</p> <p>D = external diameter of main body (mm)</p> <p>t = wall thickness of main body (mm)</p> <p>D_a = equivalent diameter of attachment (mm)</p>
Tees, nozzles	$2 \left[\frac{1 + 0,75 (\rho - 0,95 \sqrt{t_r})^{0,88}}{t_r^{0,31}} \right]$ <p>where</p> $\rho = \frac{D_b}{\sqrt{2Dt}}, \quad t_r = \frac{t_b}{t}$	<p>Minimum value, $f_{th, stress} = 1,2$</p> <p>Maximum value, $f_{th, stress} = 3$</p> <p>For explanation of symbols see Figure 2, Diagram 1</p> <p>where</p> <p>D = external diameter of main body (mm)</p> <p>t = wall thickness of main body (mm)</p> <p>D_b = external diameter of tee (mm)</p> <p>t_b = wall thickness of tee (mm)</p>

The axial length of repair shall be based on the (larger) dimension of the main body and applies to the axial length of repair along both the main body and branch (where appropriate).

For the repair of tees or nozzles, the maximum allowable design pressure, p (expressed in megapascals), for the repair laminate design thickness, $t_{design, component}$ (expressed in millimetres), shall be restricted to:

$$p \leq \frac{2E_c \varepsilon_c t_{design, component}}{D + D_b} \tag{31}$$

where

ε_c is the circumferential allowable design strain, expressed in millimetres per millimetre;

D is the external diameter of main body, expressed in millimetres;

D_b is the external diameter of branch, expressed in millimetres;

E_c is the circumferential tensile modulus of repair laminate, expressed in megapascals.

The application of repairs to vessels may not be fully circumferential around the vessel body. It shall be demonstrated both by design (usually through a finite-element stress analysis) and experiment that a patch repair has identical performance to that of a fully circumferential repair, assuming that the extent of the repair is at least that of the appropriate overlay lengths.

6.5.11 Design output

The outputs of the design calculations for the repair system are the following:

- thickness of the repair laminate, t_{design} , expressed in millimetres;
- total axial repair length, l , expressed in millimetres;

The design thickness of the repair shall be expressed as the number of wraps, n_W , for installation purposes, in accordance with Equation (32):

$$n_W = \frac{t_{\text{design}}}{t_{\text{layer}}} \quad (32)$$

where t_{layer} is the thickness of an individual layer or wrap of repair laminate, expressed in millimetres.

The minimum design thickness for the repair laminate shall be 5 mm. For applications where the potential for external third-party accidental impacts is considered unlikely, then the minimum design thickness requirement may be relaxed to the greater thickness of either two wraps or 2 mm.

6.6 Requalification

6.6.1 Overview

If a change or modification to the repair system has occurred, then the testing specified in 6.6.2 and 6.6.3 shall be completed.

If the modified repair system is found to be of lower performance than the original repair system, then it shall be treated as a new system and validated according to 6.4.5.

If the modified repair system is found to be of higher performance than the original repair system, then it may be treated as a new system and validated according to 6.4.5, or the qualification data from the original repair system may be used.

6.6.2 For type A defect repairs

Requalification tests shall include the testing specified in Clause B.2.

If the repair system has been validated according to Annex B, Performance testing, then the repair system shall be subject to the survival testing specified in Annex E.

6.6.3 For type B defect repairs

Requalification tests shall include testing specified in Clauses B.2 and B.3.

Note that only three tests are required and results shall be compared with γ_{LCL} of the original repair system.

7 Installation

7.1 General

The thickness of the repair system to be installed shall be expressed as the number of wraps to be applied, see 6.5.11.

7.2 Materials of construction

The materials of construction shall be those for which the qualification testing and design (if appropriate) have been completed (see Clause 6).

7.3 Storage conditions

Storage of material shall comply with the repair system supplier's instructions. MSDS sheets shall be retained for reference. All materials shall be stored and controlled according to national safety regulations (e.g. OSHA, COSHH or similar regulations).

All materials shall be clearly labelled with relevant health and safety data, batch number, expiry date and any other relevant technical information.

Control of the temperature during storage shall be maintained. (Shelf lives can be reduced significantly if temperatures are allowed to exceed those specified by the repair system supplier.) Freezing temperatures shall be avoided.

Reinforcements shall be stored to ensure that condensation, due either to storage of material below the dew point or to movement between areas at different temperatures, does not occur.

Shelf lives quoted by the repair system supplier shall be observed.

Disposal of time-expired material shall be carried out in the required manner and according to the repair system supplier's instructions.

7.4 Method statements

Each repair shall be covered by a method statement that describes each of the main procedures to be carried out prior to and during repair system application.

Input to the method statement comes from the following:

- risk assessment (supplied by owner);
- working conditions (supplied by owner);
- installer training/qualification (supplied by repair system supplier);
- design information, including
 - plant operating conditions, layout, etc. (supplied by owner), and
 - design of repair (supplied by repair system supplier);
- materials information for repair system (supplied by repair system supplier).

Typically the method statement includes the following information:

a) **Health and Safety**, comprising

- 1) a list of materials to be handled, including copies of MSDS sheets,
- 2) national safety regulations,
- 3) details of protective measures to be adopted,
- 4) a list of hazards associated with equipment to be repaired and equipment in the vicinity of the repair site with protective measures.

- b) **Installer Training**, comprising details of training requirements for installers.
- c) **Repair Design**, comprising details of laminate lay-up:
 - 1) number of wraps,
 - 2) repair area covered,
 - 3) orientation of individual layers of reinforcement (this may be presented as a written description or a drawing incorporating standard details such as overlap and taper dimensions and length information).
- d) **Repair Application**, comprising
 - 1) details of surface preparation procedure, including method of application, equipment to be used and inspection method,
 - 2) details of in-fill required to achieve a smooth outer profile prior to the application of the laminate,
 - 3) details of time limitations between stages of the repair, e.g. between surface preparation and lamination,
 - 4) details of lay-up procedure, including if the repair laminate is to be applied in stages,
 - 5) details of curing procedure, including post-curing if required.
- e) **Quality Assurance**, comprising
 - 1) details of hold/inspection points in the repair application procedure (see 7.6),
 - 2) details of any materials tests to be carried out, if specified by the owner (see Annex B),
 - 3) details of any systems tests to be carried out (see Clause 9).
- f) **Environmental**, including information on disposal of unused material.

7.5 Installer qualifications

Personnel involved in the installation of a repair system shall be trained and qualified in accordance with Annex I.

7.6 Installation guidance

Repair system suppliers shall provide full installation instructions. These instructions shall include:

- acceptable environmental conditions of the site at the time of repair;
- material storage;
- surface preparation;
- resin system mixing;
- laminate lay-up;
- laminate consolidation procedure (fibre wetting);
- cure;
- key hold points.

Further details of these requirements are listed in Annex J.

The key hold points to be observed during repair system installation are dependent on the repair class and are summarized in Table 13.

Table 13 — Hold points during installation of a repair system

Hold point	Class	Checked by
Method statement	All classes	Installer
Materials preparation		Installer
— reinforcement	All classes	
— resin	All classes	
Surface preparation		
— inspection	All classes	Installer (Class 1)
— surface profile test	Class 3	Supervisor (Classes 2 and 3)
— mechanical test (stipple test)	Class 3	
Filler profile	All classes (where appropriate)	Installer
Stage check on reinforcement	Class 3	Installer
Tests on repair laminate		
— cure (and post-cure) through-hardness test	All classes	Installer (Class 1)
— thickness	All classes	Supervisor (Classes 2 and 3)
— dimensions	All classes	
— external inspection (see Table 14)	All classes	
Pressure test	Class 3	Inspection authority

The results of the tests on the repair laminate shall be compared with the qualification data. Acceptance values of the test results shall be provided by the resin system supplier prior to repair system installation.

7.7 Live repairs

Repairs to defects that are not through-wall within live substrates may be performed, provided that the associated hazards are fully considered in the risk assessment for the operation, e.g. for grit blasting. This shall include any hazards to surrounding live equipment in addition to that being repaired.

7.8 Repair of clamps, piping components, tanks or vessels

Guidance for the surface preparation of clamps, piping components, tanks and vessels is the same as for repairs on straight pipe (see Annex J).

The details of the repair, e.g. repair laminate lay-up and orientation relative to clamps, piping components, tanks or vessels, shall be provided by the repair system supplier. The arrangements at the edges of the repair, e.g. tapering, profiling onto raised faces, shall also be provided by the repair system supplier.

7.9 Environmental considerations

Only repair materials that allow for satisfactory disposal according to prevailing environmental regulations shall be used.

Information and procedures for disposing of unused chemicals, resins and waste shall be provided by the repair system supplier. Incineration in the open air shall not be performed.

8 Testing and inspection

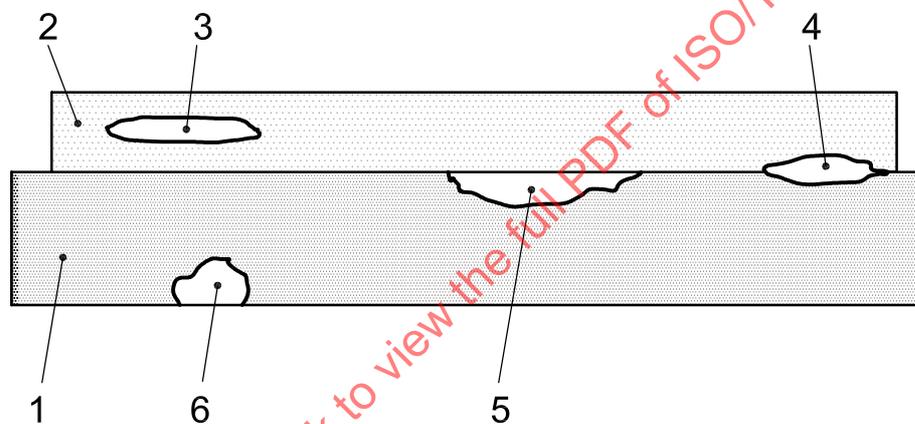
8.1 General

This subclause provides guidance on the post-installation operational issues of repair systems. The installation of a repair system should not influence or prevent any internal inspections (e.g. from pigging inspection tools) that are performed on the substrate.

The main issues for the non-destructive examination of a composite repair system are:

- inspection of the repair laminate;
- inspection of the bond quality between the repair laminate and the substrate;
- inspection of the substrate underneath the repair.

The basic structure of a composite repair system in this context is considered in Figure 3.



Key

- 1 substrate, pipe wall
- 2 composite repair
- 3 internal laminate defect
- 4 interface delamination de-bond
- 5 external defect
- 6 internal defect

Figure 3 — Schematic of a repair system and location of defects

8.2 Allowable defects for the repair system

The defect types and respective allowable limits for the different sections of the repair system are given in Table 14.

The defects that are listed for the repair laminate and resin-rich layer are likely to arise during installation, as opposed to being caused as a result of deterioration in service. As a result, process control and monitoring of the repair material as it is being applied is the primary means of assuring good quality. The information given in Table 14 is typical of that used for composite process equipment, e.g. GRP piping (see ISO 14692).

The defects that are listed for the interface between the repair laminate and the substrate refer primarily to the loss of adhesion. As with the repair laminate, the defects listed for the interface are generated during initial application. In the majority of cases, deterioration during service manifests itself as an interfacial delamination.

The defects that are listed for the substrate relate to those that have been repaired and to possible continued degradation of the wall thickness after repair, due to internal corrosion or erosion. Monitoring of the remaining wall thickness may be required to ensure that the repair system continues to operate within the original design assumptions.

Table 14 — Defect types and allowable limits

Repair section	Defect	Allowable limits	
Substrate prior to repair application	Check substrate material is that for which the repair has been designed		
	Changes in geometry	Repair area to be free of sharp changes in geometry (all radii > 5 mm), or sharp geometry to be faired-in	
	Surface preparation		In accordance with repair system specification
			Axial extent to be in accordance with design
	Surface temperature	In accordance with repair design	
	Defect		Dimensions do not exceed those for which the repair has been designed
			Defect nature to be that for which the repair has been designed
Location of repair	Axial extent and positioning to be in accordance with design		
Interface	Delamination	None at ends of repair	
Resin-rich layer	Cracks	None (check adhesive fillets)	
	Foreign matter, blisters and pits	Maximum 10 mm in width, 2,5 mm in height	
	Wrinkles	No step changes in thickness greater than 2,5 mm in height	
	Pin holes	None deeper than resin-rich layer	
	Resin colour	Uniform	
	Dry spots	None	
Repair laminate	Fibre orientation	As specified in design	
	Unimpregnated/dry fibre	None	
	Exposed cut edges/fibres	None	
	Foreign matter	None	
	Axial extent and positioning of the repair		As specified in the design
		Does not extend beyond prepared surface	

8.3 Repair of defects within the repair system

Repairs containing defects that exceed the limits in Table 14 should be removed and a new repair system applied. However, on agreement with the owner, local removal of the damaged area and reapplication of the repair system materials to this area are allowable if the repair system supplier can demonstrate that this will restore the full performance of the repair.

Dry areas in the resin-rich surface layer should be repaired by abrading and cleaning the affected area and then wetting out with more resin.

8.4 Inspection methods

The repair system supplier should provide guidance on techniques and methods for inspecting the repair system. These techniques may be applied immediately after the repair system application or during the lifetime of the repair system. In most cases the requirement is not to inspect the repair (composite) laminate, but to inspect the defect within the substrate.

8.5 Repair system maintenance and replacement strategy

8.5.1 Overview

The maintenance and replacement strategy for repair systems is a function of the type of original defect in the substrate.

For above-ground systems, visual inspection of the repair laminate for defects in accordance with Table 14 is recommended as part of the maintenance strategy. If defects are located, then further assessment is required. The frequency of inspection should be determined in accordance with the risk assessment.

If the assessment determines that replacement is required, then replacement options include:

- removal of the repair (e.g. through ultra-high-pressure water jetting or grit blasting) and replacement;
- repair of the repair laminate; in this case, the damaged repair laminate should be considered as the defect for design purposes, and a new repair designed according to 6.5;
- localized repair of the damaged area, see 8.3.

8.5.2 External defects

For external defects, it is assumed that further deterioration of the defect is stopped on application of the repair laminate. Therefore the maintenance strategy should be to ensure that the repair laminate remains intact, i.e. the repair laminate is not damaged or partially delaminated from the substrate.

8.5.3 Internal or through-wall defects

For internal corrosion or through-wall defects, further deterioration or growth of the defect may continue despite application of the repair laminate. Therefore in addition to the requirements set out in 8.5.2, the maintenance strategy should ensure that the internal defect does not grow to a size greater than assumed in the design or that the repair laminate does not delaminate from the substrate.

The frequency of inspection should be determined in accordance with the risk assessment.

9 System testing

System pressure testing should be specified by the owner if required or as recommended by the relevant design standard for the substrate.

All repairs shall be cured in accordance with the repair system supplier instructions before system testing.

The repaired system shall be flushed with an appropriate medium prior to testing.

The recommended procedure for hydro-testing is as follows. The hydro-test should be performed at 1,1 times the operating pressure for a period of at least 60 min, during which any changes in pressure and temperature shall be recorded. Any signs of leakage from the repair laminate shall be cause for rejection of the repair system.

In some circumstances, the owner may specify a hydro-test to 1,5 times the design pressure instead of the requirements of the previous paragraph. All supports and anchors shall be in place prior to pressure testing. Temporary supports or restraints should be added if necessary.

If the test pressure exceeds the pressure for which the repair system has been designed, then this higher pressure shall be considered as a separate design case. For the purposes of the design calculation, the hydro-test condition shall be treated as an occasional load.

10 Future modifications

Existing repair systems may be modified, but only after a design reassessment performed by the repair system supplier.

In the event of failure of a repair system, the preferred course of action is to remove the repair laminate. The repair of a failed repair by the simple application of additional material, particularly if the leak is caused by a delamination at the repair laminate/substrate interface, is unlikely to be successful and is not recommended.

11 Decommissioning

Reference should be made to the risk assessment prior to decommissioning of a repair system. If necessary, a separate risk assessment should be carried out.

The removal of repair material may be achieved by mechanical means (e.g. grit blasting, high-pressure water jetting). Procedures should be put in place to contain any dust that may be generated. Care should be taken to avoid damage to adjacent equipment that is to remain in service.

Annex A (normative)

Design data sheet

This annex provides an example of a design data sheet. This data sheet shall form the basis of the scope of work provided by the owner to the repair system supplier, and shall be used in the preparation of the design of the repair. One data sheet shall be completed for each repair required.

Customer Details			
Contact			
Company			
Address			
Postcode		Country	
Telephone			
Fax			
E-mail			
Job Reference			

Pipe Details			
Installation			
Location			
Quantity			
Pipe identification			
Pipe reference			
Pipe specification			
Material/Grade			
External diameter (mm)			
Wall thickness (mm)			
Medium			
Design temperature (°C)	Minimum		Maximum
Operating temperature (°C)	Minimum		Maximum
Pipe coating (existing)			
Existing repair on pipe for leak sealing			

Anticipated Conditions during Implementation of Repair				
Pipe temperature (°C)	Minimum		Maximum	
Ambient temperature (°C)	Minimum		Maximum	
Pipe pressure (MPa)				
Pipe contents				
Humidity (%)				
External environment				
Constraints				

Facilities to be Provided by Client/Installation (surface prep., etc.)

Other Information
NOTE This should include any remarks on previous repairs, fire protection requirements, etc.

Prepared by:

Date:

Annex B (normative)

Qualification data

B.1 Introduction

This annex describes the qualification data that the repair system supplier shall provide.

It is a requirement that all qualification tests be carried out using the same substrate material, surface preparation procedure, repair laminate, filler material, adhesive and application method (see Clause 5).

B.2 Data for repair laminates

For all repair classes, the following data are required:

- ply or layer thickness of the repair laminate;
- tensile modulus, strain to failure and strength in the circumferential direction, determined by test according to Table 4;
- tensile modulus, strain to failure and strength in the axial direction determined by test according to Table 4;
- Poisson's ratio in the circumferential direction (i.e. load direction circumferential, contraction axial), determined by test according to Table 4;
- shear modulus, determined by test according to Table 4. The test specimen geometry is shown in Table 4 and Figure B.1. This figure presents the orientation of the test sample as defined in ASTM D5379. Alternatively, the shear modulus of the resin may be used;
- Barcol or Shore hardness determined by test according to Table 4;
- glass transition temperature (T_g) or heat distortion temperature (HDT) for the resin system, determined by test according to Table 4;
- thermal expansion coefficient in the axial and circumferential directions, determined by test according to Table 4.

B.3 Data for repair laminate/substrate interface

The objectives of the following tests are not to produce data for use in design. The intent is to demonstrate that an adhesive bond can be achieved of adequate strength and durability for the repair laminate. Note that short-term strength measurements are not necessarily a good indicator of long-term performance.

For all repair classes, data on the short-term lap shear strength determined by test according to Table 4 are required. This short-term test shall be used to determine the average shear strength (minimum value 5 MPa) or the locus of failure (composite remaining on a minimum of 30 % of the bonded area). The substrates used in this test should be identical and be of the same material and lay-up as the repair laminate. Alternatively, it shall be demonstrated that the adhesive bond is stronger than the shear strength of the repair laminate by assessing the surface of the substrate material used in a lap shear specimen after testing.

For Class 3 repairs, if evidence of long-term durability of the adhesive bond between the repair laminate and the substrate is required and performance-based testing has not been carried out to provide data for design (see 6.5.6), the long-term lap shear strength shall be determined by test according to Table 4. This test shall be carried out following immersion in water (or other relevant medium) at the qualification test temperature (minimum 40 °C) for 1 000 h. The average shear strength determined from this test shall be at least 30 % of the value from the short-term lap shear test determined above.

B.4 Requirements for repairs to substrates with non-through-wall defects (type A design case)

The objective of the required short-term pipe spool survival test, in accordance with Annex C, is not to produce data for use in design, but rather to demonstrate that the repair system can provide adequate strength to a damaged pipe spool.

B.5 Requirements for repairs to substrates with through-wall defects (type B design case)

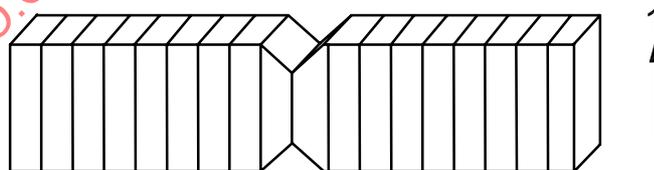
For all repair classes, the following data are required:

- fracture toughness parameter γ_{CL} , determined by test in accordance with Annex D;
- impact performance, determined by test in accordance with Annex F.

B.6 Performance testing

The supplier may carry out performance testing to determine design allowables in accordance with Annex E. The long-term strength (or strain to failure) design allowables are determined by either:

- 1 000-h survival;
- regression testing;
- representative repair laminate coupon regression testing.



Key

1 direction parallel to laminate lay-up

NOTE See ASTM D5379/D5379M-05, G₃₁, for details.

Figure B.1 — Test specimen geometry from ASTM D5379

Annex C (normative)

Short-term pipe spool survival test

C.1 Introduction

This annex describes the test method for qualification of repairs to non-through-wall defects (type A defect).

The purpose of the test is to confirm that the repair system has acceptable interlamina shear and bond strength. It demonstrates the structural integrity of the repair system up to the yield strength of the original pipe spool for the selected defect.

C.2 Method

The following test shall be completed using a metallic pipe of at least 100 mm diameter and minimum length of six times the diameter in addition to the length of the repair.

A defect shall be machined into the pipe. The defect shall have an axial length, l , of at least two pipe diameters and a circumferential width, w , of at least one-quarter of the pipe diameter. The depth of the defect shall be 80 % of the original wall thickness. A radius may be machined outside the edge of the defect, but the dimensions of machined area shall not exceed $2l$ nor $2w$, as shown in Figure C.1. To avoid stress concentrations, the interior and exterior corners should be machined with a radius. The edge of the repair shall be at least three times the pipe diameter away from the ends of the pipe spool.

The test pressure of the spool, p_f (expressed in megapascals), shall be calculated using Equation (C.1):

$$p_f = \frac{2ts_a}{D} \quad (\text{C.1})$$

where

t is the wall thickness of the undamaged spool, expressed in millimetres;

D is the external pipe spool diameter, expressed in millimetres;

s_a is the measured yield stress or mill certification, expressed in megapascals.

A repair laminate shall be applied to restore the pipe spool to pressure, p_f . The minimum thickness of the repair, t_{repair} , shall be calculated using Equation (C.2):

$$t_{\text{repair}} = \frac{1}{E_c \varepsilon_{\text{short}}} \left(\frac{p_f D}{2} - s_a t_s \right) \quad (\text{C.2})$$

where

t_s is the remaining wall thickness of the pipe spool at the defect, expressed in millimetres;

E_c is the tensile modulus in the circumferential direction of the composite laminate expressed in megapascals;

$\varepsilon_{\text{short}}$ is the short-term failure strain limit of the composite, defined as 0,008.

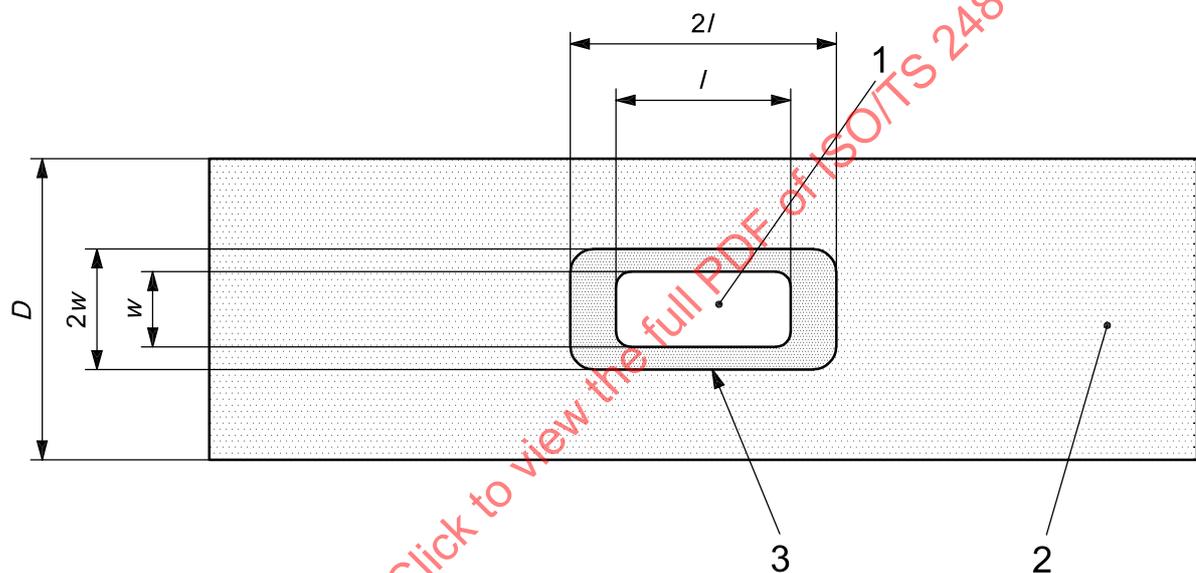
The actual repair thickness shall be determined by dividing this calculated thickness by the individual layer or wrap thickness. The required number of wraps of the repair shall be this number rounded up to the next integer. The actual repair thickness shall be the number of wraps times the individual wrap thickness.

The repaired spool shall be pressurized to p_f . Pressure testing shall be in accordance with ASTM D1599.

Successful demonstration requires the repaired pipe spool to survive the pressure loading to p_f . If successful, then the repair system shall be considered qualified for repair of defects up to the selected depth of defect used in the test.

C.3 Report

A report shall be prepared giving the test conditions, details of the repair system and the individual test results.



Key

- 1 defect with $l > D/2$ and $w > D/4$
- 2 pipe
- 3 machined area (including taper)

Figure C.1 — Defect dimensions

Annex D (normative)

Measurement of γ_{LCL} for through-wall defect calculation

D.1 Introduction

This annex describes the test method for measurement of the toughness parameter (energy release rate) for the repair laminate/substrate interface, γ_{LCL} , to be used in Equations (11), (12), (13) and (14) in 6.5.7.

D.2 Method

Sections of metallic pipe of minimum diameter 10 mm and minimum thickness 3 mm shall be used. To represent typical defects, circular holes shall be drilled through the wall thickness and the repair laminate applied following the qualification application procedure. The repair system shall be applied with the defects in the 6 o'clock orientation.

The metallic pipe section used for the preparation of the test specimen should be appropriate for the anticipated failure pressure of the repair. Yielding of the pipe prior to failure should not occur.

Internal pressure shall be applied, and the value at which the repair begins to leak shall be recorded.

The test shall be carried out at the qualification test temperature.

The test pressure shall be increased in accordance with ASTM D1599.

A minimum number of nine tests shall be carried out, covering a minimum of three hole sizes, typically of diameters 10 mm, 15 mm and 25 mm. For the larger diameters, the defect may be simulated by using a smaller hole and a circular polymeric release film of the appropriate diameter placed over the hole prior to application of the repair laminate.

Failures should take the form of delamination of the repair laminate from the substrate, followed by leaking from the edge of the repair laminate. At small hole sizes, failure can occur through weeping of the test fluid through the thickness of the laminate or through yielding of the substrate. In this event, these tests should be disregarded and a new test carried out using a larger hole size. All failure points should relate to the delamination failure mechanism.

D.3 Calculation of γ_{LCL}

The value of γ_{LCL} , expressed in joules per square metre, shall be calculated by fitting Equation (11) in 6.5.7 to the data.

The following procedure shall be followed, using Equations (D.1) through (D.5), where

n is the number of observed data points [$A(d_i), p_i$];

p_i is the pressure, expressed in megapascals, at failure of observation i , where $i = 1, n$;

$A(d_i)$ is the function of defect size and repair laminate properties of observation i , where $i = 1, n$;

$A(d_i)$ is defined as shown in Equation (D.1):

$$p_i = A(d_i)\sqrt{\gamma_i}$$

where

$$A(d_i) = \sqrt{\frac{0,001}{\frac{(1-\nu^2)}{E_{ac}} \left\{ \frac{3}{512t_i^3}d_i^4 + \frac{1}{\pi}d_i \right\} + \frac{3}{64Gt_i}d_i^2}} \quad (D.1)$$

and where

E_{ac} is the combined tensile modulus of the repair laminate $\sqrt{E_a E_c}$, expressed in megapascals;

G is the shear modulus of the repair laminate, expressed in megapascals;

ν is the Poisson's ratio of the repair laminate (see Annex B for definition);

d_i is the diameter of defect, expressed in millimetres;

t_i is the thickness of the repair laminate, expressed in millimetres.

The mean energy release rate, γ_{mean} , is calculated using Equation (D.2):

$$\gamma_{\text{mean}} = \left(\frac{\sum_{i=1}^n A(d_i)p_i}{\sum_{i=1}^n A(d_i)^2} \right)^2 \quad (D.2)$$

The lower confidence limit of the energy release rate, γ_{LCL} , is calculated using Equation (D.3):

$$\gamma_{\text{LCL}} = \left[\frac{\sum_{i=1}^n A(d_i)p_i}{\sum_{i=1}^n A(d_i)^2} - t_{\nu}\sigma \sqrt{\frac{1}{\sum_{i=1}^n A(d_i)^2}} \right]^2 \quad (D.3)$$

where σ is the variance of measurement of pressure and is given by Equation (D.4):

$$\sigma = \sqrt{\frac{\sum_{i=1}^n (p_i - A(d_i)\sqrt{\gamma_{\text{mean}}})^2}{(n-2)}} \quad (D.4)$$

and where t_{ν} is the Student's t -value and is based on a two-sided 0,025 level of significance, i.e. 95 % lower confidence limit. Values of t_{ν} are given as a function of number of variables, n , in Table D.1.

Table D.1 — Student's *t*-value for double-sided 0,025 level of significance

Number of variables <i>n</i>	Degrees of freedom <i>n</i> -2	Student's <i>t</i> -value = 0,025
7	5	2,841
8	6	2,752
9	7	2,685
10	8	2,634
11	9	2,593
12	10	2,560
13	11	2,533
14	12	2,510
15	13	2,490
16	14	2,473
17	15	2,458
18	16	2,445

The value of γ_{LCL} calculated from Equation (D.3) shall be used in Equations (11) to (14).

D.4 Qualification of other substrates

If the repair system has been fully qualified for one substrate, then a simplified qualification procedure is available for other substrates. In this procedure, only three tests are required to be completed. The three tests should be identical to three of the nine tests in terms of repair thickness and defect size used in the full qualification test programme.

The value of γ for this substrate, substrate 2, $\gamma_{LCL,substrate2}$, is given by Equation (D.5):

$$\gamma_{LCL,substrate2} = \gamma_{LCL,substrate1} \frac{\gamma_{mean,substrate2}}{\gamma_{mean,substrate1}} \tag{D.5}$$

In this equation, “mean” implies the average of the three tests.

D.5 Test report

A report shall be prepared giving the test conditions and details of the repair method, including the materials of construction and surface preparation technique, the individual data points and the derived value of γ_{LCL} .

Annex E (normative)

Measurement of performance test data

E.1 Introduction

If suppliers carry out performance-based testing, then this annex shall be followed. Suppliers do not have to carry out performance testing to qualify their system, it is an option for them to choose.

This annex describes the test methods for measurement of design allowables to be used in 6.5.6. The test method options are:

- a) survival testing, in which the repair system is subjected to a period of sustained load for 1 000 h;
- b) regression testing based on a series of tests on the repair system over different time periods and extrapolation to design life;
- c) regression testing of representative coupons, followed by confirmation of long-term coupon test results with survival testing.

All tests shall be carried out at the qualification test temperature.

E.2 Methods

E.2.1 Survival testing

Sections of pipe of minimum diameter 100 mm and minimum thickness 3 mm shall be used and the repair system applied.

A value of internal pressure, p_{test} (expressed in megapascals), shall be applied (as defined by the repair system supplier) and sustained for 1 000 h. If any deterioration of the repair laminate in the form of cracking or delamination occurs, then the repair system shall have failed the test. Three identical tests shall be performed, and repair system qualification is only achieved if the repair laminate survives all three tests.

If the strain with the composite laminate is less than the short-term failure strain limit of 0,008 defined in Annex C, then the 95 % lower confidence long-term stress, s_{lt} (expressed in megapascals), is calculated using Equation (E.1):

$$s_{\text{lt}} = \frac{p_{\text{test}} D E_{\text{c}}}{2(E_{\text{c}} t_{\text{min}} + E_{\text{s}} t_{\text{s}})} \quad (\text{E.1})$$

Otherwise, the 95 % lower confidence long-term stress, s_{lt} (expressed in megapascals), is calculated using Equation (E.2):

$$s_{\text{lt}} = \frac{1}{t_{\text{min}}} \left(\frac{p_{\text{test}} D}{2} - s_{\text{a}} t_{\text{s}} \right) \quad (\text{E.2})$$

where

E_{c} is the circumferential modulus of the repair laminate, expressed in megapascals;

- E_s is the modulus of the substrate, expressed in megapascals;
- D is the external diameter of test spool, expressed in millimetres;
- s_a is the measured yield stress of the surface, or the mill certification yield stress;
- t_{\min} is the thickness of repair laminate, expressed in millimetres;
- t_s is the thickness of substrate test spool, expressed in millimetres.

Further guidance on survival pressure testing procedures may be obtained from ASTM D1598.

E.2.2 Regression testing

Sections of pipe of minimum diameter 100 mm and minimum thickness 3 mm shall be used and the repair system applied.

A series of test specimens shall be subject to sustained pressures of different values. The time at which the repair laminate shows signs of deterioration defined as cracking or delamination shall be recorded. The results shall be plotted (log/log) and the required long-term pressure shall be determined by a regression analysis using the 95 % lower confidence limit and extrapolation to design life.

If the strain with the composite laminate is less than the short-term failure strain limit of 0,008 defined in Annex C, then the conversion from test pressure, p_{test} (expressed in megapascals), to stress, s_{lt} (expressed in megapascals), within the repair laminate for each data point shall be carried out using Equation (E.3):

$$s_{\text{lt}} = \frac{p_{\text{test}} D E_c}{2(E_c t_{\min} + E_s t_s)} \quad (\text{E.3})$$

Otherwise, the 95 % lower confidence long-term stress, s_{lt} (expressed in megapascals), is calculated using Equation (E.4):

$$s_{\text{lt}} = \frac{1}{t_{\min}} \left(\frac{p_{\text{test}} D}{2} - s_a t_s \right) \quad (\text{E.4})$$

where

- E_c is the circumferential modulus of the repair laminate, expressed in megapascals;
- E_s is the modulus of substrate, expressed in megapascals;
- D is the external diameter of test spool, expressed in millimetres;
- s_a is the measured yield stress of the surface, or the mill certification yield stress;
- t_{\min} is the thickness of repair laminate, expressed in millimetres;
- t_s is the thickness of substrate test spool, expressed in millimetres.

At least 18 results are required in order to perform the regression analysis. ASTM D2992 provides further guidance on the long-term testing of composite materials and ISO 14692 provides guidance on the analysis of the data to calculate s_{lt} .